

Benthic diatom communities  
of coastal marine environments  
in the Windmill Islands, Antarctica

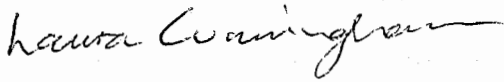
By

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Submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy,  
University of Tasmania, May 2003.

## Declaration

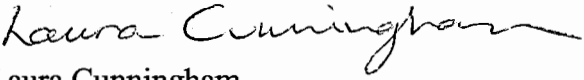
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## *Abstract*

This project examined the effects of ecological factors and anthropogenic contaminants on benthic diatom communities near Casey Station, in the Windmill Islands, Antarctica. Preliminary sampling indicated significant compositional differences occurred between diatom communities in bays immediately adjacent to Casey Station and those more distant. Subsequently, a more detailed appraisal of spatial variability in benthic diatom communities was undertaken. Significant differences in community composition were demonstrated for all scales examined, however, increased distances between samples typically corresponded to increased dissimilarity.

The influence of environmental factors on spatial variability was assessed using direct gradient ordination techniques. Grainsize, particularly the mud content, accounted for the majority of variation in diatom abundances explained by the measured environmental variables. Differences in light availability, water depth and grain-size explained 60% of the variation in community composition observed between locations. The remaining 40% of the variation in diatom community composition remains unexplained; potential causes include freshwater input, and chemical contamination.

A preliminary analysis of temporal variability in benthic diatom communities from the Windmill Islands is presented. Seasonal, short-term (100's of years) and long-term (1000's of years) changes in community composition were examined at several locations. Temporal variability of the diatom communities within Brown Bay was also assessed, in conjunction with metal and  $Pb^{210}$  data. Within one core, a shift in community composition was detected subsequent to the onset of chemical contamination. Some changes in species abundance exceeded the natural variability observed in control cores, and thus were attributable to chemical contamination.



Relationships between diatom abundances and concentrations of different metals within Brown Bay were examined using direct gradient analyses. Approximately 50% of the variation in the diatom community composition was related to metal concentrations. Further clarification of the interactions between metals, sediment grain-size and diatom community composition would be required prior to the development of predictive models. Direct gradient analyses also demonstrated a weak correlation between diatom community composition and hydrocarbon distribution.

Manipulative field experiments were used to demonstrate that the composition of diatom communities can be influenced by both metal and hydrocarbon contaminants at concentrations comparable to levels produced by station activities. This supports the conclusion that anthropogenic contaminants are responsible for some compositional differences observed in diatom communities, both within Brown Bay and between Brown Bay and reference locations.

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## List of Acronyms Used

AAD	Australian Antarctic Division
AGAL	Australian Government Analytical Laboratories
ANARE	Australian National Antarctic Research Expeditions
ANSTO	Australian Nuclear Science and Technology Organisation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
IASOS	Institute of Antarctic and Southern Ocean Studies

### ***General Introduction***

#### **The Windmill Islands**

##### **Description**

The Windmill Islands are a small deglaciaded oasis in Wilkes Land, Antarctica (Fig. 1.1) and are the only large area of seasonally snow-free terrain for over 400 km either east or west (Murray and Luders, 1980). The Windmill Islands cover an area of approximately 75 km<sup>2</sup> between 66°10'-66°35' S, 110°10'-110°50' E. They are abutted to the east and north by the Law Dome, a small ice cap approximately 200 km in diameter. This ice cap overlies several islands, thus forming small peninsulas (Goodwin, 1993). The southern end of the Windmill Island region is delineated by the Vanderford Glacier, which protrudes more than 9 km into the sea (Murray and Luders, 1980), occupying a trough 1000-2000 m below sea level (Goodwin, 1993).

The offshore bathymetry is dominated by a large region of shallow water, up to 200 m deep, known as the Peterson Bank. This feature extends up to 80 km due north of the Windmill Islands (Goodwin, 1993), while the southern end terminates in Penney Bay (still within the Windmill Islands). The local bathymetry is a complex system of islands, shoals and steep-sided submarine channels (Tate et al., 2000). The shallow marine environment consists of a sedimentary mosaic of boulders, cobbles and gravel, interspersed with mud and sand. Tidal currents are relatively insignificant in the region, whilst in the more exposed areas currents are predominantly wind-controlled (Cathers et al., 1998).

The Windmill Islands consist of several peninsulas and small island groups; these can be divided into three regions on the basis of their topography. The islands

between Mitchell Peninsula and the Vanderford Glacier are much steeper, and often bordered by abrupt cliffs (Murray and Luders, 1980). Two islands in this group, Odbert and Ardrey Islands, exceed 100 m in height. The northernmost islands, namely the Donovan and Frazier Island groups, also have extensive cliffs on their shoreline but are typically less than 100 m in height (Murray and Luders, 1980). Located further off-shore, these islands are situated in deeper water. In contrast, the islands adjacent to the Mitchell, Clarke, and Bailey Peninsulas (Fig. 1.1) are situated in relatively shallow water (Murray and Luders, 1980), and have a lower elevation (Goodwin, 1993).

The current ANARE research station, Casey Station, is situated on the Bailey Peninsula at 66° 17' S, 110° 32' E. The topography of Law Dome deflects the katabatic winds of the interior away from Casey Station, resulting in an average of 96 days of predominantly easterly gale-force winds per year (Murray & Luders, 1990; Melick & Seppelt, 1997). The frequency of gale-force winds is higher in the more southerly regions of the Windmill Islands due to the proximity of the Vanderford Glacier. The Windmill Islands have a dry climate with a mean annual snowfall of 195 mm yr<sup>-1</sup> (rainfall equivalent) (Melick & Seppelt, 1997). Mean temperatures for the warmest and coldest months recorded at Casey Station on Bailey Peninsula are 0.3 °C and -14.9 °C respectively, with extreme values ranging between 9.2 °C and -41 °C (Melick & Seppelt, 1997). The warmer spring and summer periods sees much melting of snow. Similarly, sea-ice typically disappears between December and February before reforming the next autumn. Marked seasonal variations also occur in the amount of bright sunlight experienced each day. Ten year averages (Australian Bureau of Meteorology) reveal that November experiences the most sunlight (6.7 hours per day) while June has the least amount (0.1 hours of bright sunlight per day).

The geology of the Windmill Islands consists of low-pressure metamorphic rocks, including psammitic gneisses and migmatic metapelites, interlayered with igneous intrusions of granite, dolerite and gabbro (Paul et al., 1995). The northern islands are



**Figure 1.1** Map of the Windmill Islands, with the current ANARE research station, Casey indicated by ■. Inset 1 shows the geographical position of the Windmill Islands relative to Australia.

typically comprised of metamorphic rocks, whilst the southern islands consist predominantly of igneous rocks. Quaternary sediments that overly the basement rock in the vicinity of Casey Station predominantly consist of coarse-grained sands and gravels. These unconsolidated sediments accumulate in low-lying depressions and form deposits up to several meters thick (Snape et al., 1998). Soils of the region are generally poorly developed and typically have high concentrations of coarse mineral particles and total organic carbon, combined with a low pH and low C/N ratios (Beyer et al., 2000). Despite this, the Windmill Islands are home to the best-developed terrestrial vegetation in continental Antarctica (Melick and Seppelt, 1997).

A wide variety of algae, invertebrates, and fish inhabit the near-shore marine areas, providing a food source for penguins and seals (Murray and Luders, 1980). Both Adelie and Emperor penguins are common in the Windmill Islands. Eleven species of flying birds, including the southern fulmar, the Antarctic petrel and Wilson's storm-petrel are found in the region (Murray and Luders, 1980). Weddell seals, crabeater seals, Ross seals and leopard seals have all been recorded in the Windmill Islands. In addition, the Windmill Islands are the only known place on the Antarctic continent where southern elephant seals breed (Murray and Luders, 1980).

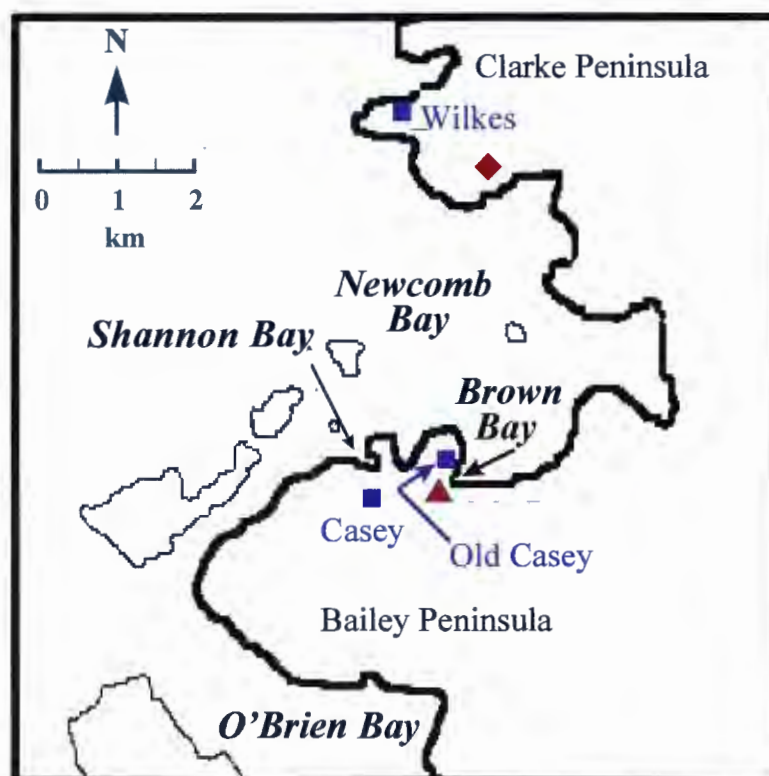
### **Human Occupation of the Windmill Islands**

The Windmill Islands are named after the US Navy 'Operation Windmill' which first discovered these islands in 1947. The first Australian research expedition to the region occurred in January, 1956 (Law, 1959 in Murray and Luders, 1980). During 1957, the International Geophysical Year, America established the first permanent research station in the region. This station, known as Wilkes, is located on the Clarke Peninsula (Fig. 1.2) and consisted of over 40 different structures and buildings. In 1959, control of Wilkes was handed over to the Australian Antarctic Program. Wilkes was used for a further ten years, until the opening of a new station (now known as "Old Casey") in 1969 on the Bailey Peninsula (Fig. 1.2). The current Casey Station was opened in 1989 and is located at a higher elevation on Bailey Peninsula, approximately 800 m southwest of Old Casey.

Waste from the first two stations was dumped into nearby tip sites until 1986, when a change of policy subsequently resulted in waste either being incinerated on station or returned to Australia. The early tip sites contained domestic waste as well as waste from the various mechanical workshops, such as engine parts, batteries, and old fuel drums (Snape et al., 2001). One of these tip sites is located near Wilkes Station and consists of an estimated 20,000 m<sup>3</sup> of rubbish which accumulated over the twelve years of operation (Snape et al., 1998). Refuse from the Old Casey station was dumped into the nearby Thala Valley (Deprez et al., 1999) and occasionally



bulldozed onto the sea-ice in the adjacent Brown Bay (Fig 1.2). Despite an attempt to clean up this site during the 1995/96 summer season, it is estimated that 500-2500 m<sup>3</sup> of rubbish still remains at the tip site and in the adjacent Brown Bay (Snape et al., 1998).



**Figure 1.2** Map showing locations of research stations (■), both past and present, within the Windmill Islands. The Thala Valley tip site (▲) and the main Wilkes tip site (◆) are also shown.

## Human Impacts in Antarctica

### General overview

Human beings can influence the Antarctic ecosystem in a multitude of ways, including chemical contamination, interruption of animal reproductive cycles or modification of animal behaviour due to the presence of humans, as well as the direct killing of animals (i.e. sealing and whaling). For the purpose of this study, the term

human impacts will be used to refer solely to the release of chemical contaminants, and any subsequent effects that these contaminants have on the Antarctic ecosystem.

Antarctica is widely regarded as the last remaining wilderness, however the integrity of this environment is threatened by chemical contamination resulting from human activities. Several major pollution events have resulted from shipping accidents. Examples of this include the wreck of the *Bahia Paraiso* in Arthur Harbour, which released 600 m<sup>3</sup> of oil into the marine environment (Kennicutt and Sweet, 1992), and the spillage of 850 m<sup>3</sup> of petroleum which resulted subsequent to the grounding of a Russian tanker at Grande Terre, Iles Kerguelen (Jouventin et al., 1994).

The impact of the *Bahia Paraiso* oil spill has been relatively well studied. Only areas within a few kilometers of the wreck were immediately affected, with intertidal macroalgae, limpets, birds, sediments and shores all coated in oil (Kennicutt and Sweet, 1992). Within several weeks of the main spillage event, limpet populations had been reduced by 50%, (Kennicutt et al., 1990) and had not fully recovered 1 year later (Kennicutt and Sweet, 1992). One month after the spill, intertidal beaches had hydrocarbon concentrations, of up to 600 ppm (Cripps, 1992a), significantly elevated above background levels. Two years after the spill, PAH concentrations in most sediments and organisms had returned to background levels, with the high energy environment assisting in the dispersal process. Sediments within Arthur Harbour are highly mobile and fine-grained sediments disappear from one year to the next (Kennicutt et al., 1995), a factor which contributed to the quick dispersal time of contaminants within this environment. In contrast, beach sediments sampled 2 years after the spill contained unusually high concentrations of petroleum hydrocarbons. Periodic leakage of fuels, prevailing currents, and calm weather conditions contributed to the build-up of contaminants in these relatively low energy areas (Kennicutt and Sweet, 1992).

The threat to the Antarctic environment comes not only from such catastrophic spillage events, but also from daily activities associated with research stations

(Kennicutt et al., 1995). A 'halo' of contaminants, typically consisting of heavy metals and petroleum hydrocarbons, has been found around all stations so far examined (Kennicutt and McDonald, 1996). Much of the chemical contamination present within the Antarctic environment is a legacy of past activities (Snape et al., 2001). Detailed information on the extent of such contamination is available for only a few sites, including McMurdo Station (Crockett, 1997; Kennicutt et al., 1995), Signy Island (Cripps, 1992b) and Casey Station (Deprez et al., 1999; Snape et al., 2001).

Hydrocarbon concentrations up to 4500 ppm have been recorded in subtidal marine sediments around McMurdo Station, significantly higher than levels recorded at the New York Dump (2900 ppm) but, similar to that seen in oil-based drilling muds (Lenihan et al., 1990). Samples taken from more remote locations within McMurdo Sound contained hydrocarbon concentrations at, or below, the detection level of 0.15ppm (Kennicutt et al., 1995). Hydrocarbon concentrations in sediments at McMurdo Station and Signy Island are significantly higher than in seawater, probably due to the deposition of compounds sorbed onto particulate mater (Cripps, 1992b). The absorbency of hydrocarbons onto particulates is increased at low temperatures (Meyers and Quinn, 1973).

Sediment samples collected adjacent to old tip sites and a sewage outfall at McMurdo station also had significantly increased concentrations of silver, arsenic, lead, antimony, tin and zinc compared to background levels (Lenihan et al., 1999). Tin was particularly enriched, with levels up to 25 ppm recorded.

### *Human impacts on Antarctic biota*

Information on the biological effects of such contamination is limited to a few studies, most of which have examined the effects on faunal communities. Faunal communities at McMurdo Sound varied dramatically along a gradient of pollution (Lenihan and Oliver, 1995). Highly contaminated sediments supported only low abundances of a few opportunistic species such as the polychaete worms

*Ophryotrocha claperedii* and *Capitella* spp., whilst large bivalves were absent in these sediments. Intermediate levels of sediment contamination resulted in communities which had a relatively high number of species, predominantly deposit feeders (Lenihan, 1992). Faunal communities from uncontaminated sediments were both abundant and diverse. Large bivalves were common while only a few polychaete worms were found. The number of opportunistic polychaete worms was significantly higher at contaminated sites, however, the total number of crustaceans and polychaetes decreased with increasing pollution, as did the abundance of sedentary and suspension feeding groups (Lenihan and Oliver, 1995).

Laboratory and field based experiments revealed that the burrowing behaviour of amphipods, heart urchins and tanaid crustaceans ceased in highly contaminated sediments taken from McMurdo Station, but continued in uncontaminated sediments (Lenihan, 1992). Furthermore, tanaid crustaceans exhibited avoidance behaviours (ie climbing walls, and swimming) when placed in enclosures containing contaminated sediments. Transplantation of faunal communities further indicated the severe nature of the impacts, demonstrated by dramatic differences in species composition. Once again, communities exposed to polluted sediments consisted almost entirely of opportunistic species, whilst control transplants were almost identical to the natural communities that occurred at uncontaminated sites (Lenihan, 1992).

The toxicity of hydrocarbons on *Euphausia superba* (Antarctic krill) and *Notothenia* (rockcod), was examined by Ogrodowczyk (1981), with krill proving to be extremely sensitive. Amphipods have also proven sensitive to hydrocarbon contamination, with survivorship greatly reduced in hydrocarbon contaminated sediments, relative to controls, in both field and laboratory experiments (Lenihan, 1992). Bioassays of trace metals present in the tissues of two benthic fish (*Trematomus hansonii* and *T. bernachii*) and a nemertean worm (*Parborlasia corrugatus*) were less conclusive, as samples taken from the polluted areas were highly variable, with both higher and lower concentrations recorded relative to samples from control locations (Lenihan et al., 1990).

To date, only one study has examined the influence of contamination on diatom communities in Antarctica. This study investigated the possible impacts of a sewage outfall at McMurdo Station on the abundance and composition of sea-ice diatom communities (Crockett, 1996). High concentrations of metals, particularly copper, and low concentrations of several organic contaminants were recorded near the sewage outfall; this corresponded with decreased microalgal biomass, measured by both total cell numbers and chlorophyll *a* content. Changes in the species composition of the sea-ice diatom communities were also recorded at sites close to the sewage outfall, relative to control sites. Increased predominance of *Fragilariopsis* spp. near the sewage outfall was particularly noticeable (Crockett, 1996), possibly indicating that this is a pollution-tolerant genus.

### **Human Impacts in Australian Antarctic Territory**

A number of small petroleum hydrocarbon spills have occurred in Australian Antarctic Territory. For example, several small spills have occurred during ship to shore transfer of fuel at Davis Station in recent years (Green and Nichols, 1995) resulting from the deterioration of the equipment involved. In addition to these spillage-related events, low-level contamination by petroleum hydrocarbons can result from daily station activities such as vehicle usage, or periodic discharge of effluent containing petroleum (Green and Nichols, 1995). Petroleum hydrocarbon contaminants have been recorded in both soils and marine sediments around both Davis Station (Green and Nichols, 1995) and Casey Station (Deprez et al., 1999; Scouller et al., 2000). Deprez and Canning (2000) state that petroleum hydrocarbons are the most frequently encountered contaminant around all Australian stations in the Antarctic.

Heavy metal contamination of areas immediately adjacent to research stations in the Australian Antarctic Territory is also of concern. Sources of heavy metal contaminants include disused tip sites (Deprez et al., 1994, 1999; Snape et al., 2001) and sewage discharge (Morris et al., 2000). No published data on heavy metal

contamination in Australian Antarctic regions, other than Casey Station, is currently available.

### *Human Impacts around Casey Station*

Casey Station has not been exempt from the contamination recorded from around other Antarctic bases. Station activities continue to contribute low levels of contaminants, one example being heavy metal contamination from sewage discharge (Morris et al., in prep). Several spillage events have also occurred. In 1982 approximately 38,000 litres of diesel fuel leaked from the storage farm adjacent to the wharf and entered Newcomb Bay, resulting in an oil slick (Deprez et al., 1994). In 1990, a temporary storage tank, adjacent to the wharf, leaked with approximately 59,000 litres of fuel lost (Deprez et al., 1994). In 1999, a further 16,000 litres of fuel was spilt at the upper fuel farm, the majority of which entered Brown Bay (Deprez et al., 1999).

Approximately twenty sites in the immediate vicinity of Old Casey have been identified as contaminated, or potentially contaminated (Deprez et al., 1994, 1999). These sites include the Old Casey mechanical workshop, the Old Casey powerhouse and the now-defunct Thala Valley tip site. A geochemical survey within Thala Valley found heavy metal and hydrocarbon concentrations were significantly greater than background values (Deprez et al., 1994, 1999), and exceeded the Australian and New Zealand Environment and Conservation Council (ANZECC) environmental investigation guidelines (Snape et al., 2001). The soils adjacent to the Old Casey mechanical workshop had the highest hydrocarbon concentrations recorded in the area; this results from numerous small fuel spills at this site between 1969 and 1989 (Snape et al., 2001).

The mobility of contaminants from the above sites increases the potential for environmental impacts. Petroleum hydrocarbons have been traced from the mechanical workshop, through the catchment area, and into Newcomb Bay (Guille et al., 1997; Cole et al., 2000). The processes responsible for this movement have yet to be fully clarified, with both surface (Guille et al., 1997) and subsurface (Cole et

al., 2000) waters implicated. Water movement through the Thala Valley tip site has also been linked to the dispersal of metal contaminants into the adjacent marine environment. An estimated eight cubic meters of contaminated tip and tip-associated material was removed by surface runoff and deposited into Brown Bay during the 1998/99 summer period (Cole et al., 2000).

Thirty nine sites from around Wilkes Station and the associated tip sites have been identified as contaminated (Snape et al., 1998). These sites include fuel bladders (condition unknown) and several caches of more than 50 fuel drums, some of which are leaking (Snape et al., 1998). One of these fuel caches is situated less than 15 meters from Newcomb Bay. Batteries, gas cylinders, ferrous silicate, aluminium chips, drums of caustic soda, and drums of other unidentified chemicals have also been recorded at these contaminated sites (Snape et al., 1998).

Some soils around Wilkes are contaminated with hydrocarbons, particularly around the old fuel farm. In summer, surface and ground waters that flow through these sediments visibly contain petroleum hydrocarbon contaminants (Snape et al., 1998). Heavy metal contaminants are also present within sediments, and surface waters, around Wilkes Station and the associated tip site. Copper and zinc are common contaminants whilst some sites have extremely high concentrations of silver and cadmium (Snape et al., 1998).

#### *Human Impacts on the Marine Environment around Casey Station.*

Recent studies have demonstrated higher concentrations of some heavy metals and hydrocarbon in sediments collected from bays adjacent to Casey Station as compared to control locations (Snape et al., 2001; Scouller et al., 2000). Brown Bay, adjacent to the Thala Valley tip site is the worst affected with some heavy metals (including copper, lead, iron and zinc) occurring in the sediments at concentrations 10 to 100 times higher than background levels. Seawater collected from Brown Bay also contains elevated concentrations of copper, cadmium, lead and zinc (Deprez et al., 1994, 1999). Petroleum hydrocarbons, derived from lubrication oil and Special Antarctic Blend diesel fuel (SAB) are present in the surface sediments of Brown Bay



at concentrations ranging between 40 and 200 mg kg<sup>-1</sup> (Snape et al., 2001). Petroleum hydrocarbons are below detection limits in sediments from control locations (Snape et al., 2001). Elevated levels of ammonia, total phosphorous and bacteria have been recorded near the station sewage outfall in Shannon Bay (Morris et al., 2000). Sediments from Shannon Bay also have elevated concentrations of some metals (Snape et al., 2001) (Table 1.1).

Contamination of the marine environment from the abandoned Wilkes station and associated tip site is also of concern, with thin films of oil observed extending outwards from Wilkes into Newcomb Bay during exceptionally warm summers (Snape et al., 1998).

Locations	Cu	Zn	Pb	Ag	Cd	Ni	Cr	Sb
Brown Bay	26.58	72.78	77.05	0.70	0.82	3.049	5.425	1.1
Brown Bay	12.18	45.33	25.67	0.57	0.55	2.962	4.642	0.3
Brown Bay	5.8	61.74	2.00	n.d.	1.75	6.203	8.517	0.7
Brown Bay	3.12	31.21	11.25	n.d.	0.39	2.169	3.075	0.3
Shannon Bay	5.89	57.71	2.34	0.47	3.49	4.816	5.873	0.2
Shannon Bay	3.01	21.73	n.d.	n.d.	0.86	3.152	3.846	n.d.
Newcomb Bay	2.13	25.36	1.19	n.d.	0.54	2.826	3.398	n.d.
Beall Island	4.09	46.32	n.d.	n.d.	1.03	5.971	6.539	n.d.
Beall Island	2.63	16.92	n.d.	n.d.	0.67	2.144	2.312	n.d.
Beall Island	2.11	16.75	n.d.	n.d.	1.92	4.127	4.619	n.d.
Beall Island	2.49	27.62	n.d.	n.d.	1.64	4.170	4.296	n.d.
O'Brien Bay	2.45	n.d.	n.d.	0.47	0.68	1.883	2.200	n.d.

Table 1.1: Heavy metal concentrations (mg kg<sup>-1</sup>) in marine sediments from several locations in the Windmill Islands. Marine bays adjacent to contaminant sources (tip site and sewage outfall) are shaded. Data from Snape et al., 2001.

### *Previous studies on human impacts on biota at Casey Station*

Benthic communities are often used in environmental monitoring because they have a fixed spatial relationship with the source of pollution, whilst planktonic species or fish can move in and out of the area and thus avoid stressful conditions (Snape et al., 2001). Several studies have examined the effects of chemical contamination on benthic fauna near Casey Station. Bioaccumulation studies have revealed that marine



invertebrates collected from Brown Bay near Thala Valley have increased concentrations of metals compared to control locations (Duquesne and Riddle, 2002); however, there was some variability between the taxa assayed. Concentrations of lead and zinc were elevated in all species examined, arsenic and copper concentrations were elevated in the heart urchin *Abatus nimrodi* and the bivalve *Laternula elliptica*, and elevated cadmium concentrations occurred in both of the heart urchins *Abatus ingens* and *A. nimrodi*.

Studies of soft-sediment infauna (Stark, 2000; Stark, 2001) have revealed significant differences in the abundances of several species between control and contaminated locations. Many taxa occurred only at control locations whilst a polychaete worm, typical of polluted areas, was recorded only at contaminated locations. Differences in the structural parameters of these infauna communities were also noted between control and contaminated locations; species number, species richness and species diversity (Shannon-Wiener) were all decreased at the contaminated locations. Additionally, the species composition of soft-sediment infauna was less variable at impacted locations than at control locations. No studies examining human impacts on benthic plant communities have yet been undertaken in the Windmill Island region.

## Diatoms

### A general overview

#### Introduction

Diatoms are microscopic algae, belonging to the class Bacillariophyceae of the division Chrysophyta (Bold and Wynne, 1985). Diatoms have a distinctive, often highly ornamented, silicate cell wall, consisting of two main pieces (valves) joined by a belt-like band called a girdle band (Round, 1990). The taxonomy of diatoms is based upon the structure of the valves; similarly, it is the valves of diatoms that are enumerated in ecological studies (Dixit et al., 1992). More recently molecular

techniques have been used to define species but this technique has not been employed in this study.

Globally, diatoms are one of the most abundant algal groups (Jones, 1996). They are also one of the more diverse with in excess of 10,000 taxa described (Anderson, 1992). Diatoms have an almost universal distribution, occurring in rivers, oceans, lakes, and even moist soils, and are abundant in most of these environments (Reid et al., 1995). Diatoms are unicellular, but may be either solitary, or colonial, with the latter forming thin mats, or long strands. Diatoms typically have either a free-floating (planktonic) or attached (benthic) mode of existence (Bold and Wynne, 1985).

### *Benthic diatoms*

Benthic diatoms were first recorded at the end of the 18th century (Round, 1971). Taxonomic studies flourished during the late nineteenth century, however ecological studies have only been undertaken over the past forty to fifty years. The number of benthic marine taxa greatly exceeds that of planktonic marine species yet comparatively little is known about them (Round, 1971).

Benthic diatoms grow on rocks, plants, and sand, with the latter including taxa which are attached to individual grains as well as taxa that live on the sediment but are not firmly attached to it (Moore and McIntire, 1977). Attached species typically occur in areas with strong, erosive currents, or scouring events, whilst motile free-living forms are generally found in environments where burial by sediments is frequent (Round, 1971). Motile species are all pennate diatoms with a raphe system on both sides of the valve and include the genera *Navicula*, *Pleurosigma* and *Amphiprora* (Round, 1971). Attached species are typically rapheless on one or both valves; examples include the genera *Achnanthes* and *Cocconeis*.

### *Benthic marine diatoms*

Diatoms are an integral, and often dominant, component of benthic microalgal communities in both estuarine and shallow coastal environments (Sullivan, 1999). Viable benthic diatom communities have been recorded at depths of 142 m (Cahoon et al., 1990). Even at these depths, 1 m<sup>2</sup> of sediment can contain more chlorophyll *a* than the overlying water column (Cahoon et al., 1990). Many benthic marine taxa have a cosmopolitan distribution (Moore and McIntire, 1977).

The environments in which benthic marine diatoms occur can be divided into three main zones: supra-tidal, inter-tidal and sub-tidal (Round, 1971). Supra-tidal communities generally have a low diversity, consisting of a few, desiccation resistant, halophilic species. *Achnanthes brevipes*, *Navicula obtuse*, *Navicula cryptocephala* and *Caloneis amphisbaena* typically occur within this environment, as do several *Amphora* and *Nitzschia* species (Round, 1971). Inter-tidal communities also consist predominantly of species resistant to drying. Small species of *Achnanthes*, *Cocconeis*, *Stauroneis*, *Toxonidea*, *Amphora* and *Catenula* are characteristic of sandy sediments within the epitidal zone (Round, 1971). The diatom flora of silty sediments within the inter-tidal regions can be extremely diverse, with Drum and Weber recording 151 taxa (Round, 1971). Sub-tidal regions have received less attention than their shallower counterparts (Round, 1971; Kennett and Hargraves, 1984). Very similar floras occur in sandy sediments in America and Great Britain; *Amphora*, *Achnanthes*, *Cocconeis*, *Dimerogramme*, *Plagiogramma*, *Raphoneis*, *Fragilaria* and *Opephora* are all common (Round, 1971).

### **Antarctic diatoms**

#### *Introduction*

Research into Antarctic diatoms has a long history, with early descriptions provided by Hooker (1844) and Van Heurck (1909). Early research was predominantly observation-based and includes such taxonomic studies as that of Mann (1937). Whilst a large body of descriptive data is available, there is only limited knowledge of the processes and ecological interactions that occur (Priddle et al., 1986). More

recently, work has focused not only on the diversity of diatom communities, but also on the relationships between these communities and various environmental parameters (Jones et al., 1994).

Diatoms are a major component of aquatic plant communities in Antarctica. Antarctic diatoms are abundant in most aquatic ecosystems, including lakes (Jones, 1996; Roberts and McMinn, 1999), meltstreams (Kawecka and Oleck, 1993), and, of course, the marine environment (Medlin and Priddle, 1990). Diatoms in Antarctic waters are subject to the same laws governing their distribution as protists in other aquatic environments. However, they are subject to more extreme conditions, such as consistently low temperatures, and extreme variations in photosynthetically available radiation which is further exacerbated by the presence of snow cover and winter sea-ice (Priddle et al., 1986). Despite these harsh conditions many diatom species thrive in Antarctic regions. Jones (1996) estimates that there are approximately 280 freshwater taxa in Antarctic regions, with a further 56 species occurring only in the marine environment.

### *Antarctic marine diatoms*

Antarctic marine diatoms live in a relatively stable environment. Water temperature varies by only a few degrees, and whilst these temperatures are low enough to slow metabolism, they don't inhibit growth (Holm-Hansen et al., 1977). The salinity of sea-water is relatively constant, at around 34 m S cm<sup>-1</sup> (Tilzer et al., 1985). Nutrients and trace elements are usually present in sufficient quantities so as not to limit algal growth (Heywood and Whitaker, 1984; Priddle et al., 1986). Depletion of nutrients has been observed synchronously with diatom blooms, both in coastal (Clarke et al., 1988; McMinn et al., 1995) and offshore regions (Priddle et al., 1986), however, the very high initial values mean that diatoms are rarely, if ever, nutrient limited (Clarke et al., 1988).

Light is the dominant environmental factor that influences diatom distribution and production in Antarctic regions (Tilzer et al., 1985). All areas beyond 66 °S

experience polar night over the austral winter, the duration of which increases with latitude (Heywood and Whitaker, 1984). Sea-ice, and the associated snow cover, can also dramatically reduce the light available to microalgae (Gilbert, 1990).

Within the near-shore marine environment, diatoms occur as plankton (McMinn and Hodgson, 1993), benthos (Gilbert, 1991) and, when present, as sea-ice algae (McMinn, 1996a; Palmisano and Sullivan, 1983; Kottmeier et al., 1983). In McMurdo Sound, a shallow water marine environment, annual primary production by phytoplankton, sea-ice algae and benthic microalgae was estimated as  $43.9 \text{ g C m}^{-2}$ ,  $11.8 \text{ g C m}^{-2}$ , and  $26.0 \text{ g C m}^{-2}$ , respectively (Knox, 1990). However, the author noted that the benthic estimate was based on summer values, when phytoplankton restrict the amount of light available to the benthos, and thus the maximum value could be considerably higher. These estimates clearly demonstrate that benthic microalgal communities are an important contributor to primary production in near-shore Antarctic waters.

Most of the information available on Antarctic diatoms is derived from planktonic studies (eg. Smith and Nelson, 1985; McMinn and Hodgson, 1993; El-Sayed et al., 1983; Hawes 1983). Over 100 species of planktonic diatoms have been identified (Medlin and Priddle, 1991). *Chaetoceros*, *Fragilariopsis* and *Thalassiosira* often dominate the plankton (Medlin and Priddle, 1991) and have a circum-Antarctic distribution. The timing, and duration of planktonic blooms is related to latitude, and typically follows the retreat of sea-ice, with the blooms extending up to 200 km from the ice edge (Wilson et al., 1986). Sea-ice algae have also been well studied (eg. McMinn, 1996; Palmisano et al. 1985; Palmisano and Sullivan, 1983) with over 50 diatom species identified (Heywood and Whitaker, 1984), however, the communities are typically dominated by only four or five species (McMinn, 1998).

Although studies of surface sediments have become more frequent in recent times (eg. Leventer, 1992, Tanimura, 1992), these sediments contain components from all three community types, as frustules from sea-ice and planktonic diatoms often settle

out of the water column following the death of the organism. Some studies of diatoms in surface sediments report assemblages consisting almost entirely of planktonic species (ie. Taylor et al., 1997), probably due to the basal sediments occurring below the depth of the photic zone.

### *Antarctic benthic marine diatoms*

Very little data exists on benthic diatom communities in Antarctica (Knox, 1990). The few benthic studies that have been undertaken have typically been located either on the Antarctic Peninsula (Gilbert, 1991) or in the Ross Sea (Dayton et al., 1986). The distribution of benthic communities has been linked primarily to the availability of light, modified by the presence of sea-ice and snow cover (Dayton et al., 1986). Productivity is also influenced by light levels available to the benthos (Gilbert, 1991). High levels of shade-adaptation have been noted in some benthic diatom species, including *Trachyneis aspera* (Palmisano et al., 1985).

The composition and structure of benthic diatom communities in the Antarctic marine environment has generally been neglected. Two notable exceptions to this are Whitehead and McMinn (1997) and Klöser (1998) who examined the influence of depth, and substrate type, respectively, on these communities.

## **Diatoms as environmental indicators**

### *Introduction*

Their position at the base of the food chain enables diatom communities to provide unique data on ecosystem health, compared to the more commonly used animal indicators (McCormick and Cairns, 1994). Diatoms have a number of qualities that make them ideal environmental indicators (Dixit et al., 1992). Diatoms are sensitive to environmental perturbations, and their short life cycle results in a rapid community response to change (Sullivan, 1999). Furthermore, diatoms occur in almost all types of water bodies, and are generally present in sufficient quantity to allow accurate analyses from only a small sample (Reid et al., 1995). The cosmopolitan distribution of many diatoms species means that results from studies conducted in other countries

can still be applicable (Round 1993). Similar ecological tolerances have even been recorded between Australian species and their morphological counterparts from the northern hemisphere (Reid et al., 1995; Vyverman et al., 1995; Hodgson et al., 2000).

One of the major difficulties associated with the use of diatoms as bioindicators is the relatively large number of taxa (Kelly et al., 1995). Relatively high numbers of valves are counted per sample, further increasing the complexity. For statistical purposes, minimum counts of 300 diatom valves per sample are recommended (Van Dam, 1982; Sullivan and Moncreiff, 1988) however sample sizes of 400-500 valves are more commonly reported (Cooper, 1999). The difficulty of large taxa and sample numbers can be overcome with the application of multivariate techniques, such as ordination and canonical correspondence analysis (CCA), which allow the relative influence of multiple environmental factors to be determined. Generic level analysis uses fewer taxa, and several indices based on this have proved effective (eg. Hill et al., 2001). Alternatively, identification can be restricted to approximately twenty of the most common species (Round, 1991). Wu's (1999) generic index took an even more radical approach, comparing the abundance of two groups each consisting of three genera (*Achnanthes*, *Cocconeis*, and *Cymbella* versus *Cyclotella*, *Melosira* and *Nitzschia*).

### *Diatoms as indicators of pollution*

Diatoms have been used as indicators of water quality since the early 20th century. Kolkwitz and Marsson (1908) described the first method of monitoring water quality, namely the Saprobic system (Round, 1981). This method, and others based on it, continued to be used until the mid-1970's but were only designed for detecting organic pollution. One problem with this, and other related methods is that they rely heavily on the presence of indicator species, however such species are not restricted to polluted waters (Round, 1981). Thus the presence of an indicator species does not necessarily mean that the water body in question is polluted.

Patrick (1964) developed a method of detecting pollution based on diversity changes in the diatom communities (Descy, 1971). Several other methods principally based

on the calculation of “diversity indices” have since evolved. The general applicability of these methods is uncertain, as the relationship between structural parameters, such as diversity, and water pollution is quite complex. High levels of disturbance usually result in decreased species richness, decreased evenness, and decreased diversity with increased dominance values (Clarke and Warwick, 1994), however, increased diversity, evenness and richness, and reduced dominance values will result from low levels of stress due to reduced competition between species (Connell, 1978). Furthermore, diversity can be restricted by a range of environmental variables and low diversity values can occur even when no pollutants are present.

Lange-Bertalot (1978, 1979) developed a method of detecting pollution based on relative abundances of the individual species present, combined with the known pollution tolerances of the individual species. The most significant contribution of this work was the realisation that any index of water quality must be based on the tolerance of individual diatoms to *increasing* levels of a particular pollutant (Sullivan, 1999). A number of diatom indices have since been based on this principle, including the Diatom Assemblage Index to Organic Pollution (DAIpo) proposed by Watanabe et al. (1988) and the modified Pantle-Buck saprobic index described by Kobaysi and Mayama (1989). These indices involve the calculation of a value, based on the tolerance of individual species, which reveals the relative quality of water from which the samples were taken (Sullivan, 1999). Whilst several such indices have been generated for freshwater systems, no such work has been undertaken in estuarine or coastal regions (Sullivan, 1999). The data available regarding pollution tolerances of diatom species from these areas is so scarce as to prevent such indices being developed at this time (Sullivan, 1999).

The component of water quality that has historically received the most attention is eutrophication. Eutrophication results from increased nutrients and organic matter (Meyer-Reil and Köster, 2000). Eutrophication can be responsible for many water quality problems, such as toxic algal blooms, anoxic bottom waters, death of fish and



shellfish, and declining diversity and habitat loss (Cooper, 1999). At its most extreme, eutrophication can result in the disappearance of diatom communities, with a subsequent increase in blue-green algae (Meyer-Reil and Köster, 2000). Eutrophication typically stimulates planktonic algal blooms, which dramatically reduce the light available to benthic microalgal communities and, in extreme cases, can result in their disappearance (Meyer-Reil and Köster, 2000). Lower levels of nutrient enrichment can also influence diatom community composition and structure. Admiraal (1977) demonstrated that concentrations of ammonia greater than  $5 \mu\text{g l}^{-1}$  resulted in the loss of some species (Sullivan, 1999). Hillebrand et al. (2000) demonstrated that increased nitrate concentrations resulted in increased biomass of benthic microalgal communities. Several species increased in abundance subsequent to nutrient enrichment, including *Melosira moniliformis*, *Melosira nummuloides*, *Tabularia fasciculata* and *Cocconeis scutullem*. Nutrient enrichment also resulted in the increased dominance of a few species, and altered structural parameters such as diversity, evenness, and richness (Hillebrand et al., 2000).

#### *Diatoms and heavy metal toxicity*

The toxicity of many metals to diatom species has long been recognised. Braeck and Jensen (1976) described three classes of metals based on their toxicity to diatoms. The first group, which included copper and zinc, resulted in the cessation of cell separation and an increased chain length. Mercury, lead, and cadmium formed a second group, and caused the elongation or deformation of cells, with minor disruptions to cell division. The least toxic group, comprised of chromium, nickel, selenium, and antimony, had no effects at concentrations less than  $1 \text{ mg l}^{-1}$ . Comparative studies of cadmium, copper, and zinc (Fisher and Frood, 1980) found copper to be both the most readily chelated and the most toxic, whilst cadmium was the least readily chelated and had the least toxic effects at equivalent concentrations.

A range of factors affect the toxicity of metals to diatoms. Ivorra et al. (1990) found that the age of the diatom community modifies the toxic effects observed from metal contamination. The sensitivity of diatoms to metal pollution also varies greatly with

the species examined. In a study of approximately 60 species, Dixit et al. (1991) found that growth optimums for copper concentrations varied between 2 and 100  $\mu\text{g l}^{-1}$ , depending on the species involved. Species-dependent processes such as extracellular binding and the excretion of ligands may also play a part in determining the sensitivity of individual species to a given metal (Rijstenbil et al., 1994). Other adaptations which increase the tolerance of diatoms to high concentrations of trace metals include membrane impermeability and the exclusion and detoxification of metals (Rijstenbil et al., 1994).

A variety of other factors can also influence the toxicity of metals. Cid et al. (1995) state that the concentration of copper required to affect the growth of microalgae is determined by several factors including the species assayed, the temperature and light conditions, the cell density, and the composition of the growth medium used. Salinity can also affect the toxic nature of metals, with an increase in salinity increasing observed toxic effects (Eriksen et al., 2001). The presence of other metals may also reduce the toxic effects observed at a given concentration; a two-fold increase in intracellular and cytoplasmic concentrations of copper in the coastal marine diatom *Thalassiosira weissflogii* was observed subsequent to a reduction in zinc concentrations (Chang and Reinfelder, 2000). Competitive interactions have been demonstrated between copper and zinc (Rueter and Morel, 1981) as well as cadmium and zinc (Lee et al., 1995). In contrast, Morel et al., (1991) demonstrated that many trace metals in solution will interact to co-limit the growth of many oceanic diatoms. The uptake of iron, however, is not affected by the presence of other metals, such as zinc, cadmium and aluminium, indicating a high specificity of the sorption sites (Santana-Casiano et al., 1997).

The term “antagonistic” is used to refer to metals that compete for sorption sites and thus reduce the overall toxicity of each other, whilst the term “synergistic” refers to metals where the presence of one amplifies the toxicity of the other. The synergism or antagonism of two given metals is dependant on the diatom species studied. For example, copper and zinc behave in a synergistic manner on cultures of *Thalassiosira*

*pseudonana*, but behave antagonistically on cultures of *Phaeodactylum tricornutum* and *Skeletonema costatum* (Braek et al., 1980).

### *Metal bioavailability*

The bioavailability of a given metal influences its toxicity. Bioavailability refers to the component that is directly available to the organisms and for several metals, including copper, cadmium, and zinc, is proportionally related to the free ion concentration. High concentrations of a given metal may be present within the water or sediments, but if they are not bioavailable no toxic effects will be observed. One example of this is given by Eriksen et al. (2001) in relation to studies conducted in Macquarie Harbour, Tasmania. Although total copper concentrations were found to be as high as 390nM, low concentrations of free copper ions meant that no toxic effects were observed for the diatom *Nitzschia closterium*.

The bioavailability of metals is affected by a number of environmental conditions. Metal bioavailability is decreased by the presence of non-ionic organic compounds, organic ligands of sulphide precipitates, and colloidal matter (Dickman, 1998). It is important to note that although the presence of colloids is generally accepted to reduce bioavailability, recent studies (Wang and Guo, 2000) have demonstrated that this is dependent on the metal examined, as colloid bound chromium and cadmium both exhibited increased bioavailability compared to the low molecular weight fraction, whilst colloidal bound zinc was less bioavailable. The bioavailability of heavy metals can also be influenced by pH. Heavy metals are generally more bioavailable at low pH (ie freshwater) than they are in sea-water sites where the pH is higher (Krebs, 1983), however, the presence of heavy metals can reduce the pH tolerance range of diatoms (Gensemer et al., 1993).

Nitrogen status can also affect the bioavailability of metals. Rijstenbil et al. (1998) demonstrated that cellular uptake of copper, manganese and zinc was increased with nitrate enrichment. Light can also influence the bioavailability of metals. One

example of this is the bioavailability of copper; photodegradation of copper chelates results in an increase of biologically available free cupric ions (Moffet et al., 1990).

### *Toxic effects of metals*

Studies examining the effects of metal toxicity on diatoms have been limited and are typically based either on experiments using a single diatom species' response to a range of metals, or multiple diatom species to a specific metal, all undertaken in controlled laboratory conditions (Mason et al., 1995). Despite this, a reasonable amount of data are available on the toxicity of individual metals. The effects of copper, in particular, have been well studied. Copper has been shown to have an inhibitory effect on photosynthesis, affecting the oxidising side of PSII (Cid et al., 1995). Diatoms respond to low levels of copper contamination by increasing the rate of ATP consumption, resulting in a decreased cellular pool of ATP. The marine diatom *Phaeodactylum tricornutum* exhibited this response at copper concentrations of only  $0.05 \text{ mg l}^{-1}$  while growth and photosynthetic rates were reduced by 50% at copper concentrations of  $0.1 \text{ mg l}^{-1}$  and  $0.5 \text{ mg l}^{-1}$  respectively (Cid et al., 2001).

Whilst these results indicate the toxicity of copper in solution, other studies have investigated the toxicity of free copper ions, that is, the component that is bioavailable. Copper ion activity in the range of  $10^{-8.3}$  to  $10^{-8.6}$  M resulted in the formation of abnormal frustules in *Thalassiosira pseudonana*, whilst higher concentrations caused the cessation of cell division (Braeck and Jensen, 1976). Rijstenbil et al., (1994) demonstrated a gradual decrease in cell division of the species with increasing  $\text{Cu}^{2+}$  activity from  $10^{-10.6}$  to  $10^{-9.6}$  M. These authors also reported an abrupt terminating of cell division for *Ditylum brightwellii* at free copper activities between  $10^{-10.3}$  and  $10^{-9.3}$  M.

Cadmium is generally regarded as a non-essential metal, although it can act as a nutrient in conditions where low zinc concentrations would otherwise limit diatom growth. Like copper, cadmium is toxic when present in sufficient concentrations. The degree of cadmium toxicity is also highly variable between diatom species.

Whilst, as a whole, diatoms have a significantly lower uptake rate than other microalgae, intracellular accumulation can vary by an order of magnitude between diatom species (Payne and Price, 1999). For example, total cadmium concentrations that reduced growth rates by 50% varied between  $89 \times 10^{-6}$  M for *Skeletonema costatum* and  $2500 \times 10^{-6}$  M for *Ditylum brightwellii* (Payne and Price, 1999). Rijstenbil et al. (1994) reported a 50% reduction in photosynthetic ability for *Ditylum brightwellii* subsequent to an addition of 10 nM cadmium, whilst the reduction in photosynthetic ability was less than 10% for *Thalassiosira pseudonana* at the same concentration.

Cadmium is known to substitute nutritionally for zinc, but at high concentrations (Tortell and Price, 1996) it interferes with the assimilation of zinc and iron. Species which are more tolerant of deficiencies of zinc and iron will therefore be less sensitive to cadmium toxicity. Near-shore diatoms have high metal requirements, and are therefore more sensitive to cadmium toxicity than oceanic taxa (Tortell and Price, 1996).

Manganese is essential for photosynthesis, both as an integral component of photosystem II and as a detoxifying agent of superoxides (Debus, 1992). Cellular uptake of manganese is inhibited by high concentrations of either copper or zinc (Sunda and Huntsman, 1998). Under low light conditions (eg. under sea-ice) intracellular demand for manganese is increased (Sunda and Huntsman, 1998). Toxic effects caused by copper and zinc will therefore be more pronounced under these conditions.

Mercury affects the species composition of phytoplankton communities at concentrations as low as  $0.5 \mu\text{g l}^{-1}$  (Grollé and Kuiper, 1980). Diatom communities exposed to mercury concentrations of  $5 \mu\text{g l}^{-1}$ , had fewer species present than control communities (Grollé and Kuiper, 1980). Mercury also affects the growth rate of diatom communities, which is inhibited at  $5 \mu\text{g Hg l}^{-1}$  and ceases at  $50 \mu\text{g Hg l}^{-1}$  (Grollé and Kuiper, 1980).

Zinc is an essential element, but interferes with the metabolism of other essential metals (with toxic effects) when present in high concentrations (Santana-Casiano et al., 1997). Zinc can also cause a reduction in the photosynthetic efficiency of diatom species. Rijstenbil et al. (1994) recorded a reduction in photosynthetic efficiency of approximately 30% in *Ditylum brightwellii* and 20% in *Thalassiosira pseudonana* subsequent to an addition of 150 nM of zinc. These authors also reported that additions of zinc caused increases in the C:N ratio of *Ditylum brightwellii*, but not in *Thalassiosira pseudonana*.

Metal pollution influences diatom communities as well as individuals. Previous studies have demonstrated that contamination by heavy metals can affect the numerical structure of benthic diatom communities, typically resulting in a decreased community complexity resulting with lower species diversity and richness values, combined with increasing dominance values (Crossey and Point, 1988). Compositional changes have also been documented in diatom communities affected by metal contamination. Ivorra et al. (2000) reported that *Cocconeis minuta*, *Fragilaria capucina* and *F. ulna* occurred in higher abundances in unpolluted water than in polluted water whilst *Achnanthes minutissima* and *F. capucina* var. *vauheriae* were significantly more abundant in polluted waters. Ruggiu et al. (1998) also found the genus *Achnanthes* to be metal tolerant, either maintaining or increasing in abundance in response to large increases in metal concentration. These authors found that *Synedra ulna* (syn. *Fragilaria ulna*) was not affected by pollution, however, a later study by Ivorra et al. (2000) showed conflicting results.

In addition to the direct toxic effects of heavy metal contamination on diatoms, the presence of many metals in water and sediments leads to increased uptake of these metals by the diatoms, both in absolute and relative terms. Absil and Scheppingen (1996) demonstrated that diatoms from areas of low pollution have a lower bioconcentration factor than diatoms from areas of high pollution. Linear relationships were shown between sediment concentrations and concentrations in

diatoms for zinc and lead, whilst concentrations of copper and cadmium in diatoms were less variable than those observed in the sediments (Absil and Scheppingen, 1996).

### *Diatoms and petroleum hydrocarbons*

Hydrocarbon contaminants have previously been shown to have a deleterious effect on diatom communities. Growth inhibition of diatoms has been recorded at hydrocarbon concentrations of only 0.04 mg TPH l<sup>-1</sup> (Siron et al., 1991); however, the extent of this inhibition varies with the species examined (Ostgaard et al., 1984). Although some field experiments have reported an increase in diatom biomass subsequent to hydrocarbon contamination, this has typically been associated with reduced grazer levels. The growth of all diatom species examined by Hsiao (1988) was inhibited at the lowest level of contamination used (10 ppm), with the observed effects increasing with exposure time. Acute toxic effects of petroleum hydrocarbons are mainly due to water-soluble components (Østgaard and Jensen, 1983). A significant linear relationship has been demonstrated between the water-soluble component of crude oil, and the growth rate of *Phaeodactylum tricornutum*, with inhibition beginning at water soluble hydrocarbon concentrations of 0.36 mg l<sup>-1</sup>.

Plante-Cuny et al. (1993) found compositional differences between control communities and those exposed to either light crude oil or diesel based oil-cuttings, with marked changes in the presence or absence of individual species. Morales-Los and Goutz (1990) found more subtle compositional differences resulted from hydrocarbon contamination, with pollution sensitive species inhibited while more tolerant species increased in abundance. Pennate diatoms may be more tolerant of petroleum hydrocarbon contamination than centric diatoms, with one study (Siron et al., 1996) reporting an increase in the relative abundances of pennate species in treatments exposed to dispersed, but not adsorbed, oil. Kusk (1981) found that most marine diatom species are more sensitive to hydrocarbon contamination than their freshwater counterparts.

The effects of petroleum hydrocarbons on the numerical structure of diatom communities are unclear. Several investigators have reported a decrease in diversity subsequent to pollution by petroleum hydrocarbons (Cooper and Wilkm, 1975; El-Dib et al., 2001), whilst others (Vargo et al., 1982) have reported increased diversity from similar exposures; however, the latter was associated with decreased grazing pressure. Although the majority of these investigations have been laboratory experiments involving planktonic species (Bott et al., 1978), more recent studies have included field experiments using benthic communities (eg. Carman et al., 1997; Bennet et al., 2000).

Several factors can influence the response of a diatom species to petroleum-hydrocarbon contamination. Light is one such factor, with significant increases in toxicity recorded for even low light conditions relative to dark conditions (Østgaard et al., 1984). Increasing temperatures and the disappearance of sea-ice at the end of winter also increase the toxicity of petroleum hydrocarbons to polar diatoms (Siron et al., 1996).

As with heavy metals, the toxicity of petroleum hydrocarbons to diatoms is species dependent. Hsiao (1978) found that the survival rate of diatoms exposed to 10 ppm of Venezuelan crude oil for a period of 10 days was 23.6%, 10.0% and 2.1% for *Chaetoceros septentrionalis*, *Navicula bahausiensis*, and *Nitzschia delicatissima* respectively. In a study of 8 species of microalgae, Østgaard et al. (1986) found that *Skeletonema costatum* was the most sensitive species, whilst *Phaeodactylum tricornatum* was the least sensitive species. Although *Skeletonema costatum* is generally regarded as being one of the more sensitive species (Mahoney and Haskin, 1980) the sensitivity of this species varies between clones (Østgaard et al., 1986). *Skeletonema costatum*, *Chaetoceros socialis* and several *Thalassiosira* species are all inhibited by the presence of dispersed oils, and tend to be replaced by more tolerant species such as *Chaetoceros septentrionalis* (Siron et al., 1996). The same study found that although all diatom species were eliminated at high oil concentrations,



once dispersed oil concentrations dropped below  $1 \text{ mg l}^{-1}$  a few oil-tolerant species, including *Chaetoceros septentrionalis*, started to grow again..

The toxicity of petroleum hydrocarbons varies between fuel types, but even within the one type, fuels from different geographical regions can have varying toxicities. Hsiao (1978) found that survival rates of *Chaetoceros septentrionalis* varied between 41.8% for Pembrina crude oil to 15.5% for Norman Wells crude oil, while the survival rates of *Nitzschia delicatissima* ranged from 11% for Atkinson Point crude oil down to 2.1% for Venezuelan crude oil.

#### *Diatoms as paleoindicators*

In addition to providing information about current environmental conditions, the high preservation potential of diatoms means that they can be extracted from sediment cores to provide information about past environmental conditions (Dixit et al., 1992). This makes it possible to determine the naturally occurring conditions of an ecosystem, against which anthropogenic changes can be measured (Smol, 1992). For many years broad changes in diatom community composition and abundance of indicator species have been used to interpret past salinity levels (Bradbury, 1971; Gasse and Street, 1978) and productivity rates (Battarbee, 1978; Bradbury and Megard, 1972) in lake environments. With the advances in multivariate statistics in recent times, more quantitative methods have been developed (Birks et al., 1995), including the use of calibration data sets.

Weighted averaging regression is currently the most popular calibration method (Reid et al., 1995) as, unlike multiple linear regression, this method is based on the ecological assumption that species respond in a unimodal fashion to environment gradients (ter Braak and van Dam, 1989). In other words, this method relies on the premise that along an environmental continuum, the highest abundance of a species will occur at its ecological optimum. The value of a taxon's optimum for a given environmental variable can therefore be determined by taking the average of all values where the species occurs, weighted by the abundance of the species at each

site (Reid et al., 1990). This method has been applied on a broad scale to define the pH optima of diatom species occurring in lakes from Europe (Birks et al., 1990) and North America (Charles and Whitehead, 1986). The modern values collected then form the basis of a calibration set, against which fossil assemblages can be compared. For accurate results, the calibration data set must cover the entire range of the variable to which the fossil assemblages were exposed (Fritz et al., 1993).

Having established the optima ranges of individual species, the paleo-conditions for the given variable can be calculated (Reid et al., 1995). For example, having determined the pH optima for many different species, this information can be applied to sediment cores to determine changes in pH over time, based on the diatom assemblages. Previous pH levels are calculated by averaging the optima of individual species, weighted by their relative abundance. This process is referred to as a transfer function. High correlations between inferred and observed pH values have previously been recorded (Birks et al., 1990; Dixit et al., 1992).

Diatom inferred pH values have been used in a number of paleoreconstructions across Europe (Renberg and Hellberg, 1992; Jones et al., 1993; Larsen, 2000) and America (Charles et al., 1989; Whitmore, 1989). Similar work has also been undertaken in East Africa (Gasse and Tekai, 1983; Gasse et al., 1995). This procedure allows the extent and timing of acidification to be determined for a given lake, or several lakes within a region (Reid et al., 1995). One example of the application of diatom inferred pH for environmental monitoring is from Falun, Sweden. Fourteen lakes were analysed to determine the historical impact of mining, and associated high levels of sulphur deposition, on the lake ecology (Ek and Renberg, 2001). Despite the high sulphur content it was found that pH decreased by only 0.4 to 0.8 units during the period of mining, however, recovery since has been non-existent.

Prior to 1990, most paleolimnological reconstructions were only developed for pH (Dixit et al., 1991). Post-1990, the use of canonical correspondence analysis (CCA)

and weighted-averaging regression techniques has enabled the development of transfer functions that inferred several environmental variables simultaneously (Dixit et al., 1991). For example, Dixit et al. (1991) established transfer functions for pH, aluminium, organic content and acid neutralising ability for Deep Lake in New York. Transfer functions have now been established for several environmental variables including salinity (Fritz, 1990; Fritz et al., 1991; Roberts and McMinn, 1998), chlorophyll *a* (Jones and Juggins, 1995), paleodepth (Whitehead and McMinn, 1997), productivity (Anderson, 1992), phosphorous (Hall and Smol, 1992; Anderson, 1992), and trophic status (Anderson, 1992, Christie and Smol, 1992).

Palaeoecological studies related to metal contamination are scarce. A diatom inference model proposed for the polluted Sudbury Lakes in Canada (Dixit et al., 1991) included three metals (aluminium, copper, and nickel). This study found that the three metals all had a similar influence on community composition and were inversely related to pH. Ruggiu et al. (1998) examined acute and persistent exposure of diatom communities to copper contamination in two sediment cores in Lake Orta (Italy). These authors found that copper contamination had disrupted the pre-existing diatom flora, and that changes in copper concentrations could be tracked through changes in three groups of diatom species. The first of these groups consisted of sensitive diatom species, predominantly *Fragilaria* and *Cyclotella*, the populations of which expired at the onset of contamination and never reappeared. Species whose abundance was apparently unaffected, or not immediately affected, such as *Synedra*, comprised the second group. The third grouping contained resistant species whose abundances increased despite the pollution, most noticeably *Achnanthes*. In the absence of other pollutants prior to the 1960's, the observed trends in diatom abundances could be clearly related to copper pollution (Ruggiu et al., 1998).

The use of calibration sets for paleoenvironmental reconstruction has largely been restricted to lake environments (Cooper, 1999); however, a few calibration sets have been developed in estuarine environments. Two such examples are a surface sediment calibration set by Wendker (1990) that included a range of physical and

chemical factors, and a nutrient calibration set by Anderson and Vos (1992). Additionally Juggins (1992) developed a salinity transfer function for use within the Thames Estuary. Estuarine and near-coastal regions typically have a higher degree of in-system variability than lakes and more complex calibration sets are required. Furthermore, there are typically only a few estuaries and near-coastal bays within the same climatic and vegetational area, thus the calibration sets would be less applicable for large-scale regional settings (Cooper, 1999).

Antarctic diatom communities have previously been used to infer past environmental conditions such as climate (Roberts and McMinn, 1999), glaciation history (Cremer et al., in press) paleodepths (Whitehead and McMinn, 1997), and to map the extent of sea-ice.

### **Statistical approaches to determining human impacts.**

Several methods have been developed to determine if biological communities are affected by a particular stress, such as chemical contamination. These include 'before and after' comparisons, 'control and impact' comparisons, and correlations. Before and after comparisons require either advanced knowledge that a disturbance will occur, or historical data (Underwood, 1989). Comparisons of the community structure or composition which occurs after the disturbance with that which occurred before the disturbance allows changes to be detected. This method of comparing community change over time is also referred to as 'Intervention Analysis'. In intervention analysis the data collected before the impact, or intervention, is modelled allowing for correlations between observations (Cairns and Smith, 1994). To obtain sufficient statistical power, a large number of "before" measurements are required. Although this procedure is widely used, spatial replication is required for the results to be valid as no single site can be expected to stay constant, even if equilibrium appears to have been maintained throughout the 'before' period (Underwood, 1989).

'Control and impact' comparisons are often used to determine the impact of a perturbation after it has occurred (Underwood, 1989). Comparisons are made between communities in the area which has been perturbed, and an area which has not been perturbed. However, if only two locations are examined, it cannot be determined whether the differences observed are due to the perturbation or any other environmental variation between the two sites.

'Control and impact' comparisons are often combined with 'before and after comparisons', forming the BACI (Before-After-Control-Impact) test (Stewart-Oaten et al., 1986), in an attempt to address some of the problems associated with comparing control and impacted sites (Cairns and Smith, 1994). Measurements are made at two or more sites, both before and after the impact. Typically, several measurements are taken over time. The mean of 'before' differences between sites is compared to the mean of differences between sites after the impact has occurred, to determine the biological effect of the impact (Cairns and Smith, 1994). It has been suggested that examining temporal differences between the two sites can overcome the problems of spatial variability (Stewart-Oaten et al., 1986), however this assumes that the differences in communities which existed before the impact would have remained constant over time (Underwood, 1989). As communities from different locations may have different temporal patterns (Chapter 6), this method fails to demonstrate that the observed variation between communities is related to the impact.

To avoid problems associated with spatial and temporal variation, several control locations, and preferably several impact locations, need to be incorporated into the analyses (Underwood, 1989). The average of the control locations can then be compared to the average of the impact locations to determine if a stress has occurred. In order to demonstrate that an impact has affected biological communities when only one impact location is available, then the 'before' and 'after' changes observed at this location need to exceed the average of control locations (Underwood, 1989). The selection of suitable control locations is crucial for environmental studies; these

locations need to contain similar habitats, which are affected by the same natural processes as the impact location.

Correlations are often used to detect stresses within sites that have varying degrees of perturbation (Underwood, 1989). Three stages are involved in this process. Firstly, measures of community health and the degree of perturbation are collected from multiple locations. Secondly, a difference in the community of interest must be shown. Finally, a relationship between the measure of community health and the degree of perturbation must be demonstrated; this usually takes the form of a significant correlation between the degree of stress and the community measure. Canonical correlation analysis, detrended correlation analysis and redundancy analysis are all methods which can be used to determine if a correlation exists between the community of interest and the potential impact. Even once such a relationship is demonstrated, it remains possible that another factor may be influencing the observed correlation, unless it is known that no other environmental variable, such as grain-size or salinity, has a similar pattern to that of the perturbation (Underwood and Peterson, 1988).

In order for any of the above methods to be applicable, certain requirements must be met. 'Before and after' comparisons require spatial replication; control and impact comparisons also require spatial replication, namely multiple control locations, preferably in conjunction with several impacted locations. Correlations require that the patterns of environmental variables are known, and that these differ to the distribution of the stressor. It is not also possible, or practical, to meet these requirements; in such situations, it is essential to show that a causal relationship exists between the stressor and observed biological patterns. A causal relationship between pollutants and observed biological patterns can only be demonstrated through experimental studies (Underwood, 1989; Underwood and Peterson, 1988; Clarke and Warwick, 1994). Ideally, the significance of this relationship would also be determined for organisms higher up the food chain (Bunn, 1995).

## Project objectives

The primary aim of this project is to assess whether benthic diatom communities are being significantly affected by chemical contaminants present within the sediments of marine bays adjacent to Casey Station. In order to achieve this aim, the following questions need to be addressed:

- What is the range of naturally occurring spatial and temporal variability within benthic diatom communities from the Windmill Islands?

Benthic diatom communities from varying locations within the Windmill Islands are briefly examined in Chapter 2. This indicated that the communities differ in composition between locations. As a consequence, the spatial variability of these communities is examined in more detail using a hierarchical nested sampling design (Chapter 4). The role of environmental factors such as light and grain-size in determining the variability observed between locations is also assessed (Chapter 5). Temporal variability of the diatom communities, and the observed spatial variability is studied over several time scales (seasonal - interglacial) using both surface sediments samples and sediment cores (Chapter 6).

- Are the diatom communities of potentially impacted bays different, in either composition or structure, to the diatom communities from uncontaminated locations? If so, do these differences exceed the observed range of natural variability?

An initial assessment of the diatom communities from potentially impacted bays relative to those of uncontaminated locations was undertaken (Chapter 3) using surface sediment samples. This theme was continued through the assessment of spatial and temporal variability covered in Chapters 4-6.

- Does a spatial, or temporal, relationship exist between the distribution of benthic diatom species and the presence, or concentration, of chemical contaminants?

Three sediment cores were used to examine whether a temporal relationship could be demonstrated between diatom communities and metal contamination within the potentially impacted Brown Bay (Chapter 7). Thirty three surface sediment samples were used in a direct gradient analysis of the spatial relationships between diatom communities and heavy metal concentrations (Chapter 8). The same techniques were used to assess the spatial relationship between diatom communities and petroleum hydrocarbon concentrations, based on 22 surface sediment samples.

- Can a causal link between chemical contaminants and the composition and structure of benthic diatom communities be established?

Both contaminated sediments from within Brown Bay (Chapter 11) and artificially contaminated sediments (Chapter 12) were used in field experiments to determine whether such a link could be demonstrated.

### **Assistance received from other people**

This project forms part of a larger, multidisciplinary study that is being undertaken by the Human Impacts Program of the Australian Antarctic Division. As such, some of samples and data incorporated into this project were provided by other scientists associated with this program. This input has enabled a more thorough investigation than would have otherwise been possible, given the constraints imposed by undertaking field research in Antarctica.

The long sediment core examined in Chapter 6 was collected as part of a research project led by Damien Gore (University of New England). The short sediment cores examined in Chapters 6 and 7 were collected by members of the Human Impacts Program dive team as part of research being undertaken by Ian Snape. The sediment samples used in Chapters 8 and 9 were also collected by this dive team, as part of Jonathan Stark's research. The diatom samples used in Chapters 10 and 11 were derived from experiments designed and implemented by Jonathan Stark. All Pb<sup>210</sup> data are based on samples prepared by Rebecca Scouller (AAD) with analyses



undertaken by ANSTO. Samples were prepared for metal and hydrocarbon analyses by Rebecca Scouller and Scott Stark. Metal analyses were undertaken at ANSTO (Chapter 7) and AGAL (Chapters 8, 10 and 11). Hydrocarbon analyses were undertaken by Analytical Services Tasmania (Chapter 9) and Andy Revile (CSIRO) (Chapter 11).

In addition, Chapter 11 is based on a paper currently submitted for publication. Although I was the primary author of this paper, Ian Snape and Jonathan Stark both made significant contributions to the content, whilst Andrew McMinn and Martin Riddle provided input with regard to the editing of this paper. Chapter 11 has therefore benefited from the input of these people, and also the comments of two anonymous referees.

### ***Diatom assemblages from near-shore surface sediments from the Windmill Islands, Eastern Antarctica.***

#### **Abstract**

The diatom assemblages present in near-shore sediments from the Windmill Islands were examined. Eighty taxa were recorded, seventy six of which were identified to genus. Where possible, taxa were further identified to species level. The diatom assemblages had high proportions of benthic species relative to other studies of Antarctic benthic marine communities. A total of thirty two exclusively benthic species were recorded in these sediments. In addition, twenty species which are found in both benthos and either sea-ice or planktonic communities were also recorded.

#### **Introduction**

Diatoms are a major component of many Antarctic aquatic plant communities, and are responsible for up to 75% of primary productivity in coastal regions. Antarctic diatoms can be found in lakes (Roberts and McMinn, 1999), melt-streams (Kawecka and Oleck, 1993), snow (Ling, 1996) and the marine environment (Everitt and Thomas, 1986). Within the near-shore marine environment, diatoms occur in the plankton (McMinn and Hodgson, 1993), benthos (Gilbert, 1991) and, when present, the sea-ice (Cota and Smith, 1991; Palmisano and Sullivan, 1983).

Surface sediments contain components from all three communities, as the frustules from sea-ice and planktonic diatoms often settle out of the water column following the death of the organism. Surface sediments therefore represent a mixture of dead and living cells. Samples of surface sediment typically contain frustules accumulated over time; the age of such accumulations can vary from several months up to twenty years (McMinn in Roberts and McMinn, 1999).

Studies of modern diatom communities have often focused on either planktonic or sea-ice communities, however, in recent years studies of surface sediments have become more popular. Little data exist on benthic diatom communities in Antarctica. The few benthic studies that have been undertaken have typically been located either on the Antarctic Peninsula (Gilbert, 1991), or in the Ross Sea (Dayton et al., 1986), however, one study (Whitehead and McMinn, 1997) examined benthic diatom communities near Davis Station. The present article addresses the paucity of documented studies of diatom communities within the surface sediments in Eastern Antarctica, and represents the first comprehensive study of modern diatom communities in the Windmill Islands.

## **The study area**

### **General description**

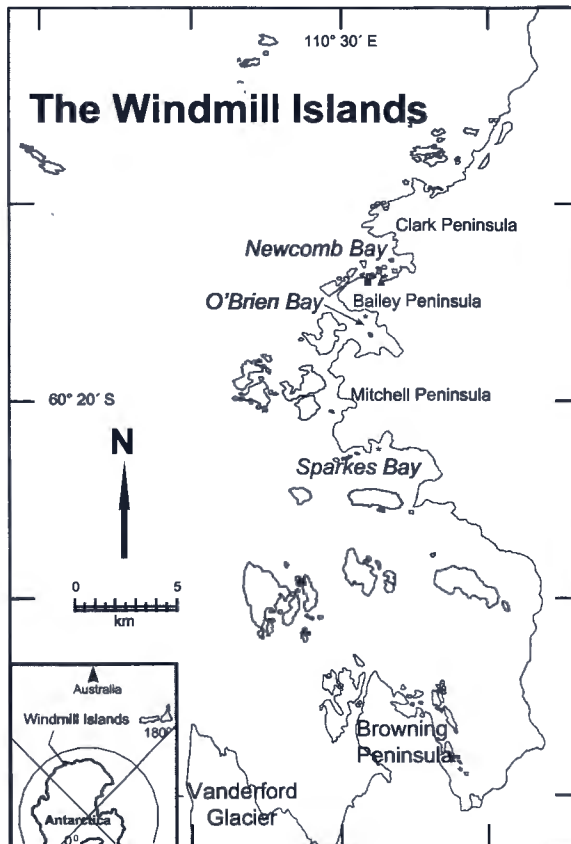
The Windmill Islands represent a small deglaciated oasis in Wilkes Land, Antarctica (Fig. 1), covering an area of approximately 75 km<sup>2</sup> between 66°10'-66°35' S, 110°10'-110°50'. The Windmill Islands consist predominantly of small islands of low elevation, typically less than 100 m. They are abutted to the East and North by a small ice-cap called the Law Dome. This ice-cap overlies several islands, forming small peninsulas including the Bailey Peninsula (Goodwin, 1993).

The climate of this area is dry with a mean annual snowfall of 195 mm yr<sup>-1</sup> (rainfall equivalent) (Melick & Seppelt, 1997). Mean temperatures for the warmest and coldest months recorded at Casey Station (66°16.9' S, 110°31.6' E) on Bailey Peninsula are 0.3 and -14.9°C respectively, with extreme values ranging between 9.2 °C and -41 °C (Melick & Seppelt, 1997). Although snow accumulates on the low-lying peninsulas during winter, this typically melts in the warm spring and summer seasons. Similarly, sea-ice typically disappears between December and February before reforming the next autumn. The Windmill Islands represent the only large

region of seasonally snow-free terrain for over 400 km of coastline, either east or west (Murray and Lauders, 1980).

### The sampling locations

The sites included were chosen to enable a representative sample of diatom taxa from near-shore marine sediments within the Windmill Islands. Sediment samples were collected from water depths between 1 and 25 m, and at varying distances from shore.



**Figure 2.1** Map of the Windmill Islands, showing the location of Casey Station. The geographical location of the Windmill Islands relative to Australia is shown in Inset 1.

Sediments were collected from bays both adjacent to the main landmass, as well as from nearby islands. The islands from which sediment was collected were Odber Island, O'Connor Island, Herring Island, Werlein Island, Sack Island, Little Herring Island, Cloyd Island and Denison Island. These islands are all located several km south of Casey Station (Fig. 1). With the exception of Denison Island which occurs at the southern end of O'Brien Bay, the islands are all located within Penny Bay. These islands vary in size, ranging from 0.04 km<sup>2</sup> to over 4 km<sup>2</sup>. Both Odber Island and O'Connor Island are home to several Adelie penguin colonies. Samples were collected at 8 m water depth from each island. In addition, samples were collected from 1, 2, 4 and 6m water depth at Odber Island, while samples from Cloyd Island were also collected from 4, 6 and 11 m water depths.

### *Newcomb Bay*

Newcomb Bay is a large, deep bay situated between the Bailey and Clarke Peninsulas. The current Casey station as well as the two previous stations, 'Old Casey' and 'Wilkes' are situated on its coast. Ice cliffs up to 30 m high border this bay. Samples from this bay were collected in line with the abandoned Wilkes tip site, at 3 distances from shore.

### *Noonans Cove*

Noonans Cove is located on the northern side of Newcomb Bay, near the abandoned Wilkes station. Small ice cliffs, approximately 10 m high, enclose the bay on three sides. Although the subtidal sides of the bay are initially rocky, they are covered by sandy sediments at depths as shallow as 2 m. Elsewhere within the bay the bedrock is exposed down to depths of 10 m. The maximum depth of 12 m occurs at the mouth of the bay. Sea-ice is usually present between March and December in this bay. Samples were collected from 1, 2, 4, 8 and 10 m water depths along the centre of this bay.

### *Brown Bay*

Brown Bay is a small embayment in the southern region of Newcomb Bay, immediately adjacent to the now defunct Thala Valley tip site. During summer, a melt stream runs down Thala Valley, through the tip site and into Brown Bay, thus carrying contaminants into the bay. Concentrations of heavy metals in marine sediments from Brown Bay are 10-100 times higher than from equivalent control sediments (Scouller et al., 2000).

The rocky sides of this bay grade to a sediment covered bottom, which consists of a mosaic of boulders, cobbles and gravels interspersed with areas of sand and mud. The maximum depth of 20 m was recorded where Brown Bay enters Newcomb Bay. Brown Bay is typically ice free for 1-2 months a year, generally between January and March. Due to its orientation, the sea-ice in Brown Bay is rarely blown out during the winter period. Samples were collected at various distances from shore, as well as at water depths between 1 and 16 m.

### *Shannon Bay*

Shannon Bay is a small embayment within the southwestern corner of Newcomb Bay, approximately 800 m east of Brown Bay. Shannon Bay is bordered by 2-15 m ice cliffs, with the sewage outfall situated 30 m landward of the eastern cliff. The input of treated wastewater from the present Casey station has resulted in elevated levels of ammonia, total phosphorous and bacteria within Shannon Bay (Morris et al., 2000, in prep). Preliminary sampling of Shannon Bay also indicated elevated concentrations of heavy metals. The subtidal sides of this bay consist of steeply sloping rock and boulder fields below which is a relatively homogenous muddy sand (Stark, 2000). A maximum depth of 32 m was recorded at the mouth of this bay. This bay is generally ice free for a longer period than Brown Bay, with open water occurring between December and March. Samples were collected at 1, 2, 4, 8 and 12 m water depth as well at varying distance from shore.

### *O'Brien Bay*

O'Brien Bay is a large bay located on the southern side of Bailey Peninsula and has a maximum depth of 80 m. Ice-cliffs 2-30 m high surround this bay, whilst the subtidal slopes vary between steep boulder fields and inclined rocky banks (Stark, 2000). Sampling has shown that the sediments of this bay are not contaminated with either heavy metals or hydrocarbons (Snape et al., 2001). Samples were collected from three different sites within this bay, two located on the northernmost side, and one near a small island in the centre of this bay.

### *Sparkes Bay*

Sparkes Bay is a large bay situated several kilometers south of Casey Station. This bay has a variety of environments; ice cliffs dropping vertically into deep water, steep rocky shorelines, as well as shallower areas where sediments can accumulate. A small embayment on the northern side of Sparkes Bay was used as one of the sampling locations. This embayment has a very similar bathymetry to that of Brown Bay with the rocky sides sloping down to a muddy bottom, the depth of which ranges between 3 and 20 m (Stark et al., in prep). Naturally high levels of some heavy metals, including cadmium, have been recorded for Sparkes Bay (Stark et al., in prep). Samples were collected near to shore in the small embayment, as well as further out into Sparkes Bay.

## **Methods**

### **Sample collection**

Sampling of sediments was undertaken during the austral summers of 1999, 2000, and 2001. In the 1999 season, surface sediments were collected by divers. These sediments were preserved in gluteraldehyde and frozen at -20 °C until processing. During the 2000 and 2001 seasons, surface sediments were collected using an Eckman grab. These samples were preserved in Lugols iodine solution, and frozen at -20 °C until processing.

### Diatom preparation and identification

Excess organic material was removed from the sediments by digestion in 10% H<sub>2</sub>O<sub>2</sub> for 72 hours. Excess liquid was decanted off, with the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. For light microscopy (LM), a subsample of this solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Enumeration of diatom taxa was undertaken on a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. A minimum of 1000 frustules was examined for 1999 samples whilst a minimum of 400 individuals was counted for samples collected in 2000 and 2001. 400 frustules have been shown to be statistically valid; due to time constraints, this figure was adopted for the latter counts. Diatoms species were expressed as relative percentages (% total diatoms) of the frustules counted. The terms common, frequent, rare and extremely rare are used forthwith to refer to relative abundances between 10-50%, 2.1-10%, 0.6-2% and 0-0.5%, respectively. Both LM and SEM was used in taxonomical determinations of species.

The identification of taxa was primarily based on the following literature: Hasle and Syvertson (1996), Medlin and Priddle (1990), Patrick and Reimer (1966, 1975), Hustedt (1985), Poulin and Cardinal (1982a, 1982b, 1983) and Dexing et al., (1985). Many additional monographs were also referred to in the identification process, including Oppenheim (1994), Whitehead (1994), Williams and Round (1997), and Sterrenburg (1993).



## Results

The diatom assemblages used in this study had components of planktonic, sea-ice and benthic communities. Seventy six different diatom taxa were identified to genus in these assemblages (Appendix 1); a further four pennate taxa have yet to be identified. Thirty two taxa only exist in benthic communities, eight taxa are restricted to sea-ice communities whilst ten taxa are only found within planktonic communities (Appendix 1). The remaining twenty six identified taxa can be present in more than one of these communities; for example, *Navicula glaciei* grows both in benthic and sea-ice associated communities. The four unidentified taxa were incorporated into analyses of benthic diatoms, however, these species rarely accounted for more than 1% of the total diatom assemblage.

Within the planktonic and sea-ice component of the diatom assemblages, *Fragilariopsis* spp. were most common. Seven different species of *Fragilariopsis* were recorded in samples from the Windmill Islands. *Fragilariopsis curta* was the most abundant non-benthic diatom.

For the purpose of this project, the term “benthic species” will be used to refer to any species which are commonly found in the benthos, regardless of whether or not they also occur in planktonic or sea-ice associated communities. The benthic diatom communities sampled in the Windmill Islands generally consisted of 30-35 species. A total of 52 benthic species was recorded from the Windmill Islands, however, several of these only occurred within a few samples. *Navicula* was the most common benthic genus, with 7 species recorded. Five species of *Cocconeis* were recorded in the sediment samples. Relative abundances of the individual *Cocconeis* spp. were typically around 5%, however, *Cocconeis pinnata* generally had relative abundances of 1%. *Cocconeis* sp. a had the highest maximum relative abundance (40%) recorded for a species of this genus

No one species dominated the benthic diatom communities at all locations. The highest relative abundance recorded for an individual species was 44.8% for

*Navicula* aff. *glaciei*, in one of the samples from Odber Island, however, this species typically had abundances below 15% in both Brown Bay and Shannon Bay. *Cocconeis schuetti* attained a maximum relative abundance of 40% at Sack Island, but values of this species were typically less than 10% at other locations.

Generally only 2 or 3 benthic species were abundant within each location, with relative abundances ranging between 10 and 20% for each of these species. Differences were observed between locations in the identity of the abundant species. For example, *Staurosira construens* var. *pumila* was the most abundant benthic species at Cloyd Island, with relative abundances ranging between 13% and 40%, however this species did not exceed 10% in either Brown Bay or Shannon Bay. Conversely, the relative abundances of *Planothidium delicatulum* typically exceeded 10 % at Brown Bay, but did not exceed this amount at either Cloyd Island or Shannon Island.

Structural parameters of the benthic diatom communities varied both within a site, and between sites. Pielou's evenness values ranged between 0.53 and 0.864, dominance values ranged between 0.068 and 0.315. Shannon-Wiener diversity values varied from 1.42 to 2.89 and Margalef's richness values varied between 2.61 and 7.2.

## Discussion

### Comparisons with other diatom studies from the Windmill Islands

Scant information is available on diatom communities from the Windmill Islands, with only two papers previously published. Roberts et al. (2001) examined the diatom flora of lakes and ponds from the Windmill Islands; Cremer et al. (2001) used diatom assemblages from a marine core to reconstruct the quaternary environmental history of the region. Cremer et al. (2001) recorded 112 different taxa, however 32 of these were not classified. The assemblages examined were primarily composed of *Chaetoceros* spp., *Fragilariopsis curta* and *F. cylindrus*, *Eucampia antarctica* and

*Thalassiosira antarctica* and *T. scotia*. Cremer et al. (2001) found that the relative abundance of *Chaetoceros* varied between 15% and 80%; in contrast, a maximum relative abundance of 10% was recorded in the sediment samples from this study. The relative abundances of *Fragilariopsis curta* and *F. cylindrus* were also much lower (0.2% - 13%) in this study, relative to the abundances (typically in excess of 40% over the last 4000 yr BP) reported by Cremer et al. (2001).

Forty four benthic species were recorded by Cremer et al. (2001), including species which are not exclusively benthic; a similar number was recorded in this study. The abundance of benthic species was much higher in this study than in Cremer et al. (2001). Cremer et al. (2001) found that over the last 10,000 years, the total abundance of *Navicula* species did not exceed 10%. In this study *Cocconeis schuettii* and *Cocconeis* sp. a each exceeded this abundance, with maximum abundances of 40% and 15%, respectively. Relative abundances of approximately 5% were typically recorded for *Cocconeis fasciolata*, *Cocconeis costata*, and *Cocconeis* sp. a. within this study.

The differences observed in the proportion of benthic and planktonic species present within the diatom assemblages, and thus the differences in relative abundances of individual genera, is probably related to the different sampling depths. The assemblages studied in Cremer et al. (2001) were sampled from a core collected at a water depth of 46 m in Browning Bay. The results presented in this chapter are based on samples collected at water depths of 1 m to 25 m. The lower proportion of planktonic species present in these samples may reflect the reduced size of the water column.

Twenty two taxa had abundances greater than 2% in a study of fourteen lakes and ponds from the Windmill Islands (Roberts et al., 2001). Of these twenty two taxa, five were recorded in the present study, namely *Achnanthes brevipes*, *Chaetoceros* spp. *Staurosira construens* var. *venter*, *Fragilariopsis curta*, and *Fragilariopsis cylindrus*. Seven other species were found to have salinity tolerances that would

have enabled them to survive in a marine environment, but were not recorded in the present study.

The relative abundances of the seven species common to both studies differed between the two studies, reflecting the different environments. For example, *Fragilariopsis curta* did not exceed 2.5% in lakes and ponds, yet reached 10% in the marine environment. Planktonic species are frequently less abundant in Antarctic lakes than in oceans, possibly due to the prolonged ice cover (Jones et al., 1993). Differences were also observed between studies in the relative abundances of benthic species. *Achnanthes brevipes* had a maximum relative abundance of 18% in the current study, but did not reach 5% in the study of lakes and ponds (Roberts et al., 2001).

Despite common components, it is concluded that the diatom assemblages examined in the current study are distinct to diatom communities previously described from freshwater lakes and deeper marine bays of the Windmill Islands.

### **Comparisons with other assemblages from Antarctic marine sediments.**

The diatom assemblages from the Windmill Islands had higher relative abundances of benthic species, and lower relative abundances of planktonic species compared to other Antarctic studies. For example, *Fragilariopsis curta* and *Fragilariopsis cylindrus* had maximum relative abundances of 45% and 11.7% respectively in sediments from the George V Coast (Leventer, 1992) and 48% and 11% from sediments in Lutz-Holm Bay (Tanimura, 1992). Maximum relative abundances of only 10% and 3%, respectively were recorded for these in surface sediments from the Windmill Islands (Appendix 1). This probably reflects the shallower sampling depths used in this study.

Similarly *Achnanthes* species have been reported at low abundances (<2.5%) in sediments from Lutz-Holm Bay (Tanimura, 1992), but were absent from sediments on the George V coast (Leventer, 1992); in contrast, diatom assemblages from the

Windmill Islands had relatively high abundances of *Achnanthes brevipes* (1.5 to 18%) and *Achnanthes* sp. a (Appendix 1). Similarly, the total abundance of *Cocconeis* species did not exceed 0.8% on the George V Coast (Leventer, 1992), or 3.1% in Lutz-Holm Bay (Tanimura, 1992), however all *Cocconeis* species identified from the Windmill Islands individually exceeded these abundances in at least one sample (Appendix 1). Furthermore, *Cocconeis schuetti* attained a maximum relative abundance of 40% in a samples from Sack Island. The higher relative abundances of benthic species in this study probably reflects the shallow depths from which samples were collected, typically 1-16 m, while samples were collected from Lutz-Holm Bay at depths up to 500 m in (Tanimura, 1992) and from 2599 m on the George V Coast (Leventer, 1992).

Many of the benthic species identified in this study were also recorded in benthic diatom assemblages from fjords in the Vestfold Hills (Whitehead and McMinn, 1997). These species include *Planothidium delicatulum*, *Cocconeis costata*, *C. fasciolata*, *C. pinnata*, *Diploneis splendida*, *Staurosira construens*, *Navicula directa*, *N. glaciei*, *N. perminuta*, *Pseudogonphonema kamtschaticum* and *Trachyneis aspera*. This reflects the wide distribution of these species, most of which are circumpolar. In Maxwell Bay, *Trachyneis aspera*, and *Cocconeis* spp. each constituted 11% of the total diatom biomass in the sediment, while *Odontella litigosa*, *Cylindrotheca closterium* constituted 43% and 19% respectively (Ahn et al., 1997). Neither of the latter two species were present in diatom communities from recent sediment samples in the Windmill Islands (Appendix 1), despite similar sampling depths. The relative abundances of *Cocconeis* spp were much higher in samples from the Windmill Islands than those reported from Maxwell Bay. In contrast, diatom assemblages from Maxwell Bay had much higher relative abundances of *Trachyneis aspera* than assemblages from the Windmill Islands, where the maximum abundance recorded was 1.5% (Appendix 1).

### **Conclusion**

The diatom assemblages from modern sediment samples in the Windmill Islands contain many species which have previously been recorded in benthic diatom communities elsewhere in Antarctica. The major difference between the assemblages described here, and those previously described is the higher proportion of benthic species, possibly due to the shallower sampling depths used in this study. In addition, the relative abundances recorded from benthic diatom communities in the Windmill Islands differ significantly to those previously reported for Antarctic benthic diatom communities.

### ***A preliminary assessment of human impacts on benthic diatom communities in the Windmill Islands.***

#### **Abstract**

A preliminary survey was undertaken to determine whether the composition or structure of benthic diatom communities in the Windmill Islands have been affected by heavy metal and petroleum hydrocarbon contaminants derived from two now-defunct tip sites. Samples were collected from marine bays immediately adjacent to the tip sites as well as from two reference locations. Significant differences were recorded between the composition of the diatom communities from Brown Bay, one of the potentially impacted locations and the average composition of the two reference locations. Relative abundances of several species of *Staurosira* and *Navicula* varied significantly between this location and both the reference locations. The composition of the diatom communities from the other potentially impacted location was within the range of variability observed at the two reference locations. No structural differences in the diatom communities were observed between either of the potentially impacted locations and the two reference locations.

#### **Introduction**

Since the establishment of the first permanent station in 1959, until a change of policy in 1986, all refuse generated by research stations in the Windmill Islands was disposed of locally. The dumped material consisted of waste chemicals, refuse from the various mechanical workshops, such as engine parts, batteries, and old fuel drums (Snape et al., 2001), as well as the domestically produced waste. During its twelve years of operation, an estimated 20,000 m<sup>3</sup> of rubbish was dumped at the waste disposal site associated with Wilkes Station (Snape et al., 1998). Refuse from the Old Casey station was dumped into the nearby Thala Valley (Deprez et al., 1999) and occasionally bulldozed onto sea-ice in Brown

Bay. Despite an attempt to clean up this site during the 1995/96 summer season, it is estimated that up to 2,500 m<sup>3</sup> of rubbish still remains (Snape et al., 1998).

Soils in the Thala Valley tip site have been contaminated with heavy metals and petroleum hydrocarbons (Deprez et al., 1999; Snape et al., 2001). Some of these contaminants have entered the marine bays immediately adjacent to these tip sites. Chemical evidence demonstrates that Brown Bay has been contaminated with both heavy metals and petroleum hydrocarbons as a result of the operation of Old Casey Station and the associated waste disposal site (Stark et al., in press; Scouller et al., 2000). Some surface waters around the Wilkes station and waste disposal site also contain such contaminants. In addition, thin oil films have been observed in Newcomb Bay, originating from Wilkes. Thus, although there is currently no chemical data on contaminant concentrations in the marine sediments of Newcomb Bay in the immediate vicinity of the station, it seems likely that these are also contaminated.

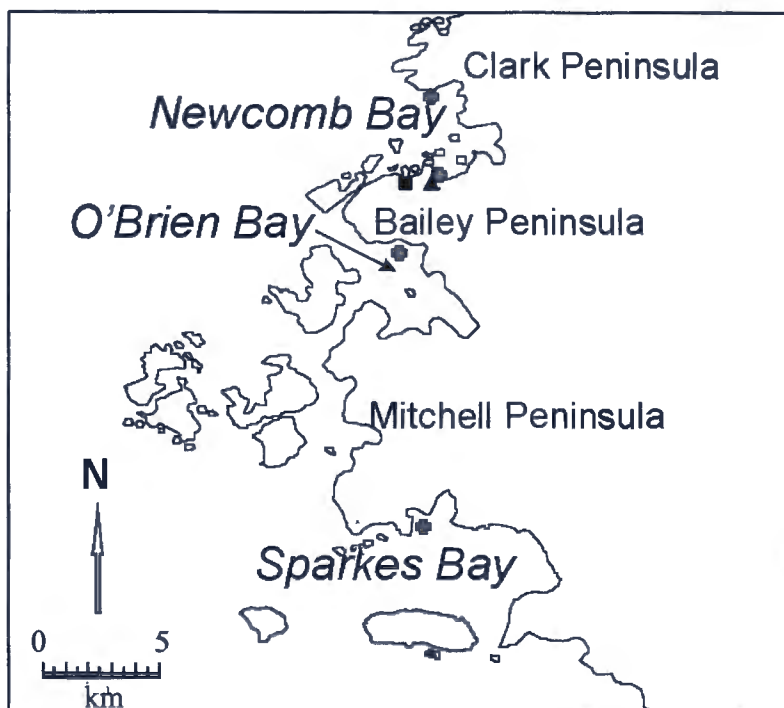
The presence of contaminants within an ecosystem does not necessarily result in a biological impact as it is possible that low concentrations of contaminants may cause no ecological effect. A preliminary investigation was therefore undertaken to examine whether any biological effects of contamination are apparent in the benthic diatom communities. It was hypothesised that the diatom communities of impacted locations would be compositionally or structurally distinct from the diatom communities of reference locations.

## **Methods**

### **Sampling design**

Four study locations were selected. These locations consisted of the two potentially impacted locations, Brown Bay and Newcomb Bay near Wilkes Station, as well as one location in each of Sparkes Bay and O'Brien Bay (Fig 3.1).





**Figure 3.1** Map of the Windmill Islands showing the position of sampling sites (+).

The latter two bays have not been contaminated by anthropogenic activities however naturally high concentrations of some metals have been recorded in Sparkes Bay (Snape et al., 2001). The locations used within these bays were selected on the basis of shared physical characteristics with the two contaminated sites.

Within each location three sampling sites were chosen, representing increasing distances from the shoreline. Within each sampling site, two replicate samples were collected. The sediment samples were collected by divers inserting small plastic tubes into the sediments. These sediments were preserved in glutaraldehyde, and frozen for return to Australia. Scrapings from the top few mm of each tube were used for the diatom analyses. No attempts were made to distinguish between live and dead diatoms within this study.

## Site description

### *Brown Bay*

Brown Bay is a small embayment at the southern end of Newcomb Bay, immediately adjacent to the Thala Valley tip site. Aligned approximately west-east, the maximum depth of 20 m occurs at the eastern end where Brown Bay enters Newcomb Bay. Brown Bay has rocky sides which grade to a muddy bottom (Stark, 2000).

Recent studies have demonstrated higher concentrations of petroleum hydrocarbons and metals in sediments collected from Brown Bay, relative to sediments collected from reference locations (Snape et al., 2001; Scouller et al., 2000). Concentrations of some metals such as copper, lead, iron and zinc occur at concentrations 10 to 100 times that of background levels (Scouller et al., 2000; Stark et al., in press). Petroleum hydrocarbons, derived from lubrication oil and diesel fuel, are present at concentrations between 40 and 200 mg kg<sup>-1</sup> in the surface sediments of Brown Bay; in contrast, no petroleum hydrocarbons have been detected in sediments from reference locations (Snape et al., 2001).

### *Newcomb Bay near Wilkes*

This sampling location is immediately adjacent to the Wilkes tip site, not Wilkes Station itself. In this chapter, this location will subsequently be referred to as “Wilkes”. In this area of Newcomb Bay, the bay is relatively shallow, and gently inclined, with a predominantly rocky bottom. Thin patches of poorly sorted sediment are randomly dispersed throughout this area.

### *The reference locations*

O'Brien Bay and Sparkes Bay, the two reference locations, are large bays situated several kilometers south of Casey Station. These bays have a variety of environments; ice cliffs dropping vertically into deep water, steep rocky shorelines, as well as shallower sediment-dominated areas. A small embayment on the northern side of Sparkes Bay was used as a sampling location as it has a

very similar bathymetry to that of Brown Bay, with the rocky sides sloping down to a muddy bottom, and a depth range between 3 and 20 m (Stark et al., submitted). Naturally high levels of some metals, including cadmium, have been recorded for Sparkes Bay (Stark, in press). The selected sampling location in O'Brien Bay was also situated on the northern side of the bay. The sides consisted of steeply sloping boulder fields as well as more gently inclined rocky banks. Patches of poorly mixed mud and sand, interspersed between gravel, cobbles and boulders formed the bottom sediments of this area (Stark, 2000).

### Diatom preparation and identification

Organic material was removed by digestion in a 10% hydrogen peroxide solution for 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Identification was as outlined in Appendix 1, with the exception of *Cocconeis costata* and *Cocconeis fasciolata* which were initially incorrectly identified. To avoid recounting all the samples, these two species have been treated as one taxon in this chapter. A minimum of 1000 individuals of the predominantly benthic taxa was counted for each sample. The relative abundances of these taxa were then calculated and used in the statistical analyses. Only taxa which had a relative abundance of 2% in at least one sample were included in the analysis. Exclusion of rare taxa is on the basis that they may be allocthanous. For example, an exclusively freshwater

species *Luticola muticopsis* was recorded in the sediment of Brown Bay, but was probably derived from the meltstream which enters Brown Bay.

### Statistical Analyses

Multivariate analyses of community composition were undertaken using non-metric multidimensional scaling (nMDS) and analysis of similarity (ANOSIM) procedures using the PRIMER software package (Plymouth Marine Laboratories, 1994). One way ANOSIMs were used to compare similarities in the composition of diatom communities from the four locations.

Similarity percentages analyses (SIMPER) were used to determine which species were responsible for compositional differences observed between diatom communities. Clarke and Warwick (1994) state that species which have a SIMPER ratio greater than 1.3 are likely to be useful for discriminating between groups. In order to determine which species were most useful the following method was used to rank species. Only species which had a simpler ratio above 1.3 in at least one comparison were considered. For each species, comparisons in which the ratio did not exceed 1.3 were excluded. The sum of the remaining ratios was then determined, and divided by the total number of comparisons possible. The ten species which had the highest values were then used for univariate analyses.

Natural logarithms were used to calculate Shannon-Wiener diversity ( $H'$ ) values, Simpsons' dominance index (SI), Margalef's species richness ( $d$ ) values, and Pielou's evenness ( $J'$ ) values. Collectively, these values will be referred to as the structural parameters of the diatom communities. Whilst these measures are not independent of each other, they can reflect slightly different trends within the community structure. Single factor analyses of variance (ANOVA) were performed to determine if significant differences occurred between locations in either structural parameters or the relative abundances of selected species.. Prior to undertaking such analyses, Cochran's C test was used to check the assumption

of homogeneity of variances. Any data transformations that were necessary to fulfil this assumption are noted in the accompanying tables. Where ANOVAs indicated significant differences between samples, SNK tests were used for multiple comparisons using GMAV5 (Underwood and Chapman, 1989). Unless otherwise stated, a significance level of  $p = 0.05$  was applied to all analyses.

## Results

### Description of the diatom communities

#### Wilkes

Three species occurred at relative abundances greater than 10% in the diatom communities samples from Wilkes: *Navicula perminuta* (20.6%), *Planothidium* spp. (13.4%) and *Navicula* aff. *glaciei* (11.7%). Five other species also had average relative abundances greater than 5%, these were *Diploneis splendida* (8.4%), *Pseudostaurosira* sp. a (7.6%), *Cocconeis costata/fasciolata* (6.3%), *Achnanthes brevipes* (6.2%) and *Navicula* sp. a (5.7%). A total of 31 different taxa were recorded in these samples. Evenness values ranged between 0.70 and 0.84, and dominance values varied between 0.079 and 0.133. Diversity values ( $H'$ ) varied between 2.4 and 2.7, whilst richness values ranged between 4.6 and 6.3.

#### Brown Bay

The diatom communities sampled from Newcomb Bay near Wilkes consisted mainly of the *Achnanthes delicatula* complex (23.3%), *Pseudostaurosira* sp. a (21.1%) and *Staurosira construens* var. *venter* (16.8%). Only one other species had an average relative abundance greater than 5%, *Navicula* sp. a (5.7%). Thirty different species were observed in these samples. Evenness values ranged between 0.60 and 0.78, and dominance values varied between 0.099 and 0.227. Diversity values ( $H'$ ) varied between 1.8 and 2.6, whilst richness values ranged between 3.7 and 6.5.

### O'Brien Bay

The most abundant taxa in the diatom communities sampled from O'Brien Bay were *Planothidium* spp. (23.4%) and *Navicula* aff. *glaciei* (12.9%). Five other species also had average relative abundances greater than 5%, these were *Pseudostaurosira* sp. a (9.9%), *Achnanthes brevipes* (8.0%), *Navicula perminuta* (6.7%), *Navicula* sp. a (5.6%), and *Cocconeis costata/fasciolata* (5.1%). Thirty four different species were recorded in samples from this location. Evenness values ranged between 0.71 and 0.81, and dominance values varied between 0.073 and 0.140. Diversity values ( $H'$ ) varied between 2.4 and 2.8, whilst richness values ranged between 5.9 and 7.2.

### Sparkes Bay

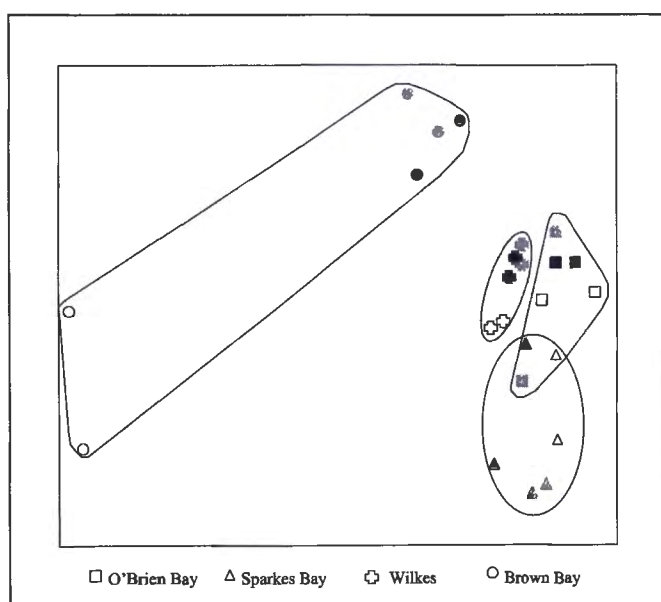
The diatom communities sampled from Sparkes Bay consisted predominantly of *Navicula* aff. *glaciei* (27.6%), *Navicula perminuta* (18.4%) and *Cocconeis costata/fasciolata* (10.2%) and *Planothidium* (10.1%). Only one other species had an average relative abundance greater than 5%, namely *Pseudostaurosira* sp. a (6.75%). A total of 31 different species were recorded in these samples. Evenness values ranged between 0.62 and 0.80, and dominance values varied between 0.093 and 0.191. Diversity values ( $H'$ ) varied between 2.0 and 2.5, whilst richness values ranged between 4.6 and 5.9.

### Comparisons between samples

The nMDS ordination indicates that the diatom communities from Brown Bay are compositionally distinct from the diatom communities from the other three locations (Fig 3.2). Furthermore, the diatom communities collected from the inner regions of Brown Bay group separately from those communities collected at a greater distance from shore within Brown Bay. Whilst the remaining three locations all plot within the same area on the nMDS, the individual locations still form separate groups.

ANOSIM results indicate that significant differences in species composition occurred between all locations (Table 3.1). Diatom communities from Sparkes Bay and Wilkes had the most similar compositions ( $R = 0.446$ ,  $p = 0.02$ ) while diatom communities from Brown Bay and Sparkes Bay had the most dissimilar compositions ( $R = 1.000$ ,  $p = 0.01$ ). Diatom communities from Wilkes were not compositionally distinct from those from reference locations (Table 3.1).

The composition of diatom communities from Brown Bay was, however, significantly different to that of the two reference locations when these were considered as a group. Compositional differences, relative to the reference locations, were more pronounced in the inner samples from Brown Bay than the other samples from Brown Bay (Table 3.1). The low number of replicates



**Figure 3.2** nMDS ordination of diatom communities from the Windmill Islands, showing the separation into location groups. The gradation from white-grey-black symbols represents increasing distance from shore. The dotted line indicates the two sub-divisions within the Brown Bay samples.

Location 1	Location 2	R value	p value
Wilkes	O'Brien	0.670	0.002
Wilkes	Sparkes	0.446	0.011
Wilkes	Brown	0.993	0.002
O'Brien	Sparkes	0.746	0.002
O'Brien	Brown	0.878	0.002
Sparkes	Brown	1.000	0.002
Wilkes	Average reference	0.150	0.09
Brown Bay (Overall)	Average reference	0.697	<0.0001
Brown Bay (Inner)	Average reference	0.908	0.011
Brown Bay (Mid and Outer)	Average reference	0.558	0.002

**Table 3.1** ANOSIM results for comparison of community composition between sites, as well as between potentially impacted sites and the average composition of reference locations.

precluded the detection of significant differences between the diatom communities from the inner Brown Bay samples, and other samples collected from within this bay.

SIMPER ratios indicated that a number of species contributed to differences observed between locations. ANOVA results confirmed that a number of species varied significantly in relative abundances between locations (Table 3.2). SNK tests (Table 3.2) indicated that several of these species differed significantly in abundances between the two reference locations. *Navicula perminuta* and *Navicula* aff. *glaciei* both had significantly higher relative abundances in Sparkes Bay than O'Brien Bay. *Planothidium* spp. occurred at significantly higher relative abundances in O'Brien Bay and Brown Bay than in Sparkes Bay.



Species Name	Transformation	ANOVA (p-value)	SNK results
<i>Achnanthes brevipes</i>	-	0.0049	O=W (=S) >B (=S)
<i>Planothidium</i> spp.	-	<0.0001	O=B>W=S
<i>Diploneis splendida</i>	$\sqrt[3]{(x+1)}$	<0.0001	W>O=S>B
<i>Staurosira construens</i> var. <i>pumila</i>	!	0.0027	B>S=O=W
<i>Staurosira construens</i> var. <i>venter</i>	$\sqrt[3]{(x+1)}$	<0.0001	B>S=O=W
<i>Navicula</i> aff. <i>glaciei</i>	log (x+1)	<0.0001	S>O=W>B
<i>Navicula perminuta</i>	-	0.0009	W=S>O=B
<i>Navicula</i> sp. a	-	0.0067	B>S=O=W
<i>Pseudostaurosira</i> sp. a	$\sqrt[3]{(x+1)}$	<0.0001	B>S=O=W
<i>Stauroneis wislouchii</i>	-	0.0297	S (=O=W) >B (=O=W)

**Table 3.2** ANOVA and SNK results showing differences in relative abundances of species between locations. Transformations used to satisfy assumptions of homogeneity of variance are shown; - indicates that no transformation was used, ! indicates that variance was always heterogenous, and that a lower significance level should therefore be applied. Each location is represented by its first letter, thus Wilkes is represented by a W, O'Brien Bay is represented by an O. The = sign indicates that no significant differences were observed between those locations. The > sign indicates that significant differences were observed ( $p = 0.05$ ) and that the location on the left of the sign had a higher relative abundance. Brackets around a letter indicate that that location was not significantly different to locations on either side of the equation. For example S=O (=W) >B (=W) would indicate that Sparkes Bay and O'Brien Bay both had significantly higher relative abundances than Brown Bay, but that the relative abundances observed in communities from Wilkes were not significantly different to any other location.

Differences in the relative abundances of individual species were also observed between the two potentially impacted locations. SNK tests (Table 3.2) revealed that diatom communities from Brown Bay had significantly higher relative abundances of several taxa than communities from Wilkes, *Staurosira construens* var. *venter* and *Staurosira construens* var. *pumila* are two such examples. On the other hand, *Diploneis splendida*, *Achnanthes brevipes* and *Navicula perminuta* all occurred at significantly higher abundances in diatom communities from Wilkes than at Brown Bay.

No species had significantly different relative abundances in both the potentially impacted locations, relative to both the reference locations, however some differences were observed between the individual potentially impacted locations and the reference locations. *Staurosira construens* var. *pumila*, *Staurosira construens* var. *venter*, *Pseudostaurosira* sp. a, and *Navicula* sp. a all had significantly higher relative abundances in Brown Bay than in the reference locations. In contrast, lower relative abundances of *Diploneis splendida*, and *Navicula* aff. *glaciei* were observed in communities from Brown Bay, relative to the reference locations. *Diploneis splendida* was also the only species to vary significantly between Wilkes and the reference locations, with higher abundances observed at Wilkes.

A few differences were also observed in the structural parameters of the diatom communities between locations. ANOVA results (Table 3.3) indicated that both diversity and richness differed significantly between locations. SNK results (Table 3.3) revealed that significant differences in diversity only occurred between O'Brien Bay and Brown Bay, with O'Brien Bay having higher values. Observed differences in richness were also due to significantly higher values in the diatom communities collected from O'Brien Bay, relative to the three other locations (Table 3.3).

Structural Parameter	ANOVA (p-value)	SNK results
Diversity (H')	0.0376	O (=S=W) > B (=S=W)
Richness	0.0105	O > S = W = B
Evenness	0.1072	N/A
Dominance	0.1525	N/A

**Table 3.3** ANOVA and SNK results for comparisons of structural parameters of the diatom communities between locations. No data transformations were required to satisfy assumptions of homogeneity of variance. N/A indicates that SNK tests weren't appropriate as ANOVAs had indicated no significant differences occurred between sites. Other symbols as in Table 3.2.

## **Discussion**

The stated objective of this study was to determine if the contaminants present in sediments from Brown Bay and Wilkes had any apparent impact on benthic diatom communities, as evidenced by differences in composition or structure between the potentially impacted locations and reference locations. In order to determine if an impact is occurring, the perturbed site needs to be compared to the average of reference locations. Diatom communities from Brown Bay were shown to be compositionally distinct to both the individual reference locations and the average composition of diatom communities from the reference locations. One of the first procedures in assessing whether contamination is having a biological effect is to establish whether a difference occurs, either spatially or temporally, between communities which are subjected to contamination, and those that are not (Underwood, 1988). This study has demonstrated that significant differences in diatom community composition do exist between the contaminated Brown Bay and uncontaminated locations within the Windmill Islands. Further investigation into potential relationships between diatom communities and chemical contamination of the marine environment near Casey Station is therefore warranted. This study has not, however, ruled out the possibility that variables other than chemical contamination are responsible for the observed differences (see chapter 8).

Both the nMDS and ANOSIM results indicated that the diatom communities from the innermost site of Brown Bay differed more significantly than the diatom communities from elsewhere in Brown Bay, relative to the reference locations. It was only within Brown Bay that such a differentiation between sampling sites was observed. This may reflect differences in the bathymetry of the different bays, or possibly chemical contamination. The innermost samples in Brown Bay are much closer to the waste disposal site than samples further out in the bay. It is likely that the inner samples would therefore be subject to higher concentrations of contaminants than the outer communities, which could explain the increased differentiation observed relative to reference locations. Further investigation

would be required to verify whether this pattern is due to chemical contamination or some other factor.

Univariate analyses also demonstrated significant differences in composition between diatom communities from Brown Bay and those of the two reference locations. Abundances of *Staurosira* spp. were significantly higher in Brown Bay than in either of the reference locations. Published reports regarding the sensitivity of this genus to contamination vary. *Staurosira* spp. (including *S. construens*) have previously been described as extremely sensitive to metal pollution, with severe decreases in abundances corresponding to increased copper contamination (Ruggiu et al., 1998). In contrast, Medley and Clements (1998) found that small *Staurosira* species were tolerant of metals. It has previously been suggested that small species, where the maximum growth rate is related to cell diameter, may become dominant in communities exposed to stress (Kinross et al., 1993). This theory may explain why increased abundances of *Staurosira construens* and *Pseudostaurosira* sp. a were observed in Brown Bay relative to the reference locations.

Significant differences in the relative abundances of *Navicula* aff. *glaciei* and *Navicula* sp. a were also observed between Brown Bay and the reference locations. *Navicula* spp. have previously been shown to be sensitive to metal pollution (Medley and Clements, 1998) with lower abundances occurring as a result of pollution (Ivorra et al., 1998). Although *Navicula* aff. *glaciei* followed this trend in this study, the opposite was true for *Navicula* sp. a.

Despite the observed compositional differences, structural parameters differed only between the diatom communities from Brown Bay and O'Brien Bay, not between the diatom communities from Brown Bay and the averaged reference locations. This suggests that composition may be a more sensitive indicator of change within diatom communities, relative to structural parameters. This differs with other studies where diversity has been shown to be equally, if not more

sensitive to metal contamination as species composition (ie. Medley and Clements, 1998).

No significant differences in structural parameters were observed between diatom communities from Wilkes and the reference locations, while univariate analyses indicated that only one species differed significantly in abundance between these locations. Multivariate analyses indicates that, although compositional differences were observed between Wilkes and the individual reference locations, the average composition of the reference location was not significantly different to the composition of diatom communities from Wilkes. Furthermore, compositional differences between diatom communities from Sparkes Bay and Wilkes were less than those observed between the two reference locations. It is therefore concluded that the diatom communities from Wilkes are within the range of natural variability, as defined by the average composition and structure observed at the reference locations. Thus, no biological impact resulting from contamination is apparent in the structure or composition of benthic diatom communities sampled from Wilkes within this study. This study examined only one bay near the abandoned Wilkes station; it remains possible that other sites near this may have been contaminated, or that there may have been an impact at the time of operation that is no longer apparent in the diatom communities currently living in the surface sediments.

The results given here represent only a preliminary survey. For simplicity, the two potentially impacted locations are compared to only two reference locations, although three sites were sampled within each location. In order to determine if an impact is occurring, the perturbed site needs to be compared to the average in a set of reference locations (Underwood, 1989). Whilst Brown Bay does fall outside the range observed in the sampled reference locations, this is based on only a few samples. A range of compositional differences will be observed in a set of reference locations and increasing the number of reference locations will generally increase accuracy (Underwood, 1989). It is also possible that

environmental conditions, such as grainsize, may differ between Brown Bay and the selected reference locations. Increasing the number of locations sampled is likely to increase the heterogeneity of the environment, thus reducing environmental differences between the reference locations and Brown Bay. Thus, although the results given here may indicate a biological impact within Brown Bay, a follow up study with sampling from additional control sites may lend greater weight to this observation.

### **Conclusions**

Compositional differences between diatom communities from Brown Bay and the averaged composition of reference locations were detected by both multivariate and univariate analyses. This may be due to the presence of contaminants within Brown Bay, however further investigation would be required to demonstrate causality. In contrast, benthic diatom communities from Wilkes were shown to be within the range of variance observed at the reference locations. It therefore seems likely that any contaminants which may be present in the marine environment at Wilkes do not occur at concentrations sufficient to influence the composition or structure of the benthic diatom communities.

## Chapter 4

### ***Spatial variability of diatom communities near Casey Station***

#### **Abstract**

The spatial variability of diatom communities within the Windmill Islands was assessed on three scales using a hierarchical nested sampling design. Six sampling locations were used, with two sites sampled per location, and two plots sampled per site. Two of the locations used have been contaminated with heavy metals and hydrocarbons, the remaining four locations were used as controls. Significant differences in diatom communities were observed on all scales however the degree of dissimilarity between diatom communities was related to the scale used. Significant differences were observed in community composition between all locations, however structural differences were all detected between a few locations. Compositional differences in diatom communities between sites within the one location were only observed in control locations; however compositional differences within sites were observed at all locations.

#### **Introduction**

The spatial distribution of benthic marine diatom communities in Antarctica is not well understood. The majority of work previously undertaken has been descriptive, and there is little quantitative information available on the scale of variation within Antarctic benthic marine diatom communities. Whitehead and McMinn (1997) found that depth was the main factor affecting the distribution of benthic diatoms, accounting for 58% of variation observed between samples. Included within this, changing light conditions accounted for 45% of the variability whilst 13% was possibly due to differences in grain size (Whitehead and McMinn, 1997). Dayton et al. (1986) examined spatial variability of chlorophyll *a*, but no attempt was made to examine variability in community composition. Whilst analysis of spatial patterns is common in population and environmental studies, few examine whether these patterns are consistent at different scales (Bendetti-Cecchi, 2001).

The aim of this investigation was to determine the spatial variability of the benthic diatom communities at three different scales within four control and two contaminated sites near Casey Station. It was hypothesised that there would be differences in diatom community composition across several scales; tens of meters, hundreds of meters and between bays. It was predicted that these differences would be expressed as changes in both community composition and structural parameters. It was expected that locations in the same vicinity would have more similar diatom communities than locations several kilometers apart.

A secondary aim was to examine whether the variability of diatom communities was affected by the contaminant concentrations currently occurring within Brown Bay and Shannon Bay.

## **Methods**

### **Sampling design**

A hierarchical, 3-level, nested design was used. The highest hierarchical level consisted of six locations. Two of these locations, Brown Bay and Sparkes Bay, are potentially impacted by heavy metals and petroleum hydrocarbons. The remaining four locations are more distant from Casey Station and were used as control locations. These locations were Denison Island, Odbert Island, O'Brien Bay and Sparkes Bay (Fig. 4.1). A full description of these sites is given below. Within each location two sites were selected at approximately 100 m apart. Within each site, two plots were sampled, each approximately 10 m apart. Although the sampling program had been designed for four replicates within each plot, the patchy distribution of bottom sediments in the Windmill Islands restricted this to two replicate samples per plot. Samples were collected using an Eckman grab sampler, deployed from a boat. All samples were collected from 8 m water depth in an attempt to reduce any variations which may have occurred to differences depth related differences in light availability or grainsize. Samples were collected within a three day period, in early February, 2000 to reduce the potential influence of sea-ice.



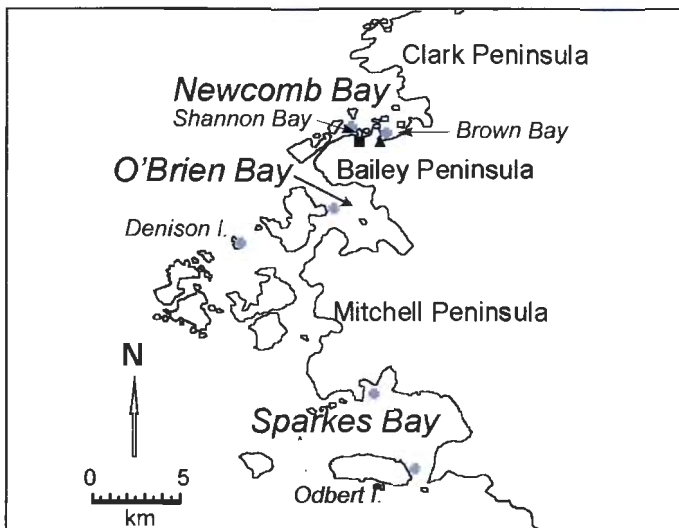


Figure 4.1 Position of sampling locations (★) around Casey Station in the Windmill Islands.

## Sampling locations

### *Brown Bay*

Brown Bay is a small embayment in the southern region of Newcomb Bay, immediately adjacent to a dis-used tip site. During summer, a melt stream runs down Thala Valley, through this tip site and into Brown Bay, transporting contaminants into the bay. Concentrations of heavy metals in marine sediments from Brown Bay are 10-100 times higher than from equivalent control sediments (Scouller et al., 2000). High concentrations of petroleum hydrocarbons have been recorded in sediments from this bay however none have been detected in sediments from control locations (Snape et al., 2001).

The rocky sides of this bay grade to a sediment covered bottom. Close to the tip site, patches of sediment occur between boulders, discarded tip material and areas of bare rock. Further away from the tip, areas of fine sediments are more extensive and relatively homogenous (Stark, 2001), but are still occasionally interrupted by large

boulders. The maximum depth of 20 m was recorded where Brown Bay enters Newcomb Bay.

Brown Bay is typically ice free for 1-2 months a year, generally between January and February. Due to its orientation, the sea-ice in Brown Bay is rarely blown out of this bay during the winter period.

### *Shannon Bay*

Shannon Bay is a small embayment within the southwestern corner of Newcomb Bay, approximately 800 m west of Brown Bay. Shannon Bay is bordered by 2-15 m ice cliffs, with the sewage outfall situated 30 m landward of the eastern cliff. The input of treated wastewater from the present Casey Station has resulted in elevated levels of ammonia, total phosphorous and bacteria within Shannon Bay (Morris et al., 2000; in prep). Preliminary sampling of Shannon Bay also indicated elevated concentrations of heavy metals (Scouller et al., 2000).

The subtidal sides of this bay consist of steeply sloping rock and boulder fields below which is a relatively homogenous muddy sand (Stark, 2000). A maximum depth of 32 m was recorded at the mouth of this bay. This bay is generally ice free for a longer period than Brown Bay, with open water occurring between December and March.

### *O'Brien Bay*

O'Brien Bay is a large bay located on the southern side of Bailey Peninsula and has a maximum depth of 80 m. Ice-cliffs 2-30 m high surround this bay, whilst the subtidal slopes vary between steep boulder fields and inclined rocky banks (Stark, 2000). Previous sampling has shown that the sediments of this bay are not contaminated with either heavy metals or hydrocarbons (Snape et al., 2001). Due to the distribution of sediments within this bay, samples for this study were collected from the western end of the bay, near Beall Island.

### *Denison Island.*

Denison Island is located several kilometers southwest from the mouth of O'Brien Bay and is approximately 500 meters southwest from the westernmost tip of Beall Island. Denison Island is small and flat, with a maximum elevation of approximately 10 m. The island consists of bedrock which, during the 2000 summer season, was covered with a layer of snow and ice several meters thick. The sides of this island typically drop steeply into the ocean. Another two small rocky islands are located just off the northern end of Denison Island. The region between Denison Island and the first of these islands is relatively shallow ( $>20$  m), and some sediments have accumulated here. These sediments are thinly dispersed and patchily distributed, occurring as small pockets between beds of macroalgae. The small size of this region meant that only one sampling site could be established within this location.

Denison Island is more exposed than the other study locations. This results in the waters surrounding it being temporarily ice-free on occasions during winter, but conversely, this area is subject to more frequent accumulations of windblown "berg bits" during the summer period.

### *Sparkes Bay*

Sparkes Bay is a large bay situated several kilometers south of Casey Station. This bay has a variety of environments; ice cliffs dropping vertically into deep water, steep rocky shorelines, and shallower, more gently sloping areas. A small embayment on the northern side of Sparkes Bay was used as the sampling location. This embayment has a very similar bathymetry to that of Brown Bay with the rocky sides sloping down to a muddy bottom, the depth of which ranges between 3 and 20 m (Stark et al., in prep). Naturally high levels of some heavy metals, including cadmium, have been recorded for Sparkes Bay (Stark et al., in prep).

### *Odbert Island*

Odbert Island is a relatively large island located at the mouth of Sparkes Bay. Odbert Island is one of the highest in the region, and the sides consist almost entirely of cliffs which terminate abruptly into the sea. An exception to this is a small area at the eastern end of the island where a small valley cuts down between the hills into a small embayment. This valley is home to several penguin colonies. The valley contours are reflected in the marine topography, which deepens towards the centre of the embayment. The bottom of this embayment consists predominantly of bedrock and boulders, however some areas of sediments do occur, typically within more central areas. The sediments are poorly sorted, however, there is a relatively large proportion of fine material that may originate from the penguin colonies. The two sampling sites were separated by approximately 80 m.

The eastern end of Odbert Island is relatively sheltered. Sea-ice breaks out of this area in late-December, and reforms at the end of February or early March.

### **Diatom preparation and identification**

Organic material was removed from the sediments by digestion in 10% H<sub>2</sub>O<sub>2</sub> for 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). This process was repeated three times. After the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Species identification was based on the taxonomy described in Appendix 1. A minimum of 400 valves was

counted for each sample. The relative abundances of the predominantly benthic taxa were then calculated and used in the statistical analyses.

### **Statistical methods**

Multivariate analyses of community composition were undertaken using non-metric multidimensional scaling (nMDS) and one-way analysis of similarity (ANOSIM) procedures using the PRIMER software package (Plymouth Marine Laboratories 1994). No data transformation was used. Similarity matrixes were calculated using the Bray-Curtis similarity measure. Overall variability was determined using Relative Dispersion values (Clarke and Warwick, 1994).

Similarity percentages analyses (SIMPER) were used to determine which species were responsible for the compositional differences observed between diatom communities. Clarke and Warwick (1994) state that species which have a SIMPER ratio greater than 1.3 are likely to be useful for discriminating between groups. When this was applied to our data, all but 3 species appeared likely to be useful for discriminating between at least 2 of the locations. In order to determine which species were most useful the following method was used to rank species. Only species which had a SIMPER ratio above 1.3 in at least one comparison were considered. For each species, comparisons in which the ratio did not exceed 1.3 were excluded. The sum of the remaining ratios was then determined, and divided by the total number of comparisons possible. The ten species which had the highest values were considered to be the best species for discriminating between groups, and were subsequently used in univariate analyses.

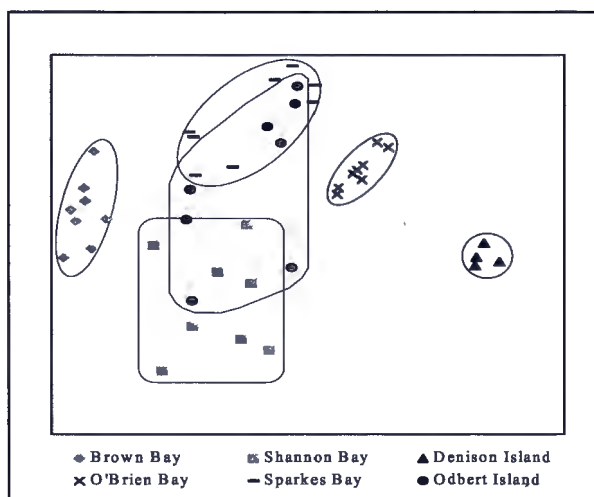
Natural logarithms were used to calculate Shannon-Wiener diversity ( $H'$ ) values, Simpsons' dominance index (SI), Margalef's species richness ( $d$ ) values, and Pielou's evenness ( $J'$ ) values. Collectively these values define structural parameters of the diatom communities. Single factor analyses of variance (ANOVA) were employed to determine if there were significant differences between samples, both for structural parameters, and the selected species. Prior to performing ANOVAs,

Cochran's C test was used to check the assumption of homogeneity of variances. Any data transformations that were necessary to fulfil this assumption are noted in the results. Where ANOVAs indicated significant differences between samples SNK tests were used for multiple comparisons ( $\alpha = 0.05$ ) using GMAV.

## Results

### Differences between locations

Multivariate analysis indicated that the greatest degree of variability was observed between locations. The nMDS ordination (Fig. 4.2) shows the separation of samples into location groups.



**Figure 4.2** nMDS ordination of diatom communities from the Windmill Islands showing separation into location groups. Potentially impacted locations are shown in grey; reference locations are shown in black.

The nMDS ordination shows that the diatom communities from Denison Island and O'Brien Bay each form a tightly clustered group. The diatom communities from samples collected in Brown Bay also form a distinct group. Some overlap between diatom communities from Odbert Island, Sparkes Bay and Shannon Bay is apparent,

resulting primarily from the greater compositional variability of diatom communities from Shannon Bay and Odbert Island. Analysis of multivariate dispersion (MVDISP) supports these observations with Denison Island and O'Brien Bay having low relative dispersion values whilst both Odbert Island and Shannon Bay had very high relative dispersion values (Table 4.1). The values for Brown Bay and Shannon Bay indicate a moderate degree of dispersion.

ANOSIM results show significant differences in community composition occurred between all locations (Table 4.2). Although a clear distinction between control and impacted sites is not apparent on the nMDS ordination, ANOSIM results indicate these groups are significantly different ( $R = 0.531$ ,  $p < 0.001$ ). The moderate  $R$  value indicates there is some similarity between these groups, probably due to the overlap of diatom communities from Shannon Bay and Odbert Island.

	Location	Site 1	Site 2	Site 1		Site 2	
	Overall	Overall	Overall	Plot 1	Plot 2	Plot 1	Plot 2
<i>Brown Bay</i>	0.91	1.02	1.38	1.30	1.13	1.48	1.57
<i>Shannon Bay</i>	1.40	1.52	1.66	1.39	1.65	1.74	1.91
Denison I.	0.06	0.06	N/A	0.26	0.09	N/A	N/A
O'Brien Bay	0.43	0.20	0.42	0.35	0.52	0.61	0.17
Sparkes Bay	1.09	0.51	0.82	0.96	0.70	1.04	0.78
Odbert I.	1.37	1.67	0.79	1.83	1.22	0.87	0.43

**Table 4.1** Relative dispersion values of diatom communities from each sampling location within the Windmill Islands. Potentially impacted locations are shown in *italics*.

Diatom communities from Denison Island had quite different compositions compared to the diatom communities from all other locations, as determined by ANOSIM. The maximum difference possible ( $R = 1.00$ ,  $p < 0.0001$ ) was recorded between the diatom communities from Denison Island and the diatom communities from each of Sparkes Bay, Brown Bay and Shannon Bay. ANOSIM results (Table 4.2) indicate

that the diatom communities from Denison Island were compositionally most similar to the diatom communities from O'Brien Bay.

ANOSIM results (Table 4.2) indicate that the two locations which had diatom communities with the most similar compositions were Sparkes Bay and Odbert Island, with a global  $R$  value of 0.400 ( $p = 0.006$ ). Shannon Bay and Odbert Island also had similar diatom communities, evidenced by a global  $R$  value of 0.456 ( $p = 0.004$ ). The composition of diatom communities from Brown Bay and Shannon Bay, geographically separated by only a few hundred meters, were significantly different ( $R = 0.819$ ,  $p < 0.001$ ).

Location 1	Location 2	$R$ Value	$p$ Value	% Dissimilarity
<i>Brown Bay</i>	<i>Shannon Bay</i>	0.819	< 0.000	34.27
<i>Brown Bay</i>	Denison I.	1.000	0.002	70.02
<i>Brown Bay</i>	O'Brien Bay	1.000	< 0.000	52.08
<i>Brown Bay</i>	Sparkes Bay	0.945	< 0.000	37.19
<i>Brown Bay</i>	Odbert I.	0.891	< 0.000	38.53
<i>Shannon Bay</i>	Denison I.	1.000	0.002	50.45
<i>Shannon Bay</i>	O'Brien Bay	0.845	< 0.000	38.84
<i>Shannon Bay</i>	Sparkes Bay	0.834	< 0.000	39.77
<i>Shannon Bay</i>	Odbert I.	0.456	0.005	32.74
Denison I.	O'Brien Bay	0.591	0.006	36.92
Denison I.	Sparkes Bay	1.000	0.002	49.50
Denison I.	Odbert I.	0.980	0.002	46.62
O'Brien Bay	Sparkes Bay	0.711	< 0.000	30.52
O'Brien Bay	Odbert I.	0.694	< 0.000	33.79
Sparkes Bay	Odbert I.	0.400	0.006	29.62

**Table 4.2** ANOSIM results showing the amount of difference ( $R$  value) and the  $p$ -value for compositional variation between diatom communities from the various study locations in the Windmill Islands. All results shown were significant. The percentage of dissimilarity between the respective diatom communities (based on SIMPER analyses) is also given. Potentially impacted locations are shown in *italics*.



SIMPER analyses were used to determine average dissimilarities between locations (Table 4.2) and the relative contribution of individual taxa to this. These results, like the ANOSIM results, indicate that the diatom communities of Sparkes Bay and Odbert Island had the most similar compositions, with an average dissimilarity of 29.6%. Unlike the ANOSIM results, the SIMPER analyses show the composition of diatom communities from O'Brien Bay and Sparkes Bay as being the next most similar. The greatest average dissimilarity in diatom community composition (70.0%) was observed between Brown Bay and Denison Island (Table 4.2). Overall, the average dissimilarity between all sites was 41.4%.

SIMPER ratios indicated that *Cocconeis* sp. a and *Navicula* aff. *glaciei* contributed the most to the observed dissimilarity between locations. *Diploneis splendida*, *Navicula perminuta*, *Navicula* sp. a, and *Navicula* sp. c also made relatively large contributions to the observed dissimilarity, as did *Planothidium* spp., *Ctenophora pulchella*, *Staurosira construens* var *venter* and *Staurosira construens* var *pumila*. ANOVA results also demonstrate that all of these species make significant contributions to compositional differences observed between locations (Table 4.3).

The SNK results show that some species contributed to differences observed between one location and all others, whilst other species account for differences between several locations. For example, *Navicula* sp. c had significantly higher abundances in Brown Bay compared to all other locations. Similarly, *Navicula perminuta* occurred at significantly higher abundances at O'Brien Bay relative to all the other locations. In contrast, different abundances were recorded between all four locations for *Navicula* sp.a, with the highest relative abundance occurring at Odbert Island, and Sparkes Bay having the next highest abundance. Both of these locations had a significantly greater abundance of *Navicula* sp. a than Shannon Bay, Brown Bay or O'Brien Bay, which in turn had significantly greater abundances of this species than was observed in the diatom communities from Denison Island.

Species Name	ANOVA	Brown v Shannon	Brown v Denison	Brown v O'Brien	Brown v Sparkes	Brown v Odbert	Shannon v Denison	Shannon v O'Brien
<i>Planothidium</i> spp.	***	*	**	*	*	**	**	-
<i>Cocconeis</i> sp. a	**	**	**	**	-	*	**	-
<i>Ctenophora pulchella</i>	*	-	*	-	-	-	-	-
<i>Diploneis splendida</i>	***	-	-	**	**	-	-	**
<i>Staurosira construens</i> var. <i>punila</i>	*	-	-	-	-	-	-	-
<i>Staurosira construens</i> var. <i>venter</i>	*	-	*	-	-	-	*	*
<i>Navicula</i> sp.b	**	**	**	**	**	**	-	-
<i>Navicula</i> aff. <i>glaciei</i>	*	-	*		-	-	*	-
<i>Navicula perminuta</i>	*	-		*	-	-	-	*
<i>Navicula</i> sp. a	***	-	**	-	-	*	**	-
Diversity (H')	-	-	-	-	-	-	-	-
Dominance	**	-	**	-	-	-	**	-
Evenness	***	-	**	*	-	-	**	-
Richness	***	-	**	-	-	-	**	*

**Table 4.3** Summary of ANOVA and SNK analyses for comparisons of diatom communities between locations in the Windmill Islands, using indicator species and community structure. Brown Bay and Shannon Bay are the potentially impacted sites.

★ indicates a  $p$ -value <0.05; ★★ indicates a  $p$ -value <0.01; ★★★ indicates a  $p$ -value <0.001

Diversity, evenness, richness and dominance values were all used to describe the numerical structure of the diatom communities. ANOVA results (Table 4.3) indicate that significant differences occurred between locations for evenness, richness and dominance values ( $p = 0.005$ ). Diversity values were not significantly differently between locations ( $p = 0.05$ ). SNK tests revealed that the diatom communities collected from Denison Island had higher dominance values, with lower evenness and richness values than each of the other sites (Table 4.3). Additionally the evenness values recorded for diatom communities collected from Brown Bay were significantly higher than those of communities from O'Brien Bay. Further differences in numerical structure were that the diatom communities collected from O'Brien Bay and Sparkes Bay each had higher richness values than the diatom communities from both Shannon Bay and Odbert Island.

### Differences between sites within an individual location

The nMDS ordinations (Fig. 4.3) indicate that significant compositional variation occurred between sites within several locations. ANOSIM results (Table 4.4) indicate significant differences occurred in the diatom communities between sites in O'Brien Bay, Odbert Island and Sparkes Bay. No significant compositional differences were observed between sites at either of the potentially impacted locations.

Location	<i>R</i> value	<i>p</i> value	% Dissimilarity		
			Between Sites	Within Site 1	Within Site 2
<i>Brown Bay</i>	0.187	0.200	18.0	15.7	19.8
<i>Shannon Bay</i>	0.458	0.057	27.6	22.0	23.4
Denison Island	-	-	-	5.1	-
O'Brien Bay	<b>0.510</b>	<b>0.029</b>	12.5	6.8	11.6
Sparkes Bay	<b>1.000</b>	<b>0.029</b>	26.5	9.6	14.3
Odbert Island	<b>0.813</b>	<b>0.029</b>	29.8	26.0	14.9

**Table 4.4** ANOSIM results showing the extent (*R* value) and significance of (*p* value) compositional differences between diatom communities from two different sites within each location in the Windmill Islands. Significant results are shown in bold. The dissimilarity percentages between the respective diatom communities (based on SIMPER analyses) are given for both the two sites within the locations, as well as the two plots within each site. Potentially impacted locations shown in *italics*.

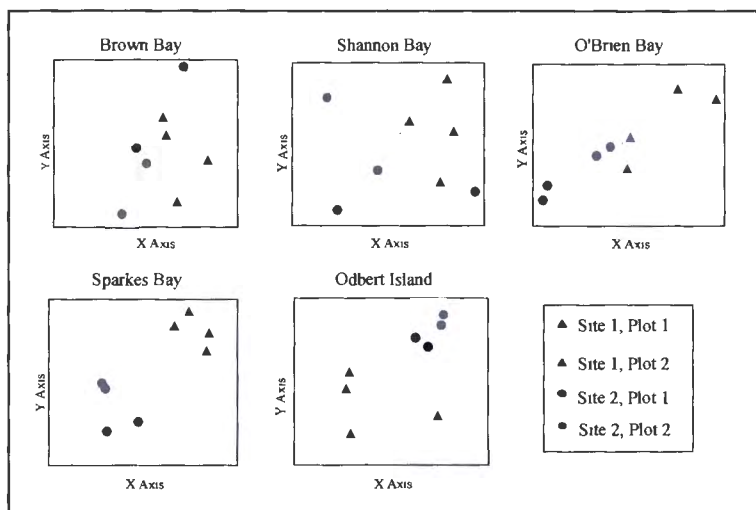


Figure 4.3 nMDS ordination showing variability in diatom community composition between sites within the one location in the Windmill Islands. Significant differences between sites are indicated in red. Brown Bay and Shannon Bay are the potentially impacted locations.

Average dissimilarities between the two sites in each location were determined using SIMPER analyses. The greatest dissimilarity in diatom community composition between sites occurred at Odbert Island (29.8%), closely followed by Shannon Bay (27.6%). O'Brien Bay had the least amount of dissimilarity in diatom community composition between sites (12.5%). As only one site was sampled at Denison Island, this location could not be included in the above comparisons. The average dissimilarity observed between sites within one location was 22.9%.

SIMPER ratios revealed that *Navicula* aff. *glaciei*, *Staurosira construens* var. *venter* and *Pseudostaurosira* sp. a would be good indicator species for discriminating between sites. SIMPER ratios also indicated *Ctenophora pulchella*, *Cocconeis costata/fasciolata*, and *Stauroneis wislouchii* would be good discriminating species. ANOVA results (Table 4.5) confirmed that *Pseudostaurosira* sp. a and *Navicula* aff. *glaciei* had significantly different abundances between sites within one location. In contrast, no significant differences were found between sites of the one location for

the relative abundances of *Ctenophora pulchella*, or *Stauroneis wislouchii*. ANOVA results also revealed that significant differences in the relative abundances of *Cocconeis costata/fasciolata* and *Navicula perminuta* occurred between sites (Table 4.5).

Species Name	ANOVA	Brown Bay	Shannon Bay	O'Brien Bay	Sparkes Bay	Odbert Island
<i>Cocconeis costata/fasciolata</i>	★			★		
<i>Ctenophora pulchella</i>						
<i>Staurosira construens</i> var. <i>venter</i>	★★★	★	★★		★★	★★
<i>Navicula</i> aff. <i>glaciei</i>	★★★				★★	★★
<i>Navicula perminuta</i>	★			★		
<i>Pseudostaurosira</i> sp. a	★		★			★
<i>Stauroneis wislouchii</i>						
Diversity	★★				★★	
Dominance	★★★				★★	
Evenness	★★		★★		★★	
Richness						

**Table 4.5** *p*-values from ANOVA and SNK analyses, using indicator species and structural parameters, for comparison between sites within sampling locations from the Windmill Islands. Potentially impacted locations are shown in grey. ★ indicates a *p*-value <0.05; ★★ indicates a *p*-value <0.01; ★★★ indicates a *p*-value <0.001.

SNK tests (Table 4.5) indicated that *Staurosira construens* var. *venter* occurred at significantly different abundances between sites within each of Brown Bay ( $p = 0.05$ ), Shannon Bay ( $p = 0.01$ ), Sparkes Bay ( $p = 0.01$ ) and Odbert Island ( $p = 0.01$ ). Significant differences between sites within Sparkes Bay and Odbert Island were also apparent in the relative abundances of *Navicula* aff. *glaciei*. SNK tests further indicated that the relative abundances of *Navicula perminuta* and *Cocconeis costata/fasciolata* were significantly different only between the two sites from O'Brien Bay. The relative abundances of *Pseudostaurosira* sp. a varied significantly between sites within each of Shannon Bay and Odbert Island.

Despite having a high overall variability, the diatom communities from Shannon Bay had the most similar relative dispersion values between sites from the one location

(Table 4.1). Although based on a small number of samples, this may indicate that variability within Shannon Bay is uniformly distributed. In contrast, the diatom communities from the two sites within O'Brien Bay had the least similar dispersion values observed within one location (Table 4.1).

ANOVA results indicated that significant differences in diversity, dominance and evenness values were observed between diatom communities from sites within the one location (Table 4.5). SNK tests revealed that the diatom communities from the two sites within Sparkes Bay differed significantly in each of the above parameters. In addition, diatom communities from Shannon Bay showed significant differences in evenness values between the two sites (Table 4.5).

#### **Differences between plots within a site.**

The nMDS ordinations (Figure 4.3) indicate that there were some compositional differences between plots within one site. The reduced number of replicates within plots increased the significance levels ( $p = 0.33$ ) such that no significant ANOSIM results could be observed between plots. SIMPER analysis was therefore used to determine the average dissimilarity in diatom community composition between plots within each site. Denison Island had the lowest dissimilarity observed in the diatom community composition between plots (5.1%), closely followed by Site 1 in O'Brien Bay (6.8%). The highest dissimilarity values were observed between diatom communities from Site 1 at Odbert Island (26.0%) and Site 2 in Shannon Bay (23.4%).

SIMPER ratios indicated that *Staurosira* cf. *construens* var. *pumila*, *Navicula perminuta*, *Cocconeis costata/fasciolata* and *Ctenophora pulchella* contributed significantly to dissimilarities between plots within the one site. According to this method, *Trachyneis aspera*, *Nitzschia dubia* var. *australis* and *Pseudostaurosira* sp. would also be good indicator species for discrimination between plots. The latter three species all had heterogeneous variances regardless of the type of data transformation applied; thus a lower significance level of  $p = 0.01$  was used for

ANOVA analyses. Under these conditions, neither *Pseudostaurosira* sp. a nor *Trachyneis aspera* varied significantly between plots within the one site. Although *Staurosira construens* var. *pumila* had heterogenous variations in the relative abundances, a  $\sqrt{(X+1)}$  transformation removed the heterogeneity. ANOVA results (Table 4.6) then indicated that this species occurred at significantly different abundances between plots within the one site. *Nitzschia dubia* var. *australis*, *Navicula perminuta* and *Ctenophora pulchella* also varied significantly in abundance between plots within the one site.

SNK tests (Table 4.6) indicated that *Staurosira construens* var. *pumila* occurred at significantly different abundances between plots in a site from each of Sparkes Bay and Odbert Island ( $p=0.01$ ). Significant differences between plots within sites from both O'Brien Bay and Odbert Island were also apparent in the relative abundances of *Navicula perminuta*. SNK tests further indicated that the relative abundances of *Ctenophora pulchella* within the diatom communities showed significant interplot variation in sites from Sparkes Bay ( $p=0.001$ ) and Odbert Island ( $p=0.001$ ).

The multivariate dispersion of plots within each site was also quite variable. The greatest difference between plots within one site was observed in Sparkes Bay, Site 2 where one plot had a relative dispersion value of 1.22 whilst the other had a value of 1.83. Typically, both plots in a site had reasonably similar relative dispersion values (Table 4.1).

Of the structural parameters used, only diversity and dominance showed significant variation between plots within the one site (Table 4.6). Diversity varied significantly between plots in one site from each of Brown Bay and Odbert Island. Dominance values varied between plots in one site from each of Odbert Island and Shannon Bay. No other differences in structural parameters were observed between plots within the one site.

	Anova	Brown Bay		Shannon Bay		Denison Island	O'Brien Bay		Sparkes Bay		Odbert Island	
		Site 1	Site 2	Site 1	Site 2	Site 1	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
<i>Ctenophora pulchella</i>	***	-	*	*	-	-	-	-	-	**	**	-
<i>Fragilaria</i> cf. <i>construens</i> var. <i>pumila</i>	**	-	**	-	-	-	-	-	-	**	**	-
<i>Nitzschia</i> sp. b	**	**	**	-	-	-	**	**	-	-	-	-
<i>Navicula perminuta</i>	***	-	-	-	-	-	-	**	-	-	-	**
<i>Pseudostaurosira</i> <i>brevistriata</i>	-	-	-	-	-	-	-	-	-	-	-	-
<i>Trachyneis aspera</i>	-	-	-	-	-	-	-	-	-	-	-	-
Diversity (H')	*	-	**	-	-	-	-	-	-	-	**	-
Dominance	***	-	-	-	**	-	-	-	-	-	**	-
Evenness	-	-	-	-	-	-	-	-	-	-	-	-
Richness	-	-	-	-	-	-	-	-	-	-	-	-

**Table 4.6** ANOVA and SNK results showing significant results for comparisons of species abundances and structural parameters between diatom communities from different plots (separated by several meters) in the one site for various locations within the Windmill Islands. Brown Bay and Shannon Bay are the potentially impacted sites. ★ indicates a  $p$ -value <0.05; ★★ indicates a  $p$ -value <0.01; ★★★ indicates a  $p$ -value <0.001.



## Discussion

Significant variation in benthic diatom communities was observed at all spatial scales; between locations (1000's of meters), between sites within the one location (100's of meters), and between plots within one site (10's of meters). This variability was expressed by differences in both the composition and numerical structure of the diatom communities. The differences observed between diatom communities at all sampling scales were apparent in both multivariate and univariate analyses.

Spatial variation decreased with the scale examined. The largest scale examined in this study was locations (1000's m), and an average dissimilarity of 41.4% was found. The mid-scale of sites (100 m) had roughly half this variability with an average of 22.9%. Plots, the finest scale, exhibited even less variability with an average of only 15.5%. In addition, the number of significant differences between diatom communities decreased with decreasing scale. The diatom communities had significantly different compositions between all locations, but only diatom communities from control sites varied significantly between sites. Furthermore, significant differences were only detected in 6 of the 11 plot comparisons, the finest scale used. Our results agree with the findings of Levin (1992), who states that the scale of observations strongly influences the variability observed. Cattaneo et al. (1994) state that small scale spatial variability (10 m) is common, usually large, and unpredictable. Our results did not conclusively support this. SIMPER results showed small (5%) to moderate (26%) variability at this scale, however univariate analysis indicated that the variability was only significant between approximately 50% of the samples.

Periphyton is naturally a heterogenous community (Cattaneo et al., 1994) and the species composition can be influenced by a range of factors including depth (Round, 1971), light availability and grain-size (Whitehead and McMinn, 1997). The sampling programme was designed to reduce variability due to the first two factors by collecting all samples from the same depth, and within a short time frame. The influence of sea-ice and it's effect on light availability was reduced by sampling in mid-summer (no sea-ice was present), however differences in community structure could have resulted from different times of sea-ice breakout earlier in the season.

Grainsize could be a significant contributor to the variation observed within this study. Unfortunately no quantitative information on grain-size was collected for this study. At the time of collection, it was noted that the samples from Denison Island consisted predominantly of coarse sands with very little mud; the opposite was true for samples collected from Brown Bay. The sediment samples collected from Shannon Bay, Sparkes Bay, O'Brien Bay and Odbert Island appeared to be poorly sorted sands and mud. On the basis of these observations, further investigation into the relationship between grain-size and diatom communities from these locations is warranted (see Chapter 5).

Other differences in the physical environment could also contribute to the pattern of variability observed. Denison Island is the furthest from shore, has the highest energy environment, and is covered by sea-ice for the least amount of time. In contrast, Brown Bay is very sheltered, and sea-ice is present within this bay for a longer duration than at any other of the locations studied. The large differences observed in both the species composition and numerical structure of Denison Island further indicates that physical characteristics of the environment may be influencing the diatom communities. Further consideration of these influences could provide valuable base-line information on spatial variability within the region. Comparisons of the diatom communities from off-shore islands, inshore islands, and coastal bays may provide further insight into the patterns of variability observed in this study.

No significant variability was observed between sites at either of the potentially impacted locations, while all control locations exhibited significant variation in diatom community composition between sites. Although the reduced variation observed at the two potentially impacted locations could be the direct result of chemical contamination, other factors cannot be ruled out. The homogeneity of sediments within each location is one such factor. Both Brown Bay and Shannon Bay have large areas of relatively homogenous sediments (Stark, 2001) whereas the sediments within the control locations had a more patchy distribution. Large areas of relatively homogenous sediments are rare around Casey Station, and the homogenous nature of sediments within both Brown and Shannon Bay may actually represent a

physical impact resulting from increased mobilisation of soils due to station activities. Further investigation would be required to confirm this, and to clarify the effects this may be having on diatom communities.

The diatom communities of control locations were compositionally most similar to locations within the same bay, or in the case of Denison Island, to the closest bay. Spatial variability may therefore be influenced at a higher level than what was examined here - namely variability within the larger-order bays. This finding was not maintained in the contaminated locations however. Although the diatom communities of Brown Bay were compositionally most similar to Shannon Bay, the diatom communities of Shannon Bay were more similar to those of Odbert Island. This could reflect similar physical environments, as discussed previously. Alternatively, the chemical environment could be influencing the variability between these bays. Shannon Bay receives the station effluent as a result of which both nitrate and phosphate levels have been elevated (Morris et al., in prep.). These levels are similar to those measured in a bay adjacent to a penguin colony at Shirley Island. It is likely that the penguin colonies at Odbert Island would have a similar effect. Further investigation to determine whether nutrient levels are influencing the composition of diatom communities within this region would be warranted.

The sampling technique used in this survey may also have influenced the variability observed. Grab sampling is not a precise technique. The majority of times that the sampler was deployed, a successful sample was not retrieved. This was due to either the grab sampler landing on bare rock, or the jaws closing around a small pebble, with any sediment then being washed out on retrieval. A bias towards sediments with a lower proportion of coarse material would therefore be expected, and could reduce the variability observed between samples. Furthermore, repeated sampling attempts may have disturbed the sediment, influencing the observed variability. Recommendations for future work would therefore include direct sampling by scuba divers. Direct sampling would also enable sampling to be undertaken on smaller scales and with greater precision.

### **Conclusion**

Significant spatial variation was observed in the benthic marine diatom communities around Casey station. This study established that this variability occurs at several scales, including between locations (1000's of meters) and between plots (10's of meters). The cause of this variation was not determined within this study.

Spatial variability between sites within contaminated locations was significantly lower than that observed at control locations, however the underlying cause was not established. Compositional similarities observed between the diatom communities of Shannon Bay and Odbert Island suggest that further investigation into the effects of increased nutrients on benthic diatom communities may be warranted.

### ***The influence of natural environmental variables on benthic diatom communities in the Windmill Islands***

#### **Abstract**

Redundancy analysis indicated that changes in sediment grain size, light availability and water depth account for 30% of the variation observed in diatom communities from four locations within the Windmill Islands. The amount of mud ( $<63 \mu\text{m}$ ) present within the sediments explained 18% of the variation observed in samples from all four locations. At two locations, the amount of mud present explained 25% or more of the total variation observed. Differences between locations explained 28% of the variation observed in diatom abundances, however, the majority of this was due to changes in grain size, light availability and depth between the locations. It is unclear what other parameters contribute to observed differences between locations.

#### **Introduction**

Benthic diatom communities can be influenced by a variety of environmental factors. These include light (Admiraal and Peletier, 1980), depth (Whitehead and McMinn, 1997), grain size (Round, 1981), nutrients (Hillebrand et al., 2000) and salinity (Roberts and McMinn, 1999). The offshore Antarctic marine environment is relatively stable. Salinity is relatively constant at approximately  $34 \text{ m S cm}^{-1}$  (Tilzer et al., 1985) and temperatures, although low, do not inhibit microalgal growth (Holm-Hansen et al., 1977). In coastal regions nutrients are generally present in sufficient quantities so as not to limit growth (Heywood and Whitaker, 1984; Priddle et al., 1986), although nutrient depletion has been observed synchronously with large algal blooms (Clarke et al., 1988; McMinn et al., 1995; McMinn et al., 2000). Light availability, water depth and grain-size are therefore likely to be the main influences on benthic diatom communities within the coastal Antarctic marine environment. Few previous studies have examined the effects of all three variables.

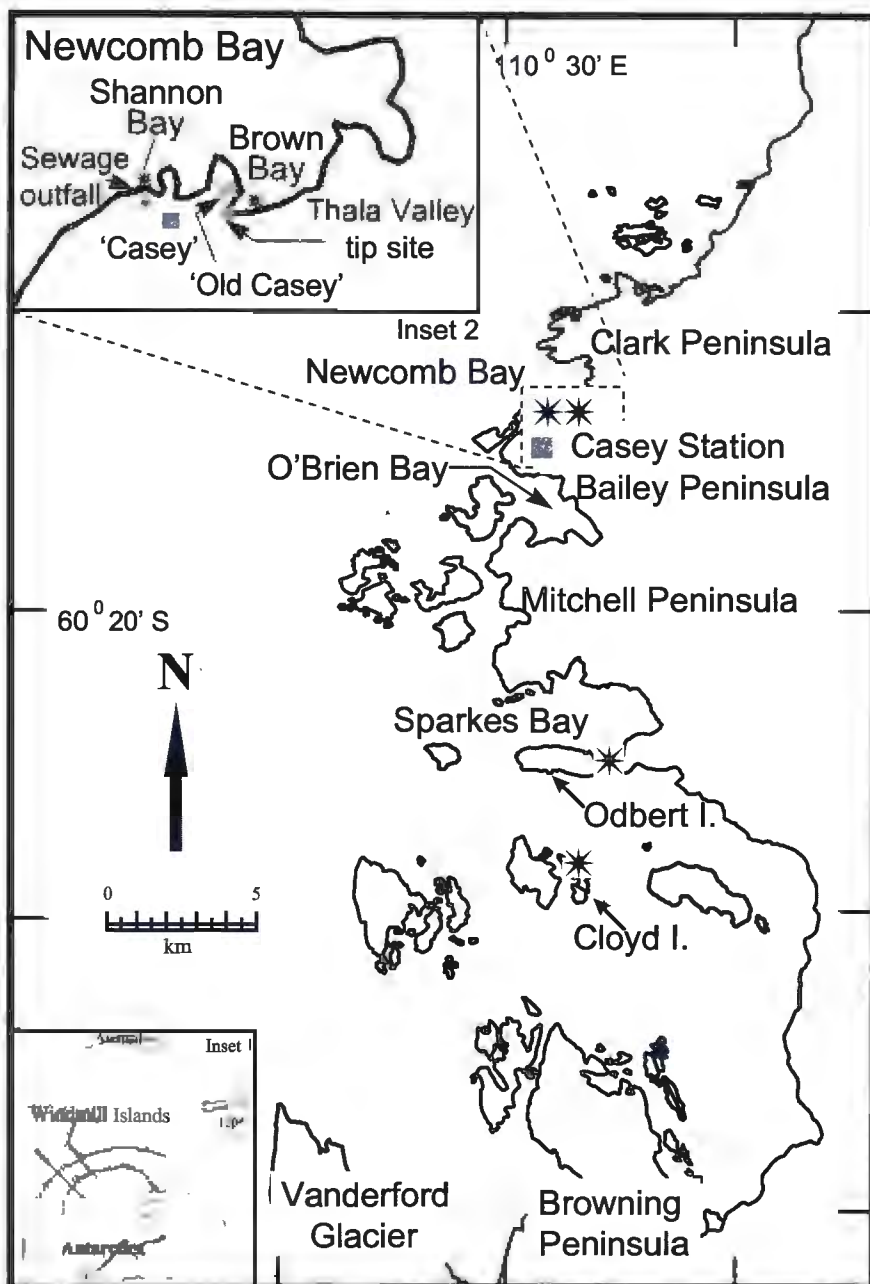
The composition and structure of benthic diatom communities in the Windmill Islands has previously been demonstrated to be strongly related to the sampling location (Chapter 4). Although differences in environmental variables, such as grain-size, were also noted between sampling locations, no quantitative assessment of this has previously been undertaken. In order to examine the relative influences of location, grain size, light and water depth on diatom abundances within the region, the following questions were addressed:

- Is the composition of diatom communities within the Windmill Islands related to the environmental variables depth, light and grain size? If so, how are the abundances of individual species related to these variables?
- Are environmental variables significant in determining spatial variation within each location. If so, which species are affected by these variables? Are the relationships observed between diatom species and environmental variables consistent between locations?
- Is the previously observed influence of location related to differences in these environmental variables?

## **Methods**

### **Sampling Regime**

Four marine bays in the Windmill Islands were selected as sampling locations (Fig. 5.1). Two of these, Brown Bay and Shannon Bay, are immediately adjacent to the permanently manned Casey Station. Both of these bays have been contaminated with a variety of metals (Stark et al., in press; Scouller et al., 2000) due to station activities. Brown Bay has also been contaminated with petroleum hydrocarbons (Snape et al., 2001). Odbert Island, and Cloyd Island, both located approximately 10 km south of Casey Station, were used as reference locations. A full description of these locations is given below.



**Figure 5.1** Map of the Windmill Islands showing sampling locations (\*) in relation to Casey Station (■). Inset 1 shows the geographical position of the Windmill Islands. Inset 2 shows the proximity of Brown Bay and Shannon Bay to the now defunct Thala Valley tip site (●) and sewage outfall (▲), respectively.

At each of the four sampling locations, samples were collected along three parallel transects. The two reference locations used were selected as they had a fairly broad distribution of sediments, and thus parallel transects could be used. Other reference locations previously used had more restricted distributions of sediments, that prevented the use of parallel transects.

Within each location, samples were taken at different depths along the three transects. It had been anticipated that samples would be collected from 1, 2, 4, 8, and 12 m water depths along each transect, however this was not possible in two of the locations used. The sampling location at Cloyd Island consisted of exposed rock and macroalgal beds at depths above 4m thus shallower samples could not be taken. Samples were therefore collected from 4, 6, 8 and 12 m at this location. In Shannon Bay, the transects were perpendicular to the ice-cliffs above which the sewage outfall is located. The base of these ice-cliffs has been slightly eroded, resulting in a small overhang, subsequently samples from 1 m water depth were not collected. Immediately on collection, the sediment samples were placed in the dark, in an insulated, ice-filled bag. The samples were frozen at -20 °C until their return to Australia and subsequent preparation for grain-size and diatom analyses.

Surface irradiance and benthic irradiance were measured at the time of collection, using Biospherical QSP 200 2  $\pi$  and 4  $\pi$  radiometers. The proportion of surface irradiance that was reaching the benthos was later calculated, and is referred to as % surface irradiance. This enables subsurface light levels to be standardised and allows for differences in surface irradiance at the time of sampling. Precise data on the number of ice-free days experienced in each bay would have been useful but is not available and collecting this data would have required more boat-time than was available. Consequently, this aspect of temporal variability has not been included within this study.



## **Sampling locations**

### *Brown Bay*

Brown Bay is a small embayment in the southern region of Newcomb Bay, immediately adjacent to an abandoned tip site (Inset 2, Fig1). During summer a melt stream runs down Thala Valley, through the tip site and into Brown Bay, transporting contaminants into the bay. Concentrations of heavy metals in marine sediments from Brown Bay are 10-100 times higher than from equivalent control sediments (Scouller et al., 2000). High concentrations of petroleum hydrocarbons have been recorded in sediments from this bay, however none have been detected in sediments from control locations (Snape et al., 2001).

The rocky sides of this bay grade to a sediment covered bottom. Close to the tip site, patches of sediment occur between boulders, discarded tip material and areas of bare rock. Further away from the tip, areas of fine sediments are more extensive and relatively homogenous (Stark, 2001), but are still occasionally interrupted by large boulders. The maximum depth of 20 m was recorded at the eastern end of Brown Bay, where it enters Newcomb Bay. Brown Bay is typically ice free for 1-2 months a year, generally between January and February. Due to its alignment with the predominant wind direction (east-west), Brown Bay rarely has the sea-ice blown out during the winter period.

The sampling transects were aligned roughly parallel with the length of the bay. Transect 1 was situated in the centre of the bay; Transect 2 was located on the southern side of the bay, whilst Transect 3 was located on the northern side. The transects were separated by approximately 30 m.

### *Shannon Bay*

Shannon Bay is a small embayment within the south-western corner of Newcomb Bay, approximately 800 m west of Brown Bay. Shannon Bay is bordered by 2-15 m ice cliffs, with the sewage outfall situated 30 m landward of the eastern cliff (Inset 2, Fig. 5.1). The input of treated waste-water from the present Casey station has resulted in elevated levels of ammonia, total phosphorous and bacteria within

Shannon Bay (Morris et al., 2000; in prep). Preliminary sampling of Shannon Bay also indicated elevated concentrations of heavy metals (Scouller et al., 2000).

The subtidal sides of this bay consist of steeply sloping rock and boulder fields below which is a relatively homogenous muddy sand (Stark, 2000). A maximum depth of 32 m was recorded at the mouth of this bay. This bay is generally ice free for a longer period than Brown Bay, with open water occurring between December and March.

The three sampling transects were perpendicular to, and extended from, the ice-cliffs on the eastern side of the bay. This resulted in the transects being orientated across the width of the bay, not along the length; it was felt that this arrangement would be more likely to reflect any changes in diatom communities which resulted from the sewage outfall. The transects were separated by approximately 30 m.

### *Odbert Island*

Odbert Island is a relatively large island located roughly 10 km south of Casey Station, at the junction of Sparkes Bay and Penney Bay (Fig. 5.1). Odbert Island is one of the highest in the region, and the sides consist almost entirely of cliffs which terminate abruptly into the sea. An exception to this is a small area at the eastern end of the island where a more gradual decline occurs forming a small bowl-shaped valley. This valley is home to several penguin colonies. The valley contours are reflected in the marine topography, which deepens towards the centre of the embayment. This embayment is aligned roughly west to east. The bottom of this embayment is predominantly rocky, however some patches of sediment do occur, typically within the central area of the embayment. The sediments are poorly sorted but with a relatively large proportion of fine material which possibly results from the penguin colonies. The eastern end of Odbert island is relatively sheltered. Sea-ice breaks out of this area in late-December, and reforms at the end of February or early March.

The three sampling transects were aligned roughly west to east. The first sampling transect was located on the southern side of the bay, the second transect roughly central, whilst the third transect was situated towards the northern end of the embayment. The first transect was separated from the second by approximately 30 meters; the third transect was located roughly 20 m north of the second transect.

### *Cloyd Island*

Cloyd Island is located in Penney Bay, approximately 14 km south of Casey Station, and roughly 3 km from the nearest point of the continental coastline (Fig. 5.1). A short sub-surface reef extends westward from the northern end of Cloyd Island, forming a small area in which wave motion is reduced. The shallow (<4 m.) areas of this bay consist of exposed rock or beds of macroalgae. Below 4 m water depth, pockets of sediments occur between patches of algae.

The transects were orientated east to west, extending from the shoreline out into a channel between Cloyd Island and Ford Island. The first transect was located at the southern end of this location, the second transect was roughly central, whilst the third transect was at the northern end, but approximately 10 m inside the rocky reef. These transects were separated by approximately 15 m.

### **Diatom preparation and identification**

Organic material was removed from the sediment by digestion in a 10% hydrogen peroxide solution for 72 hours. As some organic material remained, samples were further digested in a 15% hydrogen peroxide solution for a further 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10%

and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Species identification was based on the taxonomy discussed in Appendix 1. A minimum of 400 individuals was counted for each sample. The relative abundances of the predominantly benthic taxa were then calculated. Only taxa which had a relative abundance of 2% in at least one sample and that also occurred in at least 3 samples, were included in the analysis. Exclusion of rare taxa is on the basis that they may be allocthanous (eg. an exclusively freshwater species *Luticola muticopsis* was recorded in the sediment of Brown Bay, but was probably derived from the meltstream which enters Brown Bay). Species abundances were  $\log(x+1)$  transformed prior to analyses.

### Statistical Analyses

Two statistical methods are commonly used to examine the relationship between communities and environmental variables, namely BIOENV and ordinations. BIOENV essentially determines which environmental variables, or combination thereof, best matches the observed communities. This method does not allow an examination of how the communities change in response to the variations in environmental factors. For this reason, ordination techniques were used within this study.

A preliminary correspondence analysis was performed to determine whether a unimodal or linear model was most appropriate for the data. This revealed that the maximum length of the ordination axes was 1.6 standard deviations, thus a linear response model is most applicable (ter Braak, 1987). A direct gradient ordination was required to examine the relationships between diatom abundances and measured environmental variables, and to determine which variables were directly responsible for the variations observed in the diatom abundances. Redundancy analysis (RDA) was therefore selected as the ordination method.

All of the environmental variables examined had skewed distributions, and were therefore  $\log(x+1)$  transformed prior to analysis. All ordinations were performed using CANOCO version 3.12 (ter Braak, 1988, 1990). Multiple collinearity between environmental variables were examined using variance inflation factors (VIFs). Large VIFs ( $>20$ ) indicate that a variable is highly correlated with other variables, and thus contributes little information to the ordination (ter Braak, 1998). Correlation scores were used to determine which variables were highly correlated ( $>0.90$ ).

Redundancy analysis was performed using the selected variables. Ordination scores were scaled for covariance biplots, as this maximises interpretation of the relationship between species and environmental variables (ter Braak, 1987-92). Intra-set correlations were used to examine the relative contribution of the environmental variables to the separate ordination axis. Eigenvalues indicate the importance of an ordination axis in explaining variation within the species data. The significance of the combined environmental variables, in relation to the diatom species abundance, was determined by performing unrestricted Monte Carlo permutation tests

(99 permutations) on the trace statistic. The significance of the first and second ordination axes were determined in a similar manner, however the first ordination axis was used as a covariable when the significance of the second ordination axis was determined. Forward selection, with unrestricted Monte Carlo permutation tests (99 permutations), was used to determine which variables explained a significant proportion ( $p = 0.05$ ) of the variation in diatom abundances. Graphical representation of the ordination results was undertaken using CANODRAW (Smilauer, 1992).

Location has previously been shown to explain a large proportion of the variance within the diatom community, however, grain size was also observed to differ between location (Chapter 4). In order to assess what proportion of the observed

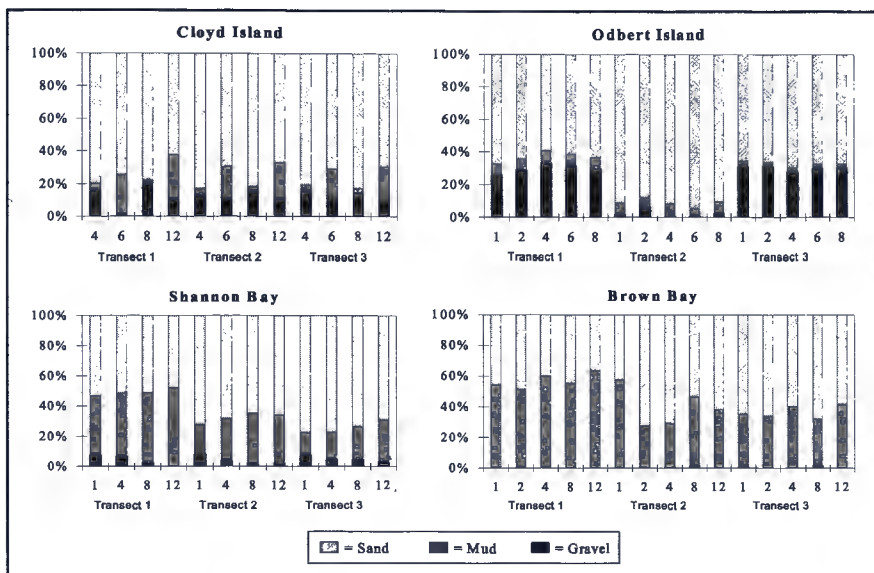
differences in location are due to the measured environmental variables, two separate ordinations needed to be performed. Firstly, an ordination based on the environmental variables, but with a dummy "location" variable added. In order to create the location variable, each of the sampling locations was labelled 1-4. Redundancy analysis was then performed on the resulting set of 6 environmental variables. Secondly, a partial redundancy analysis was performed. The five measured environmental variables were used as covariables and location was used as the active variable. The resulting constrained ordination axis therefore represents the response that is "uniquely" attributable to this variable (ter Braak, 1987-1992). Comparisons of the amount of variation in diatom data that is explained by location in each of these ordinations, enable the contribution of the measured environmental variables to observed differences in location to be assessed.

## **Results**

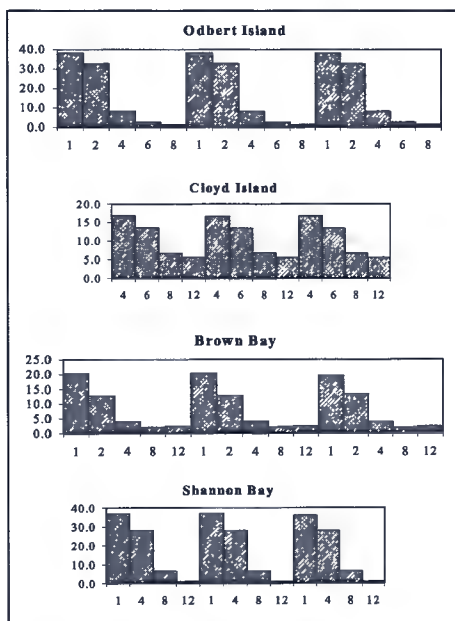
### **Environmental variables**

The values of the measured environmental variables are summarised in Figures 5.2 and 5.3. Differences in grain-size were observed between locations and within locations. Generally, Cloyd Island and Odbert Island had higher proportions of gravel, and lower proportions of mud than either Brown Bay or Shannon Bay. A high degree of variability was observed in the proportion of sand and gravel between transects at Odbert Island (Fig. 5.2).

At each location, depth and the % surface irradiance typically had a very high, negative correlation ( $R > -0.9$ ). Brown Bay was an exception with a lower correlation observed at this site ( $R = -0.80$ ). In Brown Bay, the % surface irradiance available at 12 m location (further from shore) was slightly greater than that observed at 8 m location (Fig. 5.3); this may reflect water turbidity or phytoplankton distribution within the water column. Although water depth and the % surface irradiance were strongly correlated within each location, this relationship varied between locations; when data from all locations was combined these two variables were only weakly correlated.



**Figure 5.2** Grain size percentages from samples collected at four locations in the Windmill Islands, Antarctica.



**Figure 5.3** % of surface irradiance that penetrates through to the benthos at various depths within four locations from the Windmill Islands.

When all locations were included, the highest correlation between environmental variables occurred between depth and % sand ( $R = -0.65$ ). Depth, % sand and % surface irradiance were all correlated with each other (Table 5.1), however these correlations were weak when all locations were examined. A preliminary ordination indicated there was no multicollinearity between environmental variables. All environmental variables had very low VIFs ( $<3$ ) and therefore contributed “unique” information to the ordination.

### Benthic diatom communities of the Windmill Islands

The diatom communities sampled typically consisted of 30-35 benthic species although several of species only occurred within a few samples. The relative abundances of diatom species within each of the samples is shown in Table 5.2. No one species dominated the diatom communities at all locations. The highest relative abundance recorded for an individual species was 44.8% for *Navicula* aff. *glaciei*, in one of the samples from Odbert Island; this species typically had abundances below 15% in both Brown Bay and Shannon Bay. Most commonly, only 2 or 3 species were abundant within each location, with abundances ranging between 10 and 20% for each species. Differences were observed between locations in the identity of the abundant species. For example, *Staurosira construens* var. *pumila* was the most abundant species at Cloyd Island, with relative abundances ranging between 13% and 40%, however this species did not exceed 10 % in either Brown Bay or Shannon Bay. Conversely, the relative abundances of *Planothidium* spp. typically exceeded 10 % at Brown Bay, but did not exceed this amount at either Cloyd Island or Shannon Island.

Depth	1				
Gravel	0.3644	1			
Mud	0.2738	0.2535	1		
Sand	-0.6522	-0.3941	0.4497	1	
Light	-0.5903	-0.2326	-0.4670	-0.6383	1
Depth	Gravel	Mud	Sand	Light	

**Table 5.1** Correlation coefficients between environmental variables for sampling points in four different locations within the Windmill Islands



		Cloyd I.											
		Transect 1				Transect 2				Transect 3			
		4 m	6 m	8 m	12 m	4 m	6 m	8 m	12 m	4 m	6 m	8 m	12 m
<i>Achnanthes brevipes</i>	1	4.0	8.0	17.2	9.2	5.2	5.8	17.7	6.9	4.6	6.9	17.4	8.1
<i>Achnanthes</i> sp. A	8	2.4	3.3	2.5	6.1	4.8	4.3	1.7	3.0	3.6	3.8	2.1	4.5
<i>Amphora libyca</i>	3	1.2	3.5	2.5	2.7	0.4	5.1	0.2	2.1	0.8	4.3	1.4	2.4
<i>Amphora ovalis</i>	4	0.5	2.8	1.0	0.0	0.0	1.8	2.6	0.5	0.2	2.3	1.8	0.2
<i>Amphora</i> sp. A	5	0.0	0.7	0.2	0.2	0.2	0.0	2.1	0.2	0.1	0.4	1.2	0.2
<i>Cocconeis costata</i>	6	0.5	0.2	1.0	0.0	0.7	0.3	0.0	0.7	0.6	0.2	0.5	0.3
<i>Cocconeis fasciolata</i>	7	0.2	0.5	0.7	1.0	0.4	0.8	0.2	0.5	0.3	0.6	0.5	0.7
<i>Ctenophora pulchella</i>	9	1.9	3.5	6.2	1.0	1.1	0.5	3.1	1.4	1.5	2.0	4.6	1.2
<i>Navicula</i> aff. <i>glaciei</i>	15	28.6	21.5	14.4	9.7	23.9	14.1	12.3	13.8	26.2	17.8	13.3	11.8
<i>Navicula directa</i>	14	0.2	0.0	0.5	0.2	0.4	0.0	0.7	0.0	0.3	0.0	0.6	0.1
<i>Navicula perminuta</i>	16	3.6	6.4	2.5	4.9	7.2	8.3	3.3	4.6	5.4	7.4	2.9	4.7
<i>Navicula</i> sp. A	17	9.5	2.4	4.0	2.2	4.3	2.5	5.9	6.0	6.9	2.4	4.9	4.1
<i>Navicula</i> sp. B	12	1.2	2.4	1.5	0.5	0.4	0.3	0.0	1.2	0.8	1.3	0.7	0.8
<i>Navicula</i> sp. C	13	8.1	3.8	6.5	1.2	8.9	2.0	9.4	2.3	8.5	2.9	8.0	1.8
<i>Planothidium</i> spp.	2	4.8	6.6	8.5	9.7	6.5	13.1	7.8	7.8	5.6	9.9	8.1	8.8
<i>Pseudostaurosira brevistriata</i>	18	1.2	4.2	3.0	3.2	0.9	6.6	5.9	3.0	1.0	5.4	4.4	3.1
<i>Stauroneis wislouchii</i>	19	4.3	1.9	1.7	0.5	0.0	1.5	0.7	2.3	2.1	1.7	1.2	1.4
<i>Staurosira construens</i> var. <i>pumila</i>	10	17.4	18.9	13.2	40.6	26.0	19.4	16.7	35.7	21.7	19.2	15.0	38.2
<i>Staurosira construens</i> var. <i>venter</i>	11	1.2	1.7	1.7	1.7	0.4	3.8	1.7	1.8	0.8	2.7	1.7	1.8

Table 5.2 (1) Relative abundances of benthic diatom species in each of the four marine bays sampled from the Windmill Islands, Antarctica.

		Shannon Bay											
		Transect 1				Transect 2				Transect 3			
		2 m	4 m	8 m	12 m	2 m	4 m	8 m	12 m	2 m	4 m	8 m	12 m
<i>Achnanthes brevipes</i>	1	4.1	5.5	2.0	4.7	5.5	9.4	2.3	5.0	4.2	7.4	2.2	4.9
<i>Achnanthes</i> sp. A	8	21.9	22.7	9.2	5.5	18.9	24.7	24.2	16.6	19.0	23.7	16.5	11.0
<i>Amphora libyca</i>	3	0.8	0.5	0.3	0.5	1.0	2.3	0.5	0.8	0.9	1.4	0.4	0.6
<i>Amphora ovalis</i>	4	1.0	0.2	0.3	0.0	0.0	0.5	0.0	0.8	0.5	0.3	0.1	0.4
<i>Amphora</i> sp. A	5	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0
<i>Cocconeis costata</i>	6	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3
<i>Cocconeis fasciolata</i>	7	4.9	3.3	2.8	4.9	1.3	3.2	2.1	3.5	3.2	3.4	2.4	4.2
<i>Ctenophora pulchella</i>	9	2.1	2.4	1.0	1.6	2.4	2.5	0.0	0.8	2.2	2.5	0.5	1.2
<i>Navicula</i> aff. <i>glaciei</i>	15	11.2	9.7	7.9	15.6	17.8	9.2	11.8	8.8	14.5	9.4	9.9	12.2
<i>Navicula directa</i>	14	0.3	0.2	0.3	0.5	0.5	0.9	1.3	0.0	0.4	0.6	0.8	0.3
<i>Navicula perminuta</i>	16	0.0	0.2	0.5	0.3	0.0	0.2	0.8	0.5	0.0	0.2	0.6	0.4
<i>Navicula</i> sp. A	17	5.4	2.4	2.6	3.9	5.0	5.0	2.1	2.8	5.4	3.7	2.3	3.3
<i>Navicula</i> sp. B	12	2.1	0.7	2.3	1.0	1.3	3.4	0.5	1.5	1.5	2.1	1.4	1.3
<i>Navicula</i> sp. C	13	4.4	2.4	4.8	2.9	1.6	2.5	2.6	6.5	3.0	2.4	3.5	4.7
<i>Planothidium</i> spp.	2	14.1	4.0	5.9	13.5	12.3	5.5	6.2	5.0	13.5	4.8	6.0	10.0
<i>Pseudostaurosira brevistriata</i>	18	13.9	21.1	30.4	18.0	12.9	12.3	25.2	24.4	13.5	16.7	27.8	21.2
<i>Stauroneis wislouchii</i>	19	1.5	1.7	0.8	2.1	2.4	2.1	0.0	1.0	2.0	2.0	0.2	1.5
<i>Staurosira construens</i> var. <i>pumila</i>	10	2.3	6.4	2.8	1.0	1.3	2.1	4.4	1.8	1.8	4.2	3.5	1.4
<i>Staurosira construens</i> var. <i>venter</i>	11	9.0	14.5	21.4	16.7	7.6	13.2	12.3	15.8	8.3	13.8	17.0	16.2

Table 5.2 (2) Relative abundances of benthic diatom species in each of the four marine bays sampled from the Windmill Islands, Antarctica.

		Odbert I.														
		Transect 1					Transect 2					Transect 3				
		1 m	2 m	4 m	6 m	8 m	1 m	2 m	4 m	6 m	8 m	1 m	2 m	4 m	6 m	8 m
<i>Achnanthes brevipes</i>	1	18.0	12.8	8.5	7.8	7.0	16.4	11.0	8.0	10.1	4.4	17.2	11.9	8.3	9.0	5.7
<i>Achnanthes</i> sp. a	8	0.0	0.2	0.7	0.5	1.3	3.2	0.2	0.7	1.5	0.8	1.6	0.2	0.7	1.0	1.0
<i>Amphora libyca</i>	3	0.3	0.2	0.2	1.3	1.3	0.0	0.2	1.1	2.0	2.6	0.1	0.2	0.7	1.6	1.9
<i>Amphora ovalis</i>	4	1.0	0.2	0.0	2.0	0.3	0.2	0.2	0.9	1.5	0.8	0.6	0.2	0.5	1.8	0.5
<i>Amphora</i> sp. a	5	0.0	0.2	0.2	0.3	1.5	0.0	0.0	0.7	0.5	1.0	0.0	0.1	0.5	0.4	1.3
<i>Cocconeis costata</i>	6	0.0	0.0	0.0	0.5	0.3	0.0	0.2	0.0	1.0	0.5	0.0	0.1	0.0	0.8	0.4
<i>Cocconeis fasciolata</i>	7	0.0	0.0	0.7	1.0	0.3	0.2	0.0	0.5	1.3	0.3	0.1	0.0	0.6	1.1	0.3
<i>Ctenophora pulchella</i>	9	2.0	0.5	4.6	2.8	5.0	4.1	0.0	11.0	0.5	3.1	3.1	0.2	7.8	1.6	4.1
<i>Navicula</i> aff. <i>glaciei</i>	15	31.3	43.5	20.7	20.4	24.3	30.8	44.9	19.5	27.8	22.4	31.0	44.2	20.1	24.1	23.3
<i>Navicula directa</i>	14	1.0	0.0	1.0	2.3	2.0	0.7	0.0	1.8	2.5	1.6	0.8	0.0	1.4	2.4	1.8
<i>Navicula perminuta</i>	16	0.3	2.9	3.7	1.5	0.8	0.9	0.2	1.1	4.0	0.5	0.6	1.6	2.4	2.8	0.6
<i>Navicula</i> sp. a	17	3.0	6.0	11.5	13.4	7.5	7.8	7.9	6.4	8.3	8.9	5.4	7.0	9.0	10.8	8.2
<i>Navicula</i> sp. b	12	0.5	0.7	1.5	1.0	3.0	0.5	0.0	2.1	3.5	4.9	0.5	0.4	1.8	2.3	4.0
<i>Navicula</i> sp. c	13	6.3	4.3	6.3	6.5	1.5	3.2	7.9	5.5	2.0	3.1	4.7	6.1	5.9	4.3	2.3
<i>Planothidium</i> spp.	2	10.8	8.0	5.9	7.8	12.3	8.2	8.4	6.7	3.5	11.7	9.5	8.2	6.3	5.7	12.0
<i>Pseudostaurosira brevistriata</i>	18	5.8	6.3	3.2	5.5	11.0	2.5	6.0	6.4	6.3	7.6	4.1	6.1	4.8	5.9	9.3
<i>Stauroneis wislouchii</i>	19	4.8	2.7	2.4	0.5	0.8	5.5	3.6	0.5	1.0	0.5	5.1	3.1	1.4	0.8	0.6
<i>Staurosira construens</i> var. <i>pumila</i>	10	2.5	3.9	16.1	14.1	4.3	0.5	3.8	9.9	16.4	7.8	1.5	3.8	13.0	15.3	6.0
<i>Staurosira construens</i> var. <i>venter</i>	11	0.8	0.0	0.5	1.3	2.5	0.2	0.5	2.5	1.3	3.1	0.5	0.2	1.5	1.3	2.8

Table 5.2 (3) Relative abundances of benthic diatom species in each of the four marine bays sampled from the Windmill Islands, Antarctica.

	Brown Bay															
	Transect 1					Transect 2					Transect 3					
	1 m	2 m	4 m	8 m	12 m	1 m	2 m	4 m	8 m	12 m	1 m	2 m	4 m	8 m	12 m	
<i>Achnanthes brevipes</i>	1	14.9	17.9	6.2	6.0	7.6	15.1	17.0	3.1	13.7	7.9	15.0	17.4	4.6	9.9	7.7
<i>Achnanthes</i> sp. a	8	0.0	0.0	0.7	0.3	0.0	0.0	0.0	0.3	0.7	0.3	0.0	0.0	0.5	0.5	0.1
<i>Amphora libyca</i>	3	0.0	1.0	1.6	0.3	0.5	0.0	0.2	1.5	1.0	0.9	0.0	0.6	1.6	0.6	0.7
<i>Amphora ovalis</i>	4	0.0	0.2	0.7	0.3	0.5	0.0	0.0	0.9	2.2	2.3	0.0	0.1	0.8	1.2	1.4
<i>Amphora</i> sp. a	5	0.3	0.7	1.0	0.5	0.8	0.3	0.0	1.5	0.5	3.5	0.3	0.4	1.3	0.5	2.2
<i>Cocconeis costata</i>	6	0.8	1.7	3.9	1.6	0.8	0.3	0.2	2.1	1.7	1.5	0.5	0.9	3.0	1.6	1.1
<i>Cocconeis fasciolata</i>	7	2.1	1.7	3.6	1.6	2.2	1.8	0.5	2.8	2.7	4.4	1.9	1.1	3.2	2.1	3.3
<i>Ctenophora pulchella</i>	9	7.3	6.7	1.6	2.1	7.6	3.3	0.5	1.8	2.0	6.4	5.3	3.6	1.7	2.0	7.0
<i>Navicula</i> aff. <i>glaciei</i>	15	5.0	3.3	2.9	4.2	5.4	5.8	8.5	3.4	5.9	3.5	5.4	5.9	3.2	5.0	4.5
<i>Navicula directa</i>	14	1.0	1.4	1.6	1.0	1.9	1.0	0.7	0.6	1.5	1.5	1.0	1.1	1.1	1.3	1.7
<i>Navicula perminuta</i>	16	5.5	2.9	1.3	1.6	0.0	2.5	0.2	1.2	1.2	0.0	4.0	1.5	1.3	1.4	0.0
<i>Navicula</i> sp. a	17	2.9	2.1	4.9	4.4	4.3	2.0	0.9	4.6	2.9	4.1	2.4	1.5	4.8	3.7	4.2
<i>Navicula</i> sp. b	12	0.8	4.0	2.9	2.3	2.2	0.8	0.2	6.7	2.0	0.3	0.8	2.1	4.8	2.2	1.2
<i>Navicula</i> sp. c	13	1.8	2.4	4.9	7.6	7.8	3.0	3.4	4.9	2.2	2.9	2.4	2.9	4.9	4.9	5.4
<i>Planothidium</i> spp.	2	16.0	11.7	8.5	11.7	12.7	17.6	10.8	12.9	11.0	12.9	16.8	11.2	10.7	11.4	12.8
<i>Pseudostaurosira brevistriata</i>	18	2.1	3.1	7.8	9.7	5.9	5.8	1.6	10.7	6.9	4.4	3.9	2.4	9.3	8.3	5.2
<i>Stauroneis wislouchii</i>	19	3.4	1.2	1.6	2.6	2.7	5.3	18.4	4.6	1.5	2.6	4.3	9.8	3.1	2.0	2.7
<i>Staurosira construens</i> var. <i>pumila</i>	10	4.7	4.8	4.2	9.9	4.1	3.3	3.9	4.0	4.2	5.8	4.0	4.3	4.1	7.0	5.0
<i>Staurosira construens</i> var. <i>venter</i>	11	1.6	1.9	3.9	7.0	4.9	2.0	1.6	5.5	6.4	4.7	1.8	1.8	4.7	6.7	4.8

**Table 5.2 (4)** Relative abundances of benthic diatom species in each of the four marine bays sampled from the Windmill Islands, Antarctica.

Conversely, the relative abundances of *Planothidium* spp. typically exceeded 10% in samples from Brown Bay, but did not exceed this amount at either Cloyd Island, or Shannon Bay.

### **The influence of environmental variables on diatom communities within individual locations**

Preliminary ordinations were performed on samples from the individual locations, using all five environmental variables. Unrestricted Monte Carlo permutation tests of the trace statistic revealed that only samples from Brown Bay and Odbert Island were significantly related to the environmental parameters used in this study ( $p = 0.05$ ).

#### ***Brown Bay***

Within this location, high correlation scores, and VIFs >20 indicated that the % sand and % mud were highly related. The variable % mud was therefore removed from the active dataset prior to further ordinations being undertaken. An ordination using the four remaining active environmental variables (depth, % gravel, % sand and % surface irradiance) showed that the first four ordination axes explained a total of 52.0% of the variation in the diatom data. An unrestricted Monte Carlo permutation test of the trace indicated that the diatom data was significantly related to these variables ( $p = 0.01$ ).

Axis 1 (eigenvalue 0.416) and axis 2 (eigenvalue 0.059) explained a total of 92.0% of the variation attributable to the environmental variables, accounting for 80.5% and 11.5% respectively. Axis 1 is highly correlated with % sand (Table 5.3). Unrestricted Monte Carlo permutation tests indicated that the species abundances were significantly related to Axis 1 ( $p = 0.01$ ). Axis 2 was not significantly correlated to any of the environmental variables (Table 5.3); unrestricted Monte Carlo permutation tests indicated that the diatom abundances were not significantly related to this axis at a significance level of  $p = 0.05$ .

	Axis 1	Axis 2
Depth	-0.190	-0.352
% Gravel	0.070	-0.444
% Sand	<b>-0.917</b>	-0.050
% S.I.	0.244	-0.206

**Table 5.3** Interset correlations showing the relative contribution of active environmental variables to RDA axes for an ordination of samples from Brown Bay.

% S.I. refers to the % of surface irradiance that reaches the benthos. % mud and % sand were highly correlated, % mud has therefore been removed from the set of active environmental variables.

Significant contributions ( $>0.5$ ) are shown in **bold**.

Forward selection and unrestricted Monte Carlo permutation tests revealed that % sand (and the negatively correlated % mud) accounted for 75% of the variation in diatom data which is explained by the environmental variables, at a significance level of  $p = 0.01$ . None of the other active variables individually explained a significant proportion of the variance ( $p = 0.05$ ).

Figure 5.4 shows the sample-environment biplot. Samples from Transect 1 all plot on the right hand side of the ordination, whilst samples from the remaining two transects plot on the left hand side of the ordination. Axis 1, the horizontal axis, is highly correlated with % sand, with this variable increasing from right to left. Thus the position of Transect 1 samples on the right hand side of the biplot indicates a lower % sand relative to the other samples. Axis 2 was not significantly correlated with any of the environmental variables; the reason for sample dispersal along this axis is not clear.

The dominant influence on samples from Brown Bay was the % sand (and the negatively correlated % mud). A number of diatom species were highly correlated with % sand, as indicated by the species-environment biplot (Fig. 5.5). *Amphora ovalis*, *Amphora* sp. a, *Navicula* sp. b, *Cocconeis costata*, *Achnanthes* sp. a, *Navicula directa*, and *Staurosira construens* var. *venter* were all positively

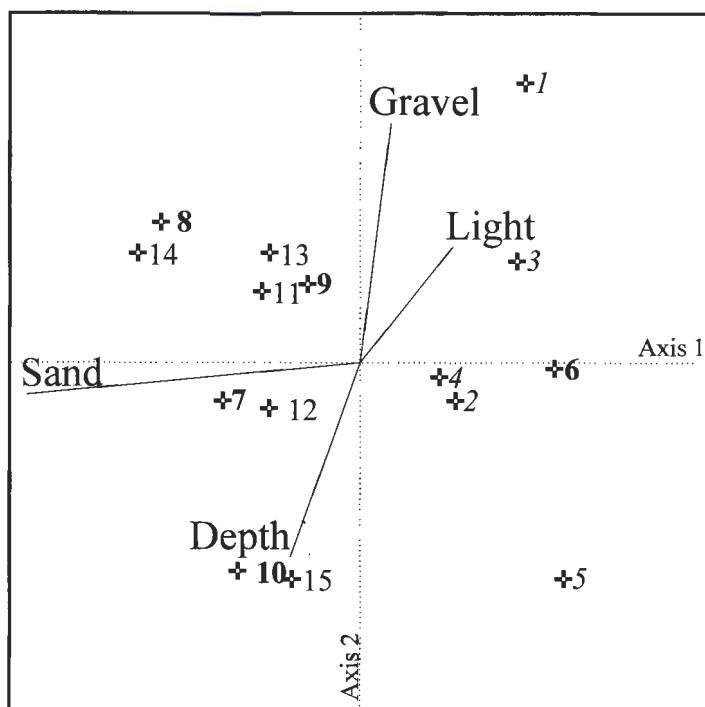


Figure 5.4 RDA ordination showing the relationships between individual samples and environmental variables within Brown Bay. Samples from Transect 1 are represented by a diamond; samples from Transect 2 are represented by a square; samples from Transect 3 are represented by a triangle. Within each transect, increasing sample numbers related to increasing water depth. % mud is not shown as a separate variable, due to its high ( $R > 0.9$ ) negative correlation with sand.

correlated with % sand. *Achnanthes brevipes*, *Navicula* aff. *glaciei* and *Stauroneis wislouchii* all showed a strong negative correlation with % sand, and thus were positively correlated with % mud.

Although the remaining environmental variables were not individually significant in explaining diatom species abundances, several correlations were observed. Depth was positively correlated with *Staurosira construens* var. *pumila*. *Ctenophora pulchella* was positively correlated with % gravel. *Planothidium* spp. and *Navicula perminuta* were positively correlated with % surface irradiance; *Navicula* sp. c and *Staurosira construens* var. *pumila* were negatively correlated with this variable.

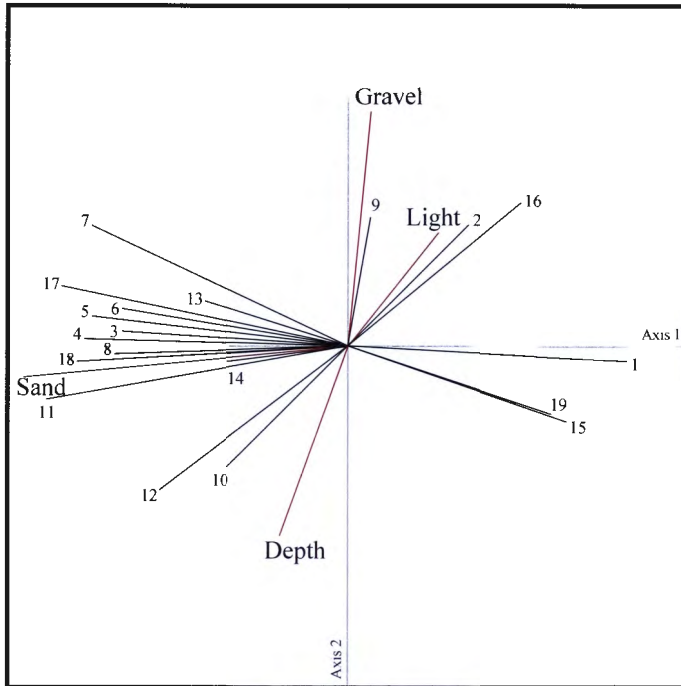


Figure 5.5 RDA ordination showing the relationships between diatom species and environmental variables within Brown Bay. % mud is not shown due to its high, negative correlation with % sand. The angle between species and environmental vectors approximates the correlation. Vectors close together show a high positive correlation; a right angle between vectors indicates no correlations; angles close to  $180^\circ$  indicate high negative correlations. Species names (and numbers) are given in Table 5.2.

### Odbert Island

High correlation scores and VIFs  $>20$  indicated that depth and % surface irradiance were highly related within this location. Depth was therefore used as a passive, not active, variable. An ordination using the four remaining active environmental variables (% gravel, % mud and % sand and % surface irradiance) showed that the first four ordination axes explained a total of 49.6% of the variation in the diatom data. An unrestricted Monte Carlo permutation test of the trace indicated that the diatom data was significantly related to these variables ( $p = 0.01$ ).

Axis 1 (eigenvalue 0.381) and Axis 2 (eigenvalue 0.073) explained a total of 91.5% of the variation attributable to the environmental variables, accounting for 76.9% and



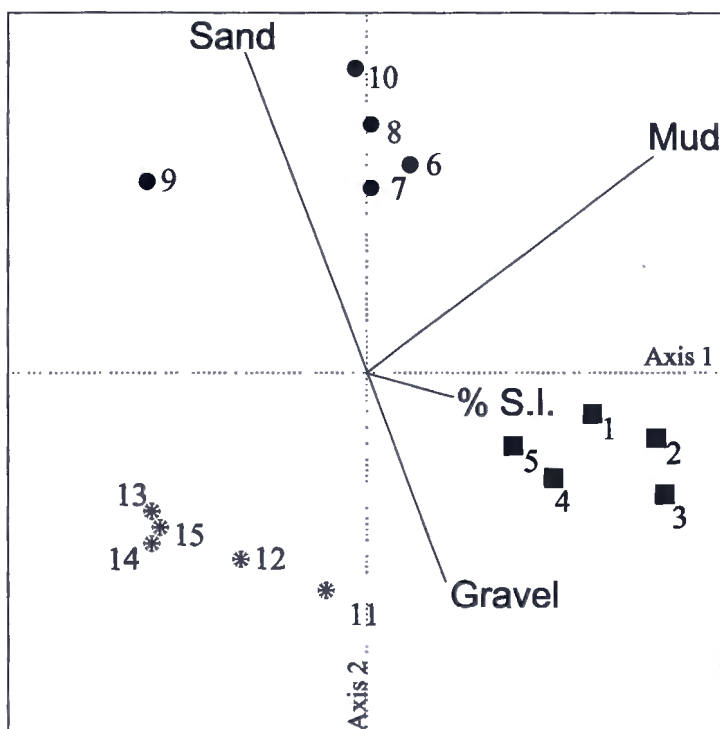
14.6% respectively. Unrestricted Monte Carlo permutation tests indicated that the species abundances were significantly related to Axis 1 ( $p = 0.01$ ), which correlated with % mud (Table 5.4). Although Axis 2 was significantly correlated to sand (Table 5.4), unrestricted Monte Carlo permutation tests revealed that the diatom species abundances were not significantly related to this axis ( $p = 0.05$ ).

	Axis 1	Axis 2
% Gravel	0.182	-0.493
% Mud	<b>0.698</b>	0.448
% Sand	-0.319	<b>0.735</b>
% S.I.	0.222	-0.039

Table 5.4 Interset correlations showing the contribution of active environmental variables to RDA axes 1 and 2 based on data from Odber Island. % S.I. is the % of surface irradiance that reaches the benthos. Within the location, depth and light were highly correlated, depth has therefore been removed from the set of active environmental variables. Significant contributions ( $>0.5$ ) are shown in **bold**.

Forward selection revealed that % mud ( $p = 0.02$ ) and % sand ( $p = 0.01$ ) explained a significant proportion of the variance attributable to the environmental variables, accounting for 54% and 34% respectively. None of the remaining environmental variables individually explained a significant proportion of the variation in diatom data attributable to the environment variables ( $p = 0.05$ )

The RDA ordination of samples (Fig. 5.6) shows a clear separation into three groups, which correspond to the sampling transect used. All three transects show some horizontal separation. As the horizontal axis, Axis 1, corresponds to % mud, this is reflecting differences in mud content between the three transects. Samples 1-5 (Transect 1) had the highest mud content, indicated by their position at the far right of the biplot; values ranged from 6.8% to 8.1%. Samples 11-15 had the lowest mud content, indicated by their position on the left hand side of the biplot; the mud content of these samples ranged from 2.6% to 3.6%.



**Figure 5.6** RDA ordination showing the relationships between individual samples and environmental variables at Odber Island. Samples from Transect 1 are represented by a square; samples from Transect 2 are represented by a circle; samples from Transect 3 are represented by an asterisk. Within each transect, increasing sample numbers related to increasing water depth. Depth is not shown as a separate variable, due to its high ( $R > 0.9$ ) negative correlation with %S.I. (the % of surface irradiance that reaches the benthos).

Axis 2 is correlated to the % sand, with values increasing from the bottom towards the top of the biplot. Despite unrestricted Monte Carlo permutation tests indicating the diatom composition wasn't significantly related to this axis, the vertical distribution of the three sample groups does roughly correspond to the % sand. The sand content of samples 6-10 (Transect 2) varied between 87.8% and 94.4%; these samples plot towards the top of the biplot. The sand content of samples 1-5 varied between 59.0% and 67.4%; samples 11-15 had sand contents between 65.5% and 69.3%. Both of these groups of samples plotted towards the bottom of the biplot, as one would have predicted based on the sand content.

Mud was the most significant variable at this location, and a number of species were highly correlated with this variable, however most correlations were negative (Figure 5.7). Species negatively correlated with mud included: *Amphora ovalis*, *Amphora libyca*, *Amphora* sp. a, *Navicula directa*, *Staurosira construens* var. *venter*, *Pseudostaurosira brevistriata*, and *Cocconeis costata*. *Navicula* sp. b was the only species whose distribution was positively correlated with mud within this location.

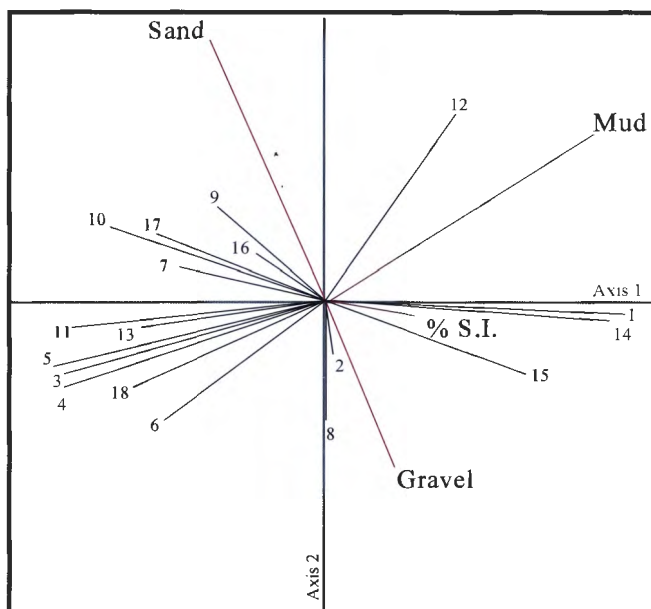


Figure 5.7. RDA ordination showing the relationships between active environmental variables and species abundances from samples collected at Odber Island. The angle between species and environmental vectors approximates the correlation. Vectors close together show a high positive correlation; a right angle between vectors indicates no correlations; angles close to 180° indicate high negative correlations. Depth is not shown due to its strong, negative correlation with % S.I. (the % of surface irradiance that reaches the benthos). Species names are given in Table 5.2.

Several species were positively correlated with either sand or gravel at this location. *Navicula perminuta* and *Ctenophora pulchella* were both positively correlated with % sand (Fig. 5.7). *Planothidium* spp. and *Cocconeis* sp. a were positively correlated with gravel within this location.

### The influence of environmental variables on diatom communities of the Windmill Islands.

The total variation within the diatom data explained by the measured environmental variables was 30.0%. Unrestricted Monte Carlo permutation tests indicated there was a significant relationship between the environmental variables and the diatom data ( $p = 0.01$ ). Axis 1 (eigenvalue .224) explained 74.6% of the variation in diatom abundances accounted for by the active environmental variables; Axis 2 (eigenvalue 0.61) explained a further 20.3%. Unrestricted Monte Carlo permutation tests revealed the diatom abundances were significantly related to both axis 1 and axis 2 ( $p = 0.01$ ).

Inter-set correlations (Table 5.5) revealed that Axis 1 was correlated with four of the five environmental variables although most of these correlations were weak. Mud was the exception, with a moderately strong positive correlation observed between this variable and Axis 1 (Table 5.5). Of the weaker correlations observed, depth was positively correlated, whilst both sand and light were negatively correlated, with this axis (Table 5.5). Although none of the environmental variables were significantly correlated to Axis 2, gravel exerted the greatest influence on this axis (Table 5.5).

	Axis 1	Axis 2
Depth	<b>0.565</b>	0.180
% Gravel	0.028	0.380
% Mud	<b>0.717</b>	-0.129
% Sand	<b>-0.548</b>	-0.099
% S.I.	<b>-0.585</b>	0.018

**Table 5.5** Inter-set correlations showing the relative contribution of environmental variables to the RDA axes when all four sampling locations from the Windmill Islands are considered.

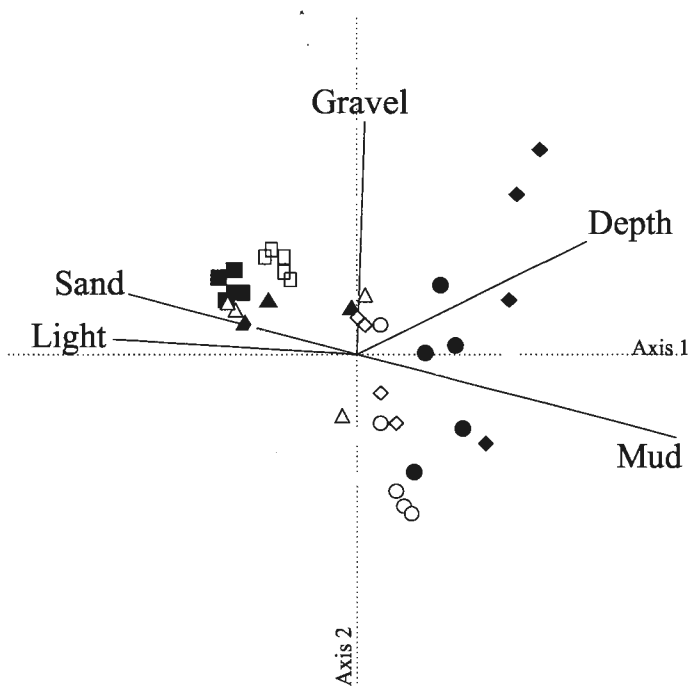
% S.I. represents the amount of surface irradiance that penetrates through to the benthos.

Significant contributions are shown in **bold**.

Forward selection with unrestricted Monte Carlo permutation tests revealed that two variables explained 80.0% of the variation in the diatom data accounted for by the environmental variables. Mud explained 60.0% of the variation ( $p = 0.01$ ) while

depth explained 20.0% ( $p = 0.01$ ). No significant proportion of the variation was individually explained by any of the remaining variables. If gravel was substituted for depth as the second variable, gravel explained 13.3% of the variation attributable to the environmental variables.

Figure 5.8 shows the relationship between environmental variables and samples from the four selected locations in the Windmill Islands. Axis 1, from left to right, corresponds strongly to an increase in the percentage of mud in the sediment, although decreasing sand content, decreasing % surface irradiance and increasing depth all show weak correlations with this axis.



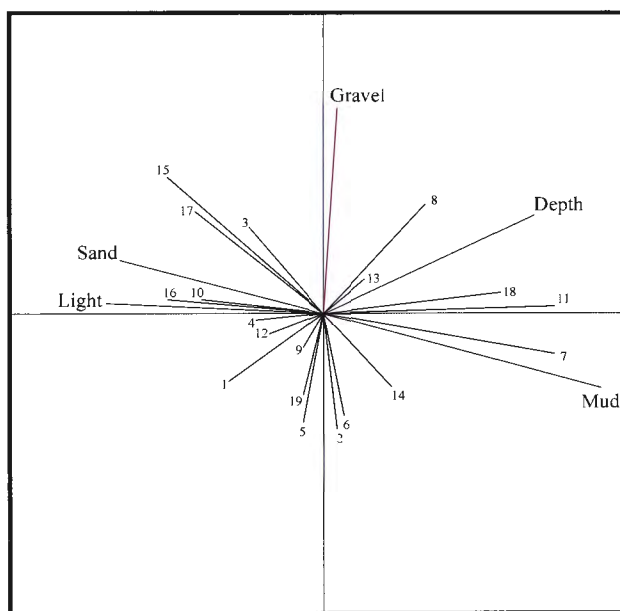
**Figure 5.8** RDA ordination showing the relationship between environmental variables and samples from the four selected locations in the Windmill Islands. Samples from Cloyd Island are indicated with a triangle. Odber Island samples are indicated by a square. Samples from Brown Bay are depicted with a circle whilst samples from Shannon Bay are indicated by a diamond. The colour of the symbol is related to the transect number. Transect 1 is shown in black, Transect 2 is shown in light grey, while Transect 3 is shown as hollow symbols. See the site description for the orientation of transects within each location.

Samples from Brown Bay and Shannon Bay had higher proportions of mud than samples from either Cloyd Island or Odbert Island. This is reflected in the sample-environment biplot, with samples from Brown and Shannon Bays clustering on the right hand side, whilst those from Cloyd and Odbert Islands group on the left hand side of the ordination (Fig. 5.8). The locations which plotted on the right hand side of the biplot typically have higher relative abundances of *Pseudostaurosira brevistriata*, *Navicula directa*, and *Staurosira construens* var. *venter* than the locations on the left of the biplot. Conversely, higher abundances of *Amphora libyca*, *Navicula* aff. *glaciei* and *Navicula* sp. *a* occurred at locations on the left hand side of the biplot.

Axis 2, from top to bottom of the ordination, corresponds to a gradient of increasing gravel content in the sediment. Samples from Cloyd Island typically varied between 10 and 20% gravel, however Sample 17 had only 0.9% gravel. All samples collected from Cloyd Island plot above the horizontal axis on Figure 5.8, apart from sample 17 thus reflecting its lower gravel content. Samples collected from Odbert Island also had highly variable gravel content. Samples 6-10, from the second transect, had much lower percentages of gravel than any of the other samples (Fig. 5.2). This is also reflected on the sample-environment biplot (Fig. 5.8), with samples from Transect 2 plotting below the horizontal axis, whilst all other samples from Odbert Island all occur above this axis.

Samples from Shannon Bay are widely dispersed along the vertical axis, however within each of the transect sampled, a pattern can be detected. The samples collected closest to the shoreline plot at the top of the ordination, with a transition downwards such that the samples collected furthest from the shore, within each transect, plot lowest on the ordination. Although samples from this location only varied between 0.2% and 8.5% gravel, within each transect a general trend of decreasing gravel content with increasing distance from shore was observed (Figure 5.2), thus correlating with the observed vertical distribution of these samples on Figure 5.8.

The correlation between species and environmental variables can be interpreted from the angle between the corresponding arrows on the species-environment biplot (ter Braak, 1988). From the species-environment biplot (Fig. 5.9) it can be seen that *Cocconeis* sp. a, and *Navicula directa* both have a strong positive correlations to depth. *Achnanthes brevipes* is negatively correlated with depth. *Cocconeis costata*, *Amphora* sp. a, and *Planorhynchium* spp. show a strong, negative correlation to % gravel. *Cocconeis fasciolata* is the primary species to be correlated with % mud, however *Navicula directa* and *Staurosira construens* var. *venter* also show a moderate correlation to this variable. *Navicula* sp. a and *Navicula* aff. *glaciei* are both positively correlated to % sand (Fig. 5.9). *Staurosira construens* var. *pumila* has a strong positive correlation with both % sand and % surface irradiance. *Navicula perminuta* and *Amphora libyca* were both positively correlated with % surface irradiance.



**Figure 5.9** RDA ordination showing the correlation between species and environmental factors when all four sampling locations in the Windmill Islands are considered. The angle between species and environmental vectors approximate the correlation. Vectors close together show a high positive correlation; a right angle between vectors indicates no correlation; angles close to 180° indicate high negative correlations. Species names (and numbers) are given in Table 5.2.

### **Did differences in the sampling regime influence the apparent relationship between environmental variables and diatom communities?**

Two of the locations sampled had diatom communities that were significantly related to environmental variables, however two other locations did not. Several differences occurred in the sampling protocol between these two groups of locations. Firstly, the locations where a significant relationship was observed both had 15 samples collected from them, whilst the two bays which only had 12 samples collected did not show a significant relationship. Secondly, samples from 1 m water depth were only collected at the two bays where a significant relationship was observed. In order to determine if the sampling protocol was responsible for the differential responses to environmental variables observed between locations, further ordinations were undertaken.

In order to determine if the number of samples was an influencing factor, three samples were removed from each of the Brown Bay, and Odbert Island data set. Redundancy analysis was then performed on the reduced data sets. Despite the reduced sample number, unrestricted Monte Carlo permutation tests indicated that the diatom abundances were significantly related ( $p = 0.05$ ) to the environmental variables.

To determine if the absence of samples collected from 1 m water depth influenced the significance of the relationship between diatom communities and environmental variables, samples from this depth were removed from both the Brown Bay and Odbert Island data sets. Redundancy analysis was then performed on the reduced data set. These results indicated that the diatom abundances were still significantly related to the environmental variables ( $p = 0.05$ ). In addition, the proportion of variance in diatom abundances that was explained by the environmental variables increased, relative to analyses which included samples collected at 1 m water depth



### **The influence of environmental variables on compositional differences observed in diatom communities between locations**

Redundancy analysis, using a dummy variable to represent location, showed that the first four ordination axes explained 46.2% of the variation within the diatom data, with the first ordination axis explaining 30.1%. Unrestricted Monte Carlo permutation tests indicated that diatom abundances were significantly related ( $p = 0.01$ ) to both the trace statistic, and the first ordination axis. Inter-set correlations revealed that axis 1 had a strong, negative correlation with location (-0.859). Forward selection indicated that location explained 60% of the variation in diatom abundances that was attributable to environmental variables, however correlation coefficients indicated a moderate correlation between location and mud (0.759).

Constrained redundancy analysis revealed that the first constrained ordination axis (eigenvalue = 0.081) explained 11.6% of the variation within the diatom community once variation due to the covariables had been accounted for. That is, the effects of location explained a further 11.6% of the variation in diatom data once variation due to grain size, depth and light had been allowed for. A moderate correlation between location and species abundances was observed (0.748). Unrestricted Monte Carlo permutation tests indicated that the diatom data was significantly related to location ( $p = 0.01$ ).

Location accounted for 27.7% of the total variation in diatom communities in the unconstrained ordination, but only 11.6% when the measured environmental variables were used as covariables. From this it can be calculated that differences in grain-size, light and depth were responsible for 60% of the variation in diatom communities that was apparently attributable to location.

### **Discussion**

Of the environmental parameters examined, grain-size, particularly the percentage of fine ( $< 63$   $\mu$ m) sediments, has a major influence on diatom communities within the

Windmill Islands. As an individual variable, the percentage of mud (< 63  $\mu$ m) in the sediments explained the greatest proportion of the variation observed in the diatom community, both collectively over the four locations, and within Odbert Island samples. The influence of % sand and % mud could not be distinguished at Brown Bay due to their high correlation, however these variables accounted for 75% of the variation in diatom abundances that was attributable to the environmental variables. The amount of mud and sand present in sediments has previously been demonstrated to significantly affect benthic diatom communities in polar regions. Using PCA analysis, Campeau et al. (1999) found mud and sand contributed significantly to the variation observed in diatom communities in coastal regions of the Beaufort Sea.

Redundancy analysis revealed that % mud accounted for 18% of the variation observed in diatom communities from four locations in the Windmill Islands, in addition the % gravel could account for a further 4%. Thus grain size can explain up to 22% of the variation in diatom abundances. This estimate is higher than has previously been reported from Antarctic environments; Whitehead and McMinn (1997) found grain size accounted for a total of 13% of the variation in benthic diatom assemblages from fjords in the Vestfold Hills. Within our study, the influence of grain size was even more pronounced in two individual locations. At Odbert Island, the proportion of mud present in the sediments accounted for 25% of the total variation observed in the diatom abundances, with a further 15% explained by the proportion of sand present. At Brown Bay, mud accounted for 38% of the total variation in diatom community composition.

As an individual variable, depth explained 6% of the variation observed in diatom communities sampled from the four locations. This influence was separate from changes in light or grain size. Typically investigations into the influence of depth have associated observed changes with at least one of these variables (ie Whitehead and McMinn, 1997; Ahn et al., 1993). Although depth and light were highly correlated within individual locations, it was possible to distinguish between these variables in the analysis of the four locations, due to differing light/depth

relationships between locations. Both Shannon Bay and Odbert Island had large variation in the proportion of surface irradiance that reached the benthos. At both of these locations, light availability was strongly correlated with depth. The shallowest sites received about 35% of surface irradiance, whilst the deepest sites received less than 3%. The % surface irradiance which reached the benthos was reduced at both Cloyd Island, and Brown Bay. This may have resulted from increased turbidity or, at Cloyd Island, shading from macroalgae. Correlations between light and depth were also reduced at Brown Bay; this could reflect variations in turbidity or patchiness of planktonic communities within this bay.

Within this study, light did not individually explain any significant proportion of the observed variation in diatom abundances, despite differences both within sites, and between sites. However, at Odbert Island light was highly correlated with depth, which was shown to be a significant factor in explaining diatom abundances at this location. Changes in community composition of benthic diatoms have frequently been related to changes in light attenuation (ie Admiraal and Peletier). Whitehead and McMinn (1997) suggested that attenuation of light through the water column explains 45% of the variation observed in benthic diatom communities, however no actual measurements of light availability were undertaken.

The environmental variables used in this study explained 30% of variation observed in diatom abundances overall, and even higher proportions of the variance within two locations. Despite this, diatom communities from Cloyd Island and Shannon Bay were not related to these environmental variables at a 5% significance level. It was demonstrated that differences in sampling regime, such as reduced sample number, and different sampling depths did not prevent significant relationships from being observed between diatom communities and the environmental variables. It therefore remains unclear what factors are influencing species abundances in diatom communities from Cloyd Island and Shannon Bay.

Relationships between abundances of individual species, and environmental variables were complex. Only a few species were consistently correlated with the same variable in all analyses, however, one example of this is *Navicula perminuta* which was positively correlated with the % surface irradiance that penetrated to the benthos. This contrasts with previous reports of this species as shade adapted (Snoeijis and Kautsky, 1989), however Campeau et al. (1999) found this species had a depth optimum of 1.3 m., indicating preference for high light availability. *Achnanthes brevipes* consistently showed a negative correlation with depth, with maximum relative abundances occurring at shallow depths. Round (1981) describes this species as typical of a supra tidal environment, which is consistent with our results, however, Whitehead and McMinn (1997) found this species to be indicative of water depths between 9.8 and 18 m.

Some species responded to a given variable in a consistent manner within individual locations, but were not apparently related to that variable in the overall ordination. For example, *Amphora ovalis*, *Amphora* sp. a and *Navicula* sp. b all decreased in abundances at Brown Bay and Odbert Island when % mud increased, however overall the abundances of these species were correlated to light, gravel and depth, respectively. It is likely that the overall correlations reflect differences in abundances between location associated with these variables, which may exert a stronger influence than differences within location.

The distributions of *Staurosira construens* var. *venter* and *Pseudostaurosira brevistriata* were both positively correlated with mud in the ordination of all four locations, but within both the ordinations of individual locations these species were negatively correlated with mud. This negative correlation with mud is consistent with previous descriptions of *Staurosira construens* as an episammic species (Round, 1981; Whitehead and McMinn, 1997). Large differences in relative abundances of *Staurosira construens* var. *venter* and *Pseudostaurosira brevistriata* were observed between locations; the maximum relative abundance observed in Shannon Bay was more than 3 times the maximum relative abundance observed at either Cloyd Island or Odbert Island. The abundance of *Pseudostaurosira brevistriata* was not

noticeably higher in Brown Bay than at either of the two island locations, however, the maximum relative abundance of *Staurosira construens* var. *venter* in Brown Bay was more than double that observed at Cloyd and Odbert Islands. Both Brown Bay and Shannon Bay also have a higher proportion of mud than at either Cloyd Island or Odbert Island. It seems probable that the apparent correlation between this species and the mud content in the ordination of all four locations is overwhelming the negative correlation which is apparent within the individual locations. This suggests that a difference in environment, other than mud content, occurs between Shannon Bay and the two island locations, but that this difference was not distinguished from mud within this study.

Similarly, the negative correlation observed between *Planothidium* spp. and gravel in the ordination of all four locations, could be attributed to the higher abundances of this species at Brown Bay and Shannon Bay, where only small amounts of gravel occur. This signal appears to overwhelm the positive correlation observed between *Planothidium* spp. and gravel observed in ordinations of the individual locations. Campeau et al. (1999) found that the depth preference for this species ranged between 0.6 m and 1.5 m, which supports a positive correlation with gravel. Once again it seems likely that some difference between locations, other than gravel is causing the higher relative abundances in Brown and Shannon Bay.

Several species responded to a given variable consistently in the overall ordination, and at Odbert Island, but responded differently in samples from Brown Bay. For example, *Achnanthes* sp. a was positively associated with gravel, and negatively correlated with sand both overall and at Odbert Island, however, in diatom communities from Brown Bay this species was positively associated with sand. One possible explanation for the contrasting relationship with sand, is a relative lack of gravel in sediments from Brown Bay. The lack of coarser material, may be causing this species to utilise the "next best" substrate type, namely sand. Thus the differences in response may actually represent a continuum in the preference of this species for coarse substrate, with gravel preferred to sand, and sand preferred to mud.

When location was included as a dummy variable, this was shown to account for 27.7% of the total variation in diatom abundances. Differences in grain size, depth and light values between locations were responsible for 60% of the variation attributable to location. This means that 40% of differences between location are unaccounted for. Location was moderately correlated with % mud, and weakly correlated with % sand. This supports the suggestion that differences in location, other than these factors, were causing the differences between locations in the abundances of *Pseudostaurosira brevistriata*, *Staurosira construens* var. *venter* and *Planothidium* spp.. One possible explanation is annual irradiance, which will be influenced by the duration of sea-ice, and the amount of snow cover which occurs at each location. Other possible explanations for differences between Brown and Shannon Bays and the two island locations include differences in freshwater input, stratification of the water column and chemical contamination.

Human activities, associated with the operation of research stations within Newcomb Bay, have resulted in increased concentrations of many metals (including iron, copper, lead and arsenic) in both Brown Bay and Shannon Bay (Snape et al., 2001; Scouller et al., 2000). In addition, Shannon Bay has increased nutrients input, whilst sediments from Brown Bay have increased petroleum hydrocarbon concentrations, relative to reference locations (Snape et al., 2001). Cloyd and Odbert Islands, situated more than 10km from Casey Station, are unlikely to have been contaminated. It is therefore possible that the presence of metals, or greater amounts of freshwater input, may be responsible for the observed differences in species composition between these locations, and Cloyd and Odbert Islands. Should either of these suggestions be true, this could contribute to the previously discussed contradiction observed between mud content and the relative abundances of *Pseudostaurosira brevistriata* and *Staurosira construens* var. *venter*.

*Ctenophora pulchella* also appears to have different responses to grain size between locations. This species is negatively correlated with gravel in the both the ordination

of all locations, and at Odber Island but at Brown Bay a positive correlation was observed between this species and gravel. Unlike the species discussed above, the relative abundances of *Ctenophora pulchella* were relatively constant between locations. It therefore seems likely that some environmental factor within Brown Bay that isn't present at Odber Island is causing the observed difference in the correlation between this species and gravel. In order to determine what this may be, further investigation into a range of environmental variables, including chemical contamination, freshwater input, and the duration of sea-ice would be required.

### Conclusions

The sampling location was the dominant factor in determining the abundances of diatom communities in the Windmill Islands. Differences in grain-size, light and depth explained a large proportion of this, however, some of the variation observed between locations is still unexplained. Within two locations, the composition of diatom communities was not significantly related to any of the environmental variables examined. Within the remaining two locations grain-size, especially the proportion of mud, explained the majority of variation in diatom abundances that was related to the environmental variables used in this study.

## Chapter 6

### ***Temporal variability of diatom communities in the Windmill Islands***

#### **Abstract**

The temporal variability of benthic diatom communities from the Windmill Islands was assessed over three scales. Compositional changes which occur over a single summer season were examined at five different locations. Principal components analysis (PCA) indicated significant variability within the diatom communities, however the nature of these changes varied between locations. Compositional changes which have occurred over the hundreds of years were examined using short sediment cores from five different locations. PCA results indicated that the composition of diatom communities has remained relatively constant at two of these locations, however compositional changes were observed over time at the other locations.

The composition of benthic diatom communities shows a large degree of variability over thousands of years, however no consistent pattern was discernible. Complete diatom assemblages, which included both planktonic and benthic species, resulted in a greater discrimination between temporal groups than analyses restricted to benthic species. *Pseudostaurosira brevistriata*, *Cocconeis fasciolata*, *Staurosira construens* var. *venter* and several *Navicula* species all demonstrated significant variation over the temporal scales examined.

#### **Introduction**

Antarctic diatoms live in profoundly seasonal environments (Priddle et al., 1986). Irradiance and the presence of sea-ice are major contributors to this seasonal variation. South of the polar circle, solar irradiation is continuous for several weeks during summer, but unmeasurable for a similar period over winter. Sea-ice is present in coastal Antarctic regions for up to 11 months of every year, thus exerting a strong influence on diatom growth (McMinn et al., 2000).

As a result of the strong seasonality present within Antarctic ecosystems, most investigations of temporal variability in diatom communities have typically focused on the seasonal variations that occur within an annual cycle (eg. McMinn and



Hodgson, 1993; Everitt and Thomas, 1986). Despite the emphasis on seasonal changes in diatom communities, benthic diatom communities have been little studied in this regard. The few studies which have been undertaken on this topic have examined changes in chlorophyll *a* content (Gilbert, 1991a) or productivity (Gilbert, 1991b). Seasonal changes in the composition of benthic diatom communities of near-shore marine regions in Antarctic have long been neglected.

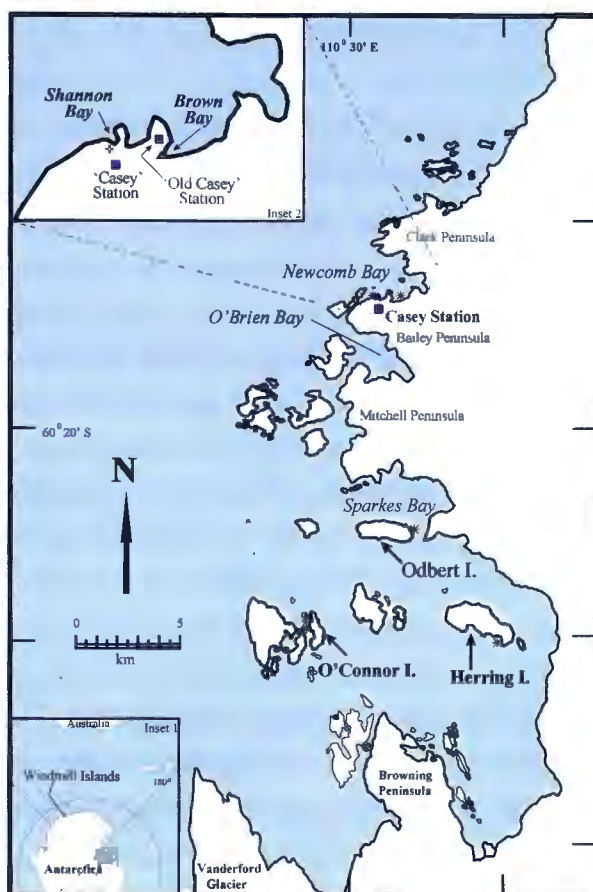
A similar lack of data exists regarding temporal variability of benthic diatom communities over longer time-scales. A number of studies have examined trends in the community composition of diatom assemblages from sediment cores, and even related these to historical events such as glaciation (Cremer et al., 2002) or sea-ice extent (McMinn, 2000; Gersonde and Zielinski, 2000) however these studies are typically based on species found in planktonic or sea-ice communities.

This study aims to address the paucity of information available on temporal variability of Antarctic marine benthic diatom communities. Temporal trends can occur on a variety of scales, over seasons, years or even thousands of years (Charles et al., 1994). Changes in the composition of benthic diatom communities from the Windmill Islands are therefore assessed over three time-scales: within a single season, over hundreds of years (short-term), and over thousands of years (long-term). Preliminary results of these investigations are given.

## **Methods**

### **Study location.**

The Windmill Islands are a small deglaciated oasis in Wilkes Land, Antarctica which cover an area of approximately 75 km<sup>2</sup> between 66°10'–66°35' S, 110°10'–110°50' E (Fig. 6.1). The Windmill Islands are the only large area of seasonally snow-free terrain for over 400 km of coastline, either east or west (Murray and Luders, 1980).



**Figure 6.1** Map of the Windmill Islands including Casey Station (■). Inset 1 shows the geographical position of the Windmill Islands. Inset 2 shows the proximity of Brown Bay and Shannon Bay to the now defunct Thala Valley tip site (▲) and sewage outfall (✚), respectively. Locations where seasonal sampling was undertaken are shown (\*).

The area consists of small islands and peninsulas, typically with elevations less than 100 m (Goodwin, 1993). The islands between Mitchell Peninsula and the Vanderford Glacier typically have more pronounced relief, and are often bordered by abrupt cliffs (Murray and Luders, 1980). Two islands in this group, Odbert and Ardrey Islands, exceed 100 m in height.

The geology of the Windmill Islands consists of low-pressure metamorphic rocks, including psammitic gneisses and migmatic metapelites, interlayered with igneous

intrusions of granite, dolerite and gabbro (Paul et al., 1995). The northern islands typically consist of metamorphic rocks whilst the southern islands are predominantly composed of igneous rocks (Paul et al., 1995). Sediments that overlie the basement rocks consist primarily of coarse-grained sands and gravels. These unconsolidated sediments accumulate in low-lying depressions and form deposits up to several meters thick (Snape et al., 1998).

The nearshore bathymetry is a complex system of islands, shoals and steep-sided submarine channels (Tate et al., 2000); the offshore bathymetry is dominated by a large region of shallow water known as the Peterson Bank which extends northward from the Windmill Islands (Goodwin, 1993). The shallow marine environment consists of a sedimentary mosaic of boulders, cobbles and gravel interspersed with mud and sand. Tidal currents are relatively insignificant in the region, with currents dominantly wind-controlled in the more exposed areas, (Cathers et al., 1998).

The permanently manned ANARE research station “Casey” is located within the Windmill Islands, at 66° 17' S, 110° 32' E. “Casey” is the third research station to have been built within the region. Many of the structures associated with the two previous stations, “Wilkes” and “Old Casey” still remain.

### ***Brown Bay***

Brown Bay is a small embayment in the southern region of Newcomb Bay, immediately adjacent to an abandoned tip site in Thala Valley (Inset 2, Fig. 6.1). During summer a meltstream runs down Thala Valley, through the tip site and into Brown Bay. As surface waters move through the tip site, they entrain contaminated material which is carried into Brown Bay. An estimated 8 m<sup>3</sup> of contaminated material was transported in this manner during one austral summer (Cole et al., 2000). Concentrations of heavy metals in marine sediments from Brown Bay are 10-100 times higher than from equivalent control sediments (Scouller et al., 2000). High concentrations of petroleum hydrocarbons have been recorded in sediments

from this bay, however none have been detected in sediments from control locations (Snape et al., 2001).

The rocky sides of this bay grade to a sediment covered bottom. Close to the tip site, patches of sediment occur between boulders, discarded tip material and areas of bare rock. Further away from the tip, areas of fine sediments are more extensive and relatively homogenous (Stark, 2001), but are still occasionally interrupted by large boulders. The maximum depth of 20 m was recorded at the eastern end of Brown Bay, where it enters Newcomb Bay. Brown Bay is typically ice free for 1-2 months a year, generally between January and February. Due to its alignment with the dominant wind direction, the sea-ice in Brown Bay is rarely blown out during the winter period.

### *Shannon Bay*

Shannon Bay is a small embayment within the south-western corner of Newcomb Bay, approximately 800 m west of Brown Bay. Shannon Bay is bordered by 2-15 m ice cliffs, with the sewage outfall situated 30 m landward of the eastern cliff (Inset 2, Fig. 6.1). The input of treated waste-water from the present Casey station has resulted in elevated levels of ammonia, total phosphorous and bacteria within Shannon Bay (Morris et al., 2000; in prep). Preliminary sampling of Shannon Bay also indicated elevated concentrations of heavy metals (Scouller et al., 2000).

The subtidal sides of this bay consist of steeply sloping rock and boulder fields below which is a relatively homogenous muddy sand (Stark, 2000). A maximum depth of 32 m was recorded at the mouth of this bay. This bay is generally ice free for a longer period than Brown Bay, with open water occurring between December and March.

### *Sparkes Bay*

Sparkes Bay is a large bay situated approximately 8 km S of Casey Station. This bay has a variety of environments; ice cliffs dropping vertically into deep water, steep

rocky shorelines, and shallower areas where sediments accumulate. A small embayment on the northern side of Sparkes Bay was used as one of the sampling locations. This embayment has a very similar bathymetry to that of Brown Bay with the rocky sides sloping down to a muddy bottom, the depth of which ranges between 3 and 20 m (Stark et al., in prep). Naturally high levels of some heavy metals, including cadmium, have been recorded for Sparkes Bay (Stark et al., in prep).

### *Pidgeon Island*

Pidgeon Island is located in an island group approximately 5 km S of Casey Station. The relief of this large island is less pronounced than that of the more southerly islands, and does not exceed 40 m in height. The eastern side of this island terminates abruptly with small rock cliffs, only 1-2 m high, dropping into the marine channel which separates this island from Mitchell Peninsula. These small cliffs are covered by several meters of snow and ice. Although both rock and ice-cliffs occur on the western margins of Pidgeon Island, some areas are more gently inclined, particularly towards the northern end of the island.

### *Odbert Island*

Odbert Island is a relatively large island located roughly 10 km S of Casey Station, at the junction of Sparkes Bay and Penney Bay (Fig. 6.1). Odbert Island is one of the highest in the region, and the sides consist almost entirely of cliffs which terminate abruptly into the sea. An exception to this is a small area at the eastern end of the island, where a more gradual decline forms a small bowl-shaped valley. This valley is home to several penguin colonies.

The valley contours are reflected in the marine topography, which deepens towards the centre of the embayment. This embayment is aligned roughly west to east. The bottom of this embayment is predominantly rocky, however some areas of finer sediments do occur, typically occur within the central regions of the embayment. The sediments are poorly sorted, however, there is a relatively large proportion of fine material which possibly results from the penguin colonies. The eastern end of

Odbert island is relatively sheltered. Sea-ice breaks out of this area in late-December, and reforms at the end of February or early March.

### *Herring Island*

Herring Island is located roughly 5 km SE of Odbert Island, within Penney Bay. The maximum elevation of this island is slightly less than that of Odbert Island, however both islands have a similarly rugged topography. A relatively large embayment at the south-eastern end of the island was used as the sampling location. The easternmost edge of this bay is delineated by almost vertical ice-cliffs. The embayment is aligned with a valley on the landward side of the bay. The distribution of sediments within this bay reflects the topography of this valley, with the finer sediments present in the deeper, central regions.

### *O'Connor Island*

O'Connor Island is located approximately 7 km W of Herring Island, but still within Penney Bay. Like Herring Island, much of O'Connor Island consists of steeply sloping hills, however the elevation is lower at O'Connor Island. This western side of O'Connor island is very sheltered, predominantly due to the proximity of Holl Island (Fig. 6.1). As a result, sea-ice breaks out later, and reforms earlier the next autumn than at other locations within Penney Bay. A small embayment located on the western side of O'Connor Island was used as a sampling location. The landward boundary of this embayment typically consisted of rocky slopes, several of which had been colonised by Adelie penguins. Once again, sediments occurred predominantly within the middle region of this embayment while the shallower sides of the bay typically consisted of exposed bedrock.

## **Sampling regime**

### *Seasonal variability*

Five sampling locations were selected. Two of these, Brown Bay and Shannon Bay, are immediately adjacent to the permanently manned Casey Station (Inset 2, Fig. 6.1). Both of these bays are potentially impacted as they have been contaminated with a variety of metals (Stark et al., in press; Scouller et al., 2000); Brown Bay has

also been contaminated with petroleum hydrocarbons (Snape et al., 2001). Three locations, namely Odbert Island, Herring Island and O'Connor Island were used as reference locations. A full description of these locations is given above.

Weekly sediment samples were collected from these five locations during the 2000/01 austral summer. The sampling period was restricted to times when the sites could be accessed by boat; sampling commenced on the 22/12/00 and continued until the 5/3/01. The presence of sea-ice prevented sampling in three locations on the 22/12/00, and at two locations on both the 28/2/01 and the 5/3/01. Sediment samples were collected using an Eckman grab, lowered from the side of a boat. Whilst the use of divers would have enabled the collection of sediments specifically from top few millimetres of sediment, such resources were not available during the field season in which this work was undertaken. Approximate sampling positions were identified using hand-held GPS. All samples were collected from 8 m water depth. Samples were preserved in Lugols Iodide and frozen for return to Australia.

In this preliminary assessment, only alternate samples from each location have been used. Furthermore, the samples used have been restricted to dates when all locations could be sampled. Thus the results presented in this paper represent fortnightly samples collected between 31/12/00 and 22/2/01.

### *Short term variability*

Five short sediment cores were collected from three bays within the Windmill Islands. Two cores were collected from Sparkes Bay, one core from Shannon Bay, and two cores from the outer area of Brown Bay. The cores were collected by divers inserting plastic tubes into the sediments. These cores were frozen, intact, for return to Australia. In preparation for analysis, these cores were sliced horizontally into sections, typically 6 mm thick, and then dried. Selected sections were sub-sampled for  $\text{Pb}^{210}$ , metal concentrations and diatom analyses. Details of which analyses were performed on individual sub-samples are shown in Appendix 2. Preparation and sub-sampling of the core sections was undertaken by Beck Scouller (AAD).

### *Long-term variability*

A previously collected sediment core was used. This core had been collected from the western side of Pidgeon Island, (66°19.3' S, 110°26.7' E) at a water depth of 82.0 m. This sediment core (PG 1411-2) was recovered using a UWITEC KOL Kolbenlot 3 m percussion piston corer, using the coring technique described in Melles et al., (1994). The total core length was 240 cm. This core was stored in the dark, at 0°C until required. Samples were taken for diatom analyses and radiocarbon (<sup>14</sup>C) dating. Prior to sub-sampling the core was split in half, along its length. One half was used for sampling, the other kept intact and stored at IASOS (University of Tasmania). To reduce potential contamination, resulting from the disturbance of sediments during the core-splitting procedure, a thin layer of sediment was removed from the exposed surface immediately prior to sampling.

In order to obtain samples for diatom analysis, a toothpick was inserted into the core segment, and used to gouge a small amount of sediment from the middle of the core. Samples for diatom analyses were initially collected every 5 mm, however, sampling frequency progressively decreased down the core. Samples for radiocarbon dating consisted of at least 1 cm<sup>3</sup> of sediment, collected from the middle of the core. These samples were collected from between 0-1 cm, 12-13 cm, 59-60 cm, 77-78 cm, 117-118 cm, and 229-230 cm depth.

## **Chemical Analyses**

### *Metal analysis*

Microwave assisted acid digestion was used to prepare the sediment samples for analysis. The procedures outlined in the instruction manual VEC-1-9-01-017 (ANSTO Environmental Chemistry Analytical Laboratories) were followed for this process. All sample preparation was performed by Beck Scouller (AAD). Samples were analysed at ANSTO by a technician using either ICPMS or ICPAES. Sediment samples were analysed for Sb, As, Cd, Cu, Cr, Fe, Pb, Mn, Hg, Ni, Ag, Sn and Zn.



### *Pb<sup>210</sup> Analysis*

The Pb<sup>210</sup> samples were prepared by Beck Scouller of the AAD. Polonium samples were prepared according to the procedures outlined in the ANSTO instruction manual VRC-1-9-03-020; radium analyses were prepared as outlined in instruction manual VRC-1-9-03-025. Analyses were performed by a technician at ANSTO, using alpha spectrometry. The brief interpretation of these results given in this paper represent the combined work of the author and Beck Scouller from the AAD.

The depth of the mixing layer influences the apparent age of sediments. Marine sediments typically have mixing layers 5-30 cm deep, as a result of bioturbation and physical mixing processes (McMinn et al., in press). This restricts the resolution of dates. In order to adjust for mixing layers of varying thickness within the core samples, the mixing model described in McMinn et al., (in press) was applied to the Pb<sup>210</sup> derived ages. The age of sediments at the base of the mixing layer is determined, and this age is then subtracted from all Pb<sup>210</sup> derived dates below this point. This procedure constrains the maximum age of introduction of sediments; the results produced are referred to as the “adjusted age”.

### *Radiocarbon (<sup>14</sup>C) Dating*

Six samples were analysed for radiocarbon (<sup>14</sup>C) content using accelerator mass spectrometry (AMS). Analyses were undertaken through the Physics division at ANSTO, using the methods described in Lawson et al. (2000). Values of  $\delta(^{13}\text{C})$  were assumed to be constant at -25.0 (<sup>13</sup>C) per mil. The ages were rounded as per Stuiver and Polach (1977). The radiocarbon ages calculated were then corrected to allow for an Antarctic marine reservoir effect of 1300 years. This reservoir effect results from the release of ancient CO<sub>2</sub> when old glacier ice melts (Goodwin, 1993). Although the reservoir effects of marine shells and sediments vary between 850 and 1312 years, 1300 years is the most commonly applied correction (Goodwin, 1993).

### **Diatom Preparation and Identification**

Excess organic material was removed by digestion in a 10% H<sub>2</sub>O<sub>2</sub> solution for 72 hours. Surplus liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Identification was as outlined in Appendix 1. A minimum of 400 individuals of the predominantly benthic taxa were counted per samples. The relative abundances of these taxa were then calculated and used in the statistical analyses.

### **Statistical Analyses**

An indirect gradient technique was used to detect major gradients in species abundances within each data set. A preliminary correspondence analysis was performed to determine whether a unimodal or linear response model was most suitable for each data set. The range of sample score were less than 1.5 standard deviations for all three data sets, thus linear response models were most applicable (ter Braak, 1987). Principal components analysis (PCA) was therefore selected as the ordination technique.

Species abundances were log (x+1) transformed prior to analysis; no down-weighting of rare species was applied. All ordinations were performed using CANOCO version 3.12 (ter Braak, 1988, 1990). Species component scores were used to identify which species contributed the most to individual ordination axes.

## Results

### Seasonal Variability

Principal components analysis (PCA) indicated that the first two ordination axes accounted for 72.4% of the variation in the diatom data. A plot of these two axis reveals that samples group according to location (Fig. 6.2). Variability within individual locations is expressed by differences in both ordination axis. Samples from Odbert Island and O'Connor Island show the greatest variability on Axis 1; samples from Herring Island show the greatest degree of variability within Axis 2 (Fig. 6.2).

Axis 1 is highly correlated with the abundance of *Achnanthes* sp. a (0.970). Moderate, negative correlations were observed between this axis, and both *Navicula* sp. c (-0.771) and *Synedropsis* cf. *recta* (-0.796). Weak correlations were also observed between this axis and several other species (Table 6.1).

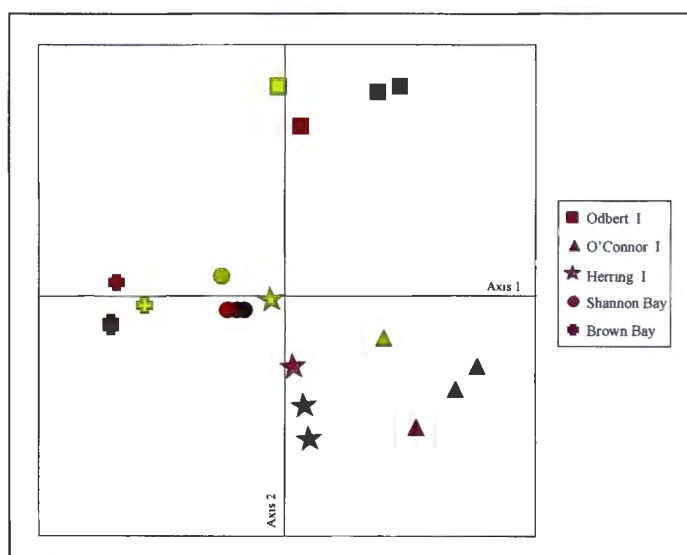


Figure 6.2 PCA showing the separation of diatom communities into location groups. Symbol colour is indicative of the time of collection: yellow = 31/12/00, red = 12/1/01, brown = 27/1/01, black = 15/2/01.

Figure 6.3 illustrates the changes in Axis 1 values which occur at each location over the sampling period. In this figure all values are normalised for the first samples, allowing for easier comparison of trends between locations. Within each location, values for this axis generally increase over the summer (Fig. 6.3), indicating increasing abundances of *Achnanthes* sp. a, and decreasing abundances of *Navicula* sp. c and *Synedropsis* cf. *recta*. Values for Shannon Bay remained constant over the first fortnight, but increased slightly over both subsequent sampling periods. Values for all three reference locations increased over each sampling period, with the most dramatic increase observed at Odbert Island between 12/1/01 and 27/1/01.

Values for Brown Bay do not follow the trend observed at the other locations. A moderate decrease in Axis 1 values is apparent in Brown Bay samples over the first fortnight. During the second fortnight, values continue to decrease, but not as sharply, subsequent to which values remained relatively constant.

		Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue		0.4935	0.2302	0.1208	0.0368
Species Name and Number					
<i>Achnanthes brevipes</i>	1	<b>-0.6103</b>	0.4317	0.4809	-0.3043
<i>Planothidium</i> spp.	11	0.2133	<b>-0.5244</b>	-0.0569	-0.1033
<i>Amphora libyca</i>	3	-0.2891	0.15	0.3657	-0.3881
<i>Amphora ovalis</i>	2	<b>-0.6794</b>	0.0622	0.3907	0.0265
<i>Cocconeis fasciolata</i>	5	<b>-0.6756</b>	-0.0166	-0.4881	-0.2906
<i>Achnanthes</i> sp. a	6	<b>0.9702</b>	-0.0883	-0.0392	-0.1474
<i>Staurosira</i> cf. <i>construens</i> var. <i>pumila</i>	9	<b>0.6023</b>	-0.4317	<b>0.6263</b>	-0.0154
<i>Staurosira construens</i> var. <i>venter</i>	12	<b>-0.6823</b>	-0.3889	<b>0.5822</b>	-0.0473
<i>Navicula</i> sp. b	4	-0.2648	0.4192	-0.0397	<b>-0.5768</b>
<i>Navicula</i> sp. c	8	<b>-0.7712</b>	0.4028	-0.1873	0.0893
<i>Navicula</i> aff. <i>glaciei</i>	15	0.4465	<b>0.8562</b>	0.1926	0.0107
<i>Navicula perminuta</i>	14	0.3043	<b>0.849</b>	0.185	-0.1044
<i>Navicula</i> sp. a	7	-0.1558	<b>0.7705</b>	0.282	0.3384
<i>Pseudostaurosira brevistriata</i>	13	<b>-0.6869</b>	<b>-0.5578</b>	-0.1635	-0.0159
<i>Synedropsis</i> cf. <i>recta</i>	10	<b>-0.7962</b>	0.2955	-0.2503	-0.2867

Table 6.1 Eigenvalues of, and relative contributions of individual species to, the PCA axes. Significant contributions (>0.50) are shown in bold.

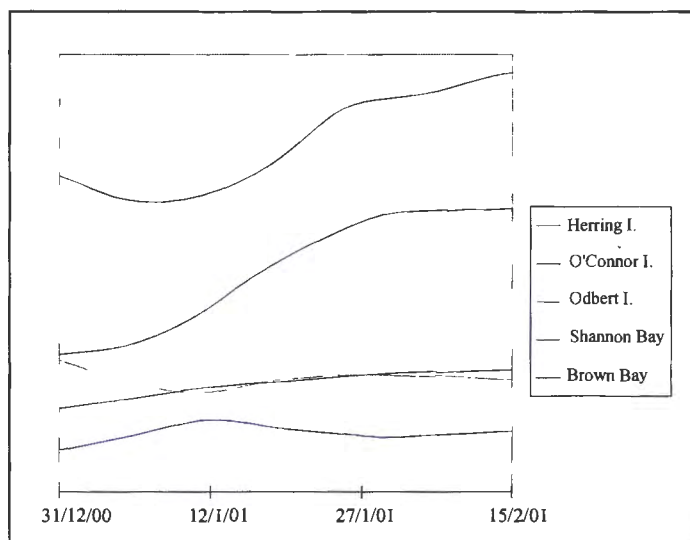
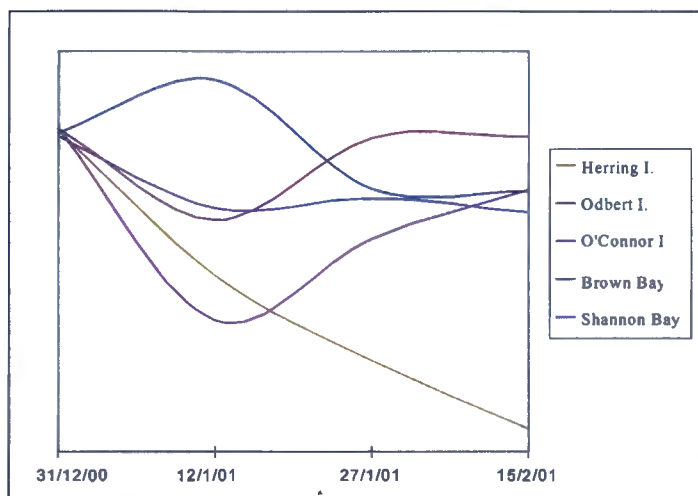


Figure 6.3 PCA Axis 1 values of benthic diatom communities from the Windmill Island, over the 8 week sampling period. The contribution of individual species to this axis is shown in Table 6.1

Axis 2 values show three broad trends within the different locations (Fig. 6.4). Three locations, namely Shannon Bay, Odbert Island and O'Connor Island, all behave in a similar manner. A decrease in values is observed over the first fortnight. During the second fortnight this trend is reversed and values increase to near the original values. Over the third fortnight, values remain relatively constant. The opposite trend was observed in Brown Bay. In this bay values initially increased, however this was followed by a decrease, subsequent to which the Axis 2 values remained relatively constant (Fig. 6.4). Herring Island initially appears to follow the same trend as the other reference sites, as values decreasing over the first fortnight. However, unlike the other reference sites, no apparent reversal occurs, and values continue to decrease over the entire period (Fig. 6.4).

Axis 2 is strongly correlated with *Navicula* aff. *glaciei* (0.856) and *Navicula perminuta* (0.849). In addition, *Navicula* sp. a was moderately correlated with this axis (0.771). Axis 2 was also weakly correlated with *Planothidium* spp. ( $R = -0.524$ )

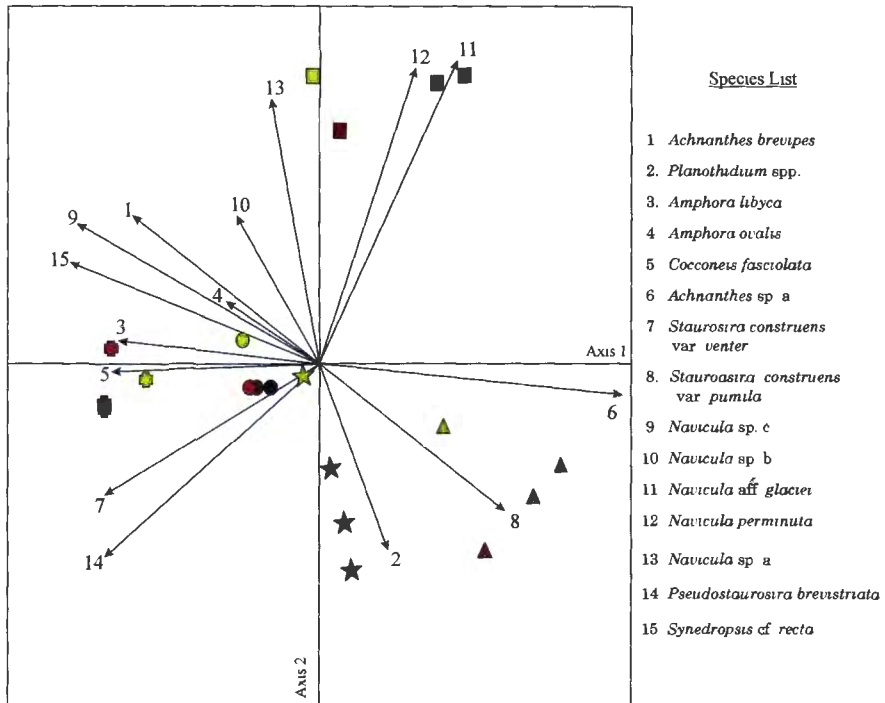


**Figure 6.4** Changes in PCA Axis 2 values of benthic diatom communities from the Windmill Islands during the 8 week sampling period. Contributions of individual species to this axis are shown in Table

6.2

and *Pseudostaurosira brevistriata* ( $R = -0.558$ ). Thus the changes observed at Herring Island correspond to a decrease in the abundances of *Navicula* spp. while *Planothidium* spp. and *Pseudostaurosira brevistriata* increase. At Odbert Island, Shannon Bay and O'Connor Island, a similar trend in the abundances of these species occurs over the first fortnight, however the relative abundances of *Navicula* spp. increase, and that of *Planothidium* spp. and *Pseudostaurosira brevistriata* decrease during the second fortnight.

Within most locations, variations in diatom community composition were most pronounced early in the sampling period. Relatively stable communities were present at the end of the sampling period. Although temporal variations in community composition were observed at all locations, this is most pronounced in the reference locations (Fig. 6.2). As a result of this increased variability, diatom communities from the reference locations became increasingly different to those observed at the potentially impacted locations over the study period.



**Figure 6.5** PCA ordination showing the relationships between samples and abundances of individual species. ★ = Herring Island, ▲ = O'Connor Island, ■ = Odbert Island, ● = Shannon Bay, ✕ = Brown Bay. Symbol colour is indicative of the time of collection: yellow = 31/12/00, red = 12/1/01, brown = 27/1/01, black = 15/2/01. The length of axes 1 and 2 is 1 SD.

Changes in species composition within the reference locations can be seen more clearly in the species-site biplot (Fig. 6.5). As previously mentioned, samples from Herring Island consistently decreased in Axis 2 values over the summer. The contributions of individual species to the ordination axes suggested that this resulted from decreasing abundances of several *Navicula* spp. combined with increasing abundances of *Planothidium* spp., and *Synedropsis* cf. *recta*. Figure 6.5 supports this, indicating that *Navicula* sp. a and *Planothidium* spp. are the species most correlated with the temporal trend observed at Herring Island.

Compositional changes observed at O'Connor Island are slightly more complex. The positions of the first two samples on the species-sample biplot suggest that a decrease

in the relative abundance of *Navicula* sp. a was primarily responsible for the observed differences although an increase in the abundance of *Achnanthes* sp. a is also apparent. Increased abundances of *Achnanthes* sp. a. continue to occur over the remaining sampling periods, however, increases in *Navicula* aff. *glaciei* and *Navicula perminuta* also contribute to the observed differences.

### Short term temporal variability

#### *Pb*<sup>210</sup> analysis

Detailed results of the *Pb*<sup>210</sup> analyses are shown for each of the five cores in Appendix 2. A brief summary of these results is given below. Dates derived from *Pb*<sup>210</sup> data are valid for approximately 150 years, samples older than this typically have background values. In this study, the sedimentation rates derived from sediments less than 150 years old have been applied for the entire length of the cores. The calculated dates will therefore underestimate the age of deeper samples as the compaction of sediments has not been accounted for.

#### Brown Bay Core 1.

The *Pb*<sup>210</sup> data was not clearly interpretable within this core. The sedimentation rate, and mixing depth from Brown Bay Core 2 were therefore applied, as these two cores were only separated by about 10 m. Given that the deepest sample was taken from 82.5 mm, a maximum age of 123.1 years was calculated for this core. The *Pb*<sup>210</sup> profile shows a mixing depth of 13.5 mm, thus the adjusted age of the deepest sample was calculated to be 103 years.

#### Brown Bay Core 2.

The line of best fit was calculated using the 'Constant Initial Concentration' (CIC) model which indicated a sedimentation rate of 0.67 mm y<sup>-1</sup>. The deepest sample in this core was taken from 224.5 mm, with a resulting age of 335 years, before adjustment. The *Pb*<sup>210</sup> profile shows a mixing depth of 13.5 mm, thus the deepest sample was calculated to be 315 years old.



### Shannon Bay.

A sedimentation rate of  $0.40 \text{ mm y}^{-1}$  was indicated by the CIC model. No mixing layer was apparent within this core, thus the ages indicated by the isotope data did not need to be adjusted. The deepest sample from this core was taken from 262.5 mm depth; the age of this sample was calculated to be 650 years old.

### Sparkes Bay Core 1.

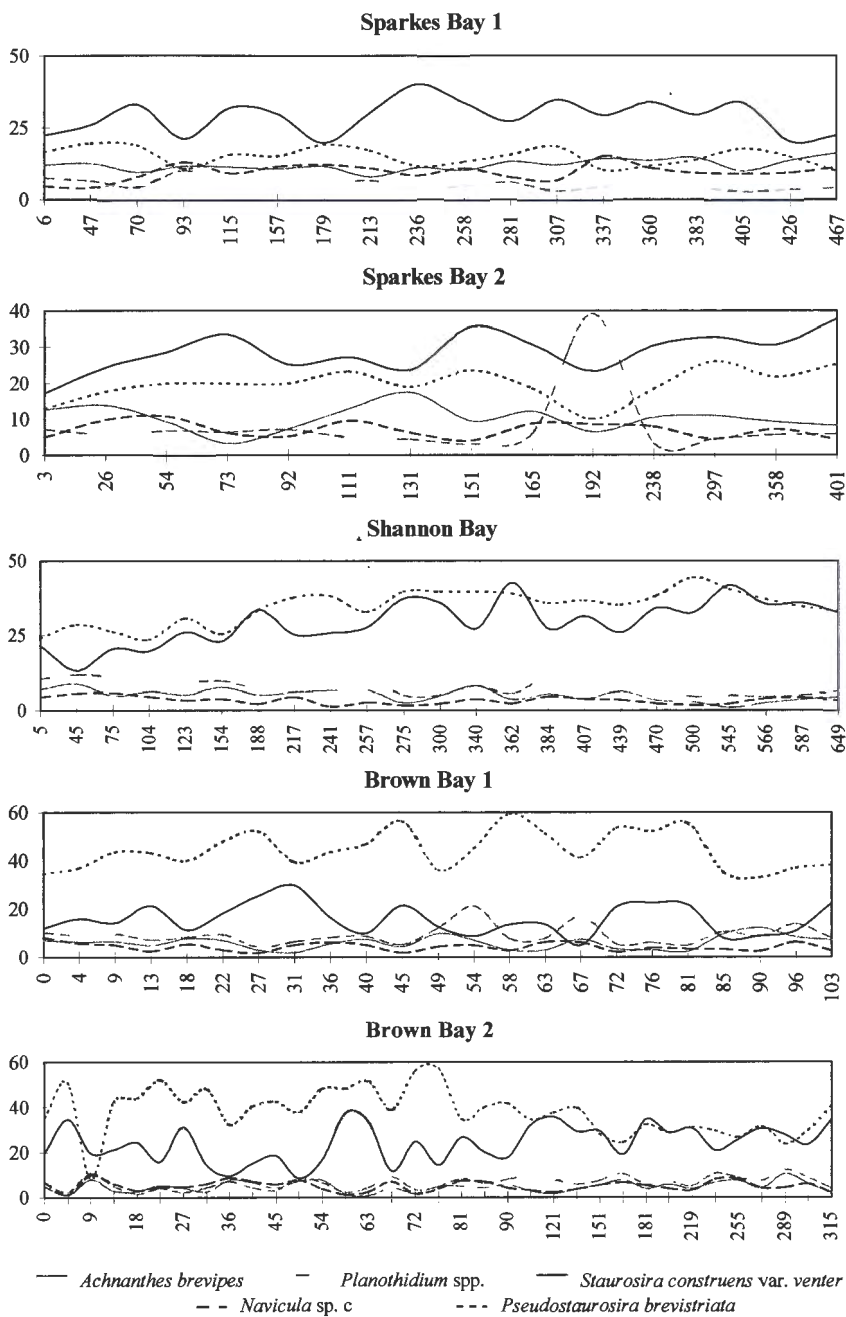
The line of best fit was calculated using the CIC model; this indicated a sedimentation rate of  $0.53 \text{ mm y}^{-1}$ . No mixing layer was apparent in this core, thus sample ages could be calculated directly from the depth of the sample divided by the sedimentation rate. The deepest sediments recovered in this core were from 247.5 mm depth; the age of these sediments was calculated to be 467 years.

### Sparkes Bay Core 2.

The  $\text{Pb}^{210}$  data from this core was not interpretable. The sedimentation rate and mixing layer depth observed in Sparkes Bay Core 1 were therefore applied to this core. The maximum depth from which samples were collected in this core was 264.5 mm. From this, a maximum age of 499 years was calculated.

### *Statistical analyses of diatom communities from core samples*

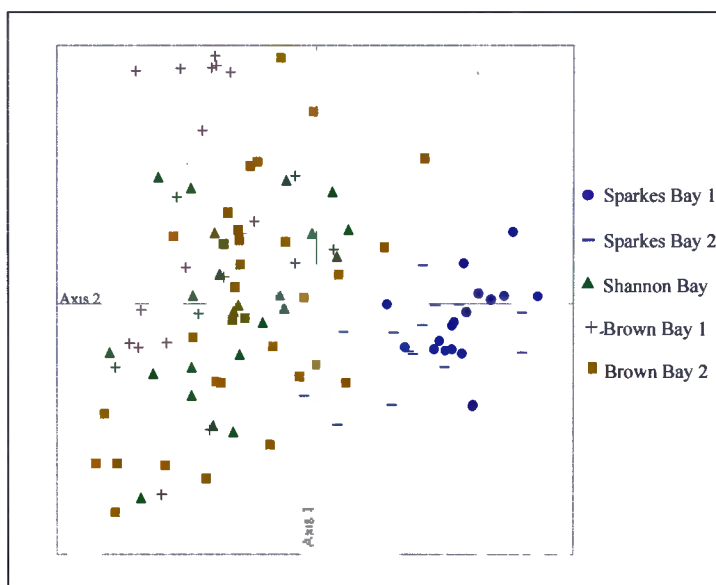
*Staurosira construens* var. *venter* and *Pseudostaurosira brevistriata* were generally the two most abundant species in each sample (Fig. 6.6). There is only one sample in which neither of these was the most abundant species, this occurred in the 192 yr old sample from Sparkes Bay Core 2. *Staurosira construens* var. *venter* was typically the most abundant species in the two Sparkes Bay cores, whilst *Pseudostaurosira brevistriata* was usually the most abundant species in both the Brown Bay cores, and the Shannon Bay core (Fig. 6.6).



**Figure 6.6** Changes in relative abundances of the most common species in short sediment cores from 3 bays in the Windmill Islands. Shannon Bay and Brown Bay are potentially impacted locations

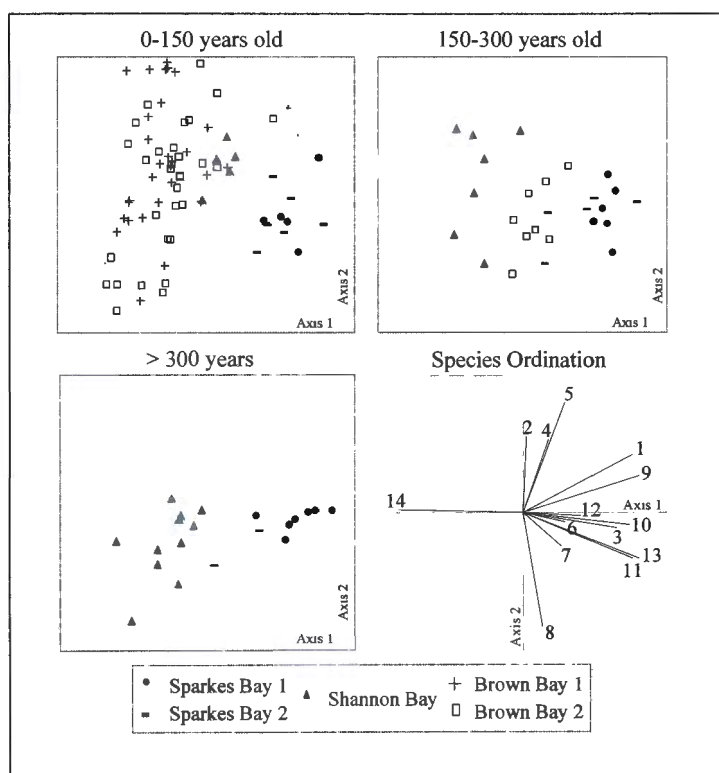
Principal component analysis of diatom communities from the core samples revealed that the first two PCA axes accounted for 49.7% of the variability within the diatom communities. On this ordination, samples tended to cluster with diatom communities from within the same bay (Fig. 6.7). Diatom communities from Sparkes Bay cores all plot towards the right hand side of the ordination, whilst communities from the three cores collected in Newcomb Bay tended to plot on the left hand side of the ordination. Despite this, some overlap was observed between diatom communities from Brown Bay Core 2, and Sparkes Bay Core 2.

In order to determine whether these differences are consistent over time, the diatom communities were divided into three groups: diatom communities less than 150 years old, diatom communities aged between 150 and 300 years old, and diatom communities older than 300 years. PCA ordinations of these three groups indicated that the separation observed between diatom communities from Sparkes Bay and Newcomb Bay has become more pronounced in the last 150 years.



**Figure 6.7** PCA ordination showing the relationship between diatom communities from different locations in the Windmill Islands. Samples from Sparkes Bay tend to plot separately from samples collected from within Newcomb Bay (Shannon Bay and Brown Bay).

The diatom communities sampled from Brown Bay were much more similar to diatom communities from Sparkes Bay (both cores) between 150 and 300 years ago than in the past 150 years. This results predominantly from a decrease in Axis 1 values in the younger diatom communities from Brown Bay, relative to 150-300 year old communities from this bay (Fig. 6.8). Benthic diatom communities from Brown Bay Core 2 and Shannon Bay were less similar 150 - 300 years ago, than in the last 150 years. Once again, the shift in Axis 1 values in diatom communities from Brown Bay appears to be responsible.



**Figure 6.8** PCA ordinations of core samples from different locations in the Windmill Islands, divided into age groups. The top sections of Brown Bay cores were sampled at finer intervals than in the other cores. To reduce potential impacts of the sampling differences, values for these cores were also averaged across the appropriate intervals; these values are indicated in Red.

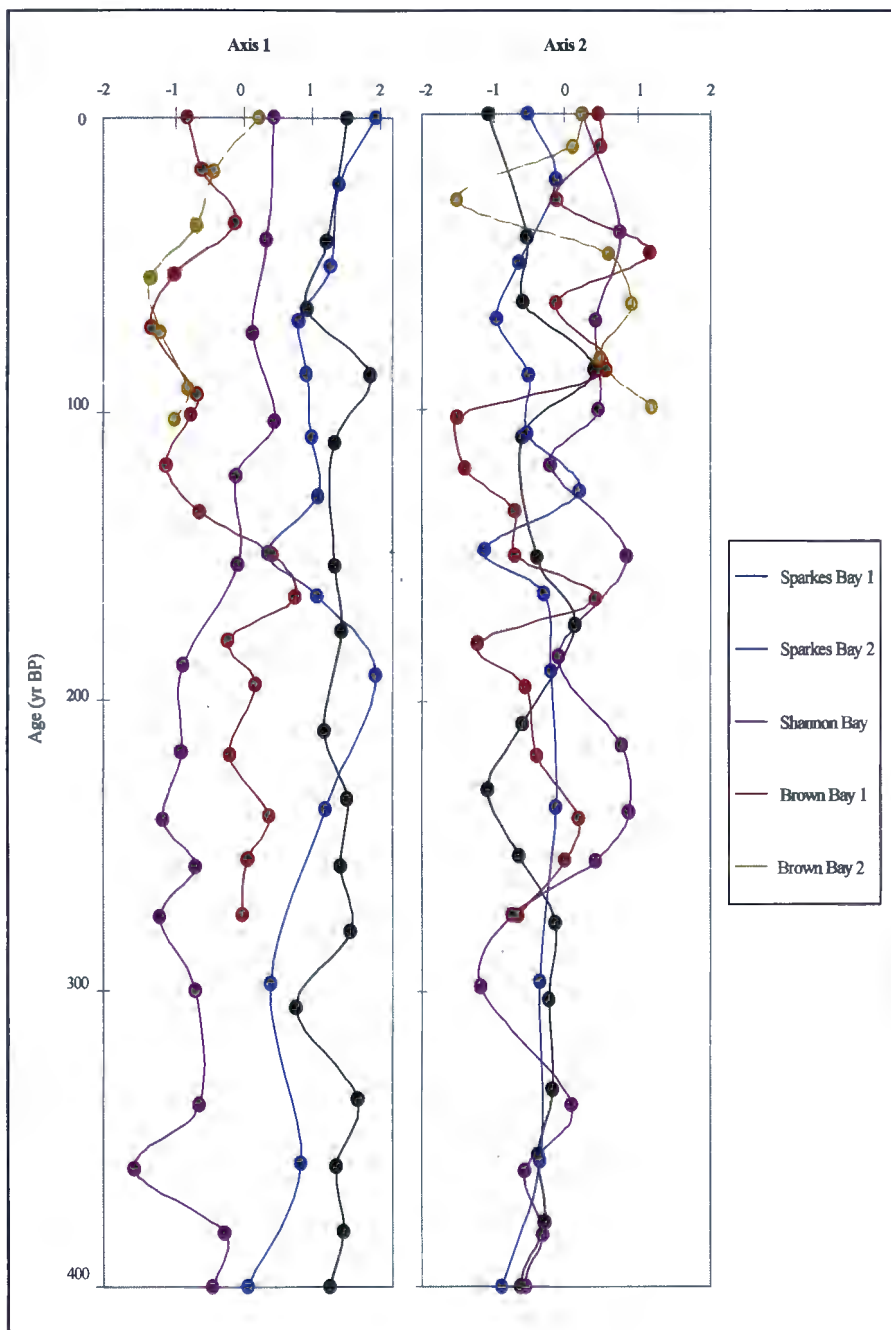
Species names (and numbers) are given in Table 6.2)

Axis 1 is correlated to a number of species (Table 6.2). The strongest correlation observed was a negative correlation between this axis and the abundances of *Pseudostaurosira brevistriata* ( $R = -0.846$ ). Nearly all of the *Navicula* spp and *Achnanthes brevipes* were positively correlated with this axis (Table 6.2). The observed changes in Axis 1 values in diatom communities from Brown Bay are therefore related to changes in the abundances of these species (Fig. 6.8).

The composition of diatom communities from Sparkes Bay Core 1 remains relatively constant between the three time periods examined, although a small increase in variability does occur within the last 200 years (Fig. 6.9). A small shift in Axis 1 values appears to occur in diatom communities from Sparkes Bay Core 2. Increased values are apparent in communities from the last 150 years relative to communities from 300-450 years ago.

		Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue		0.419	0.1750	0.0890	0.680
Species Name and Number					
<i>Achnanthes brevipes</i>	1	<b>0.7653</b>	0.4313	-0.0929	0.0767
<i>Planothidium</i> spp.	10	0.0226	<b>0.5451</b>	<b>0.6583</b>	0.2934
<i>Amphora libyca</i>	3	<b>0.6437</b>	-0.1147	-0.2034	0.3641
<i>Amphora ovalis</i>	2	0.1787	<b>0.5161</b>	<b>-0.5314</b>	0.0503
<i>Cocconeis fasciolata</i>	5	0.2906	<b>0.787</b>	-0.1515	-0.2133
<i>Achnanthes</i> sp. a	6	0.2575	-0.0467	0.3921	-0.4657
<i>Staurosira construens</i> var. <i>pumila</i>	9	0.2581	-0.233	<b>0.529</b>	-0.1945
<i>Staurosira construens</i> var. <i>venter</i>	11	0.1309	<b>-0.8078</b>	-0.2414	0.357
<i>Navicula</i> sp. b	4	<b>0.7246</b>	-0.0845	-0.3041	-0.0654
<i>Navicula</i> sp. c	8	<b>0.7932</b>	0.2652	-0.0488	-0.0386
<i>Navicula</i> aff. <i>glaciei</i>	14	<b>0.7729</b>	-0.3433	0.0967	-0.3531
<i>Navicula perminuta</i>	13	0.4065	-0.0116	0.1564	-0.357
<i>Navicula</i> sp. a	7	<b>0.7983</b>	-0.3417	-0.0182	-0.1086
<i>Pseudostaurosira brevistriata</i>	12	<b>-0.8456</b>	0.0312	-0.2511	-0.3638

Table 6.2 Eigenvalues of, and relative contributions of individual species to, the PCA axes. Significant contributions (>0.5) are shown in bold.



**Figure 6.9** Temporal variability of benthic diatom communities from sediment cores in the Windmill Islands, as evidenced by changing values of PCA ordination axes 1 and 2.

Diatom communities from Sparkes Bay Core 2 which are 150-300 years old cover the full range of values observed. Shannon Bay diatom communities from 150-300 years ago also appear to represent a transition between the communities which occurred prior to 300 years, and those < 150 years. This is indicated by shifts in values of both Axis 1 and Axis 2 (Fig. 6.9). The shift in Axis 1 values occurs approximately 170 years ago, while the shift in Axis 2 values is apparent by 250 years ago.

In Shannon Bay the diatom communities from the past 150 years have higher values for both Axis 1 and Axis 2, than diatom communities from 300-450 years ago (Fig. 6.9). Diatom communities from 150-300 years ago in Shannon Bay have Axis 1 values that are much more variable than that of younger diatom communities; although some values slightly exceed that of younger communities, much lower values were also recorded. Axis 1 values are negatively correlated with *Pseudostaurosira brevistriata* and positively correlated with *Achnanthes brevipes* and several *Navicula* spp. Thus, the recent higher Axis 1 values observed in diatom communities from Shannon Bay indicate decreasing abundances of *Pseudostaurosira brevistriata*, combined with increasing abundances of *Navicula* spp. over time.

*Staurosira construens* var. *venter* has a strong negative correlation with Axis 2 (Table 6.2). A strong positive correlation was observed between this axis and *Cocconeis fasciolata*. Diatom communities in Shannon Bay were observed to have higher Axis 2 values in recent times (<150 years) than in samples from 300-450 years ago, indicating increasing abundances of *Cocconeis fasciolata* and decreasing abundances of *Staurosira construens* var. *venter*. The observed increase in Axis 2 values within Shannon Bay means that these values are more similar to those communities from Sparkes Bay, than had previously occurred.

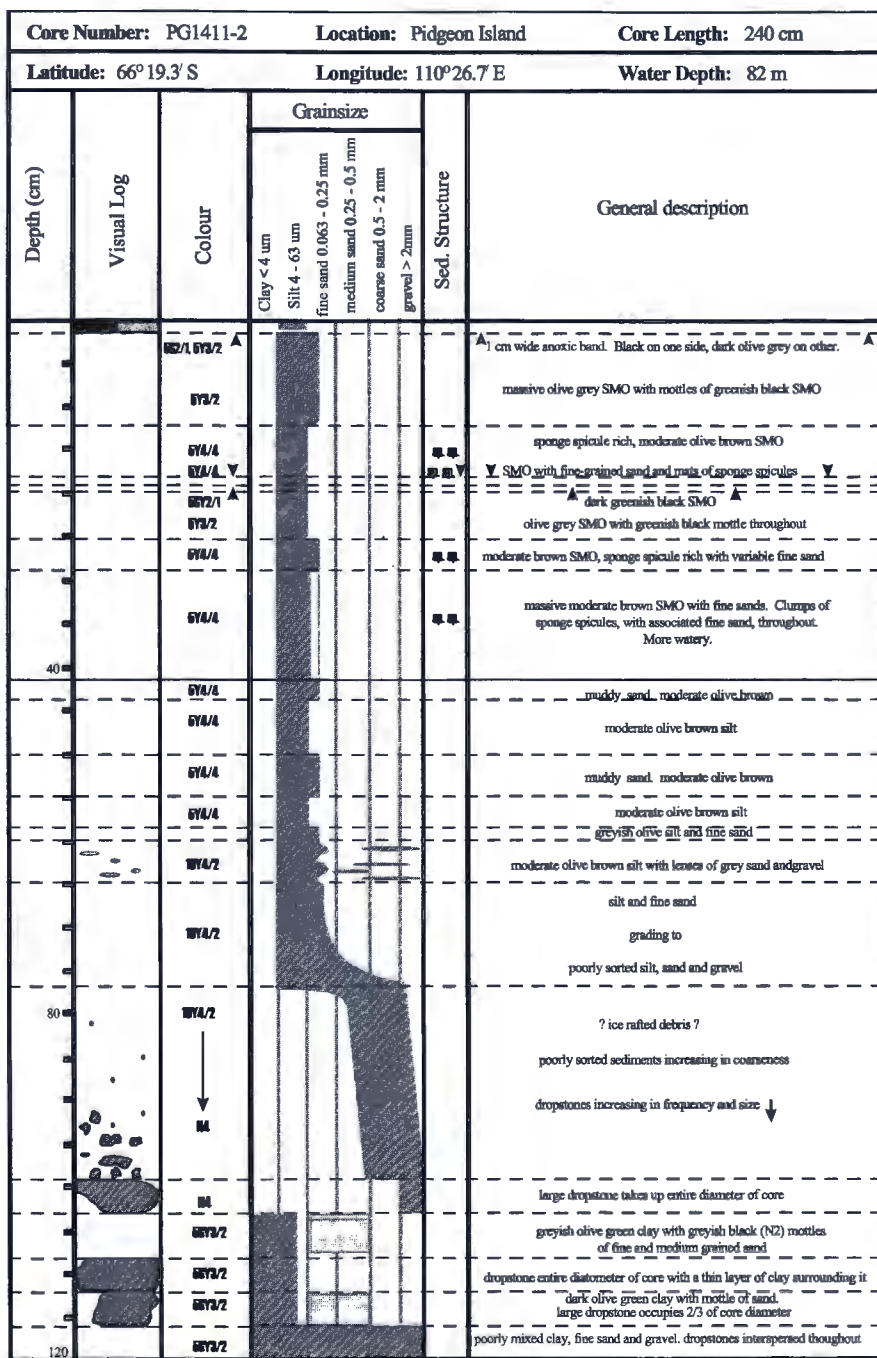


Figure 6.10 (Page 1) Sedimentary log of Core PG1411-2 from Pidgeon Island in the Windmill Islands, Antarctica.



## Long-term Variability

### *Sedimentological core description*

The core predominantly consisted of silts and fine sands to a depth of 60 cm, after which small lenses of coarser sand were present within the silty matrix for a further 5 cm. Between 65 cm and 99 cm, grain-size gradually coarsened and the frequency of dropstones increased (Fig. 6.10). Sediments between 98 cm and 117 cm consisted predominantly of large dropstones, with several occupying the full width of the core tube. From 117 cm to 155 cm the core sediments consisted of poorly mixed gravel, sand and mud with dropstones interspersed throughout (Fig. 6.10). A gradual fining of the sediments was observed over the last 5 cm of this section. A finer-grained layer of sediments, dominantly sands and silts occurred between 155 and 171 cm; fewer dropstones were present within this section. A marked change occurred at a depth of 171 cm with a return to poorly mixed, gravels, sands and mud (Fig. 6.10). The frequency and size of dropstones also increased noticeably at this point. This sediment layer continued for most of the remaining length of the core, however the last 10 cm of the core (ie 230-240 cm depth) consisted almost entirely of 2 large dropstones.

### *Radiocarbon dating*

The corrected radiocarbon dates (Table 6.3) demonstrate that samples within the top 78 cm of the core are Holocene in age. Radiocarbon ( $^{14}\text{C}$ ) dates suggest the presence of a disconformity somewhere between 98 cm and 117 cm. Given the sedimentology of the core (see above), it seems likely that this disconformity occurs at approximately 99 cm, however further dating would be required to verify this. If the disconformity does occur at this depth, then it would indicate an age of  $5888 \pm 50$  corr. yr BP. This is consistent with the de-glaciation of the northern Windmill Islands which occurred between  $5500-6000 \pm 50$  yr BP (Goodwin, 1993). The two sediment samples taken from below this depth in the core had corrected ages of  $33,100 \pm 400$  and  $26,120 \pm 220$  yr BP, and are presumed to represent pre-glacial sediments. The approximate ages of the remaining samples collected from above the proposed disconformity were calculated from the corrected dates (Table 6.3).

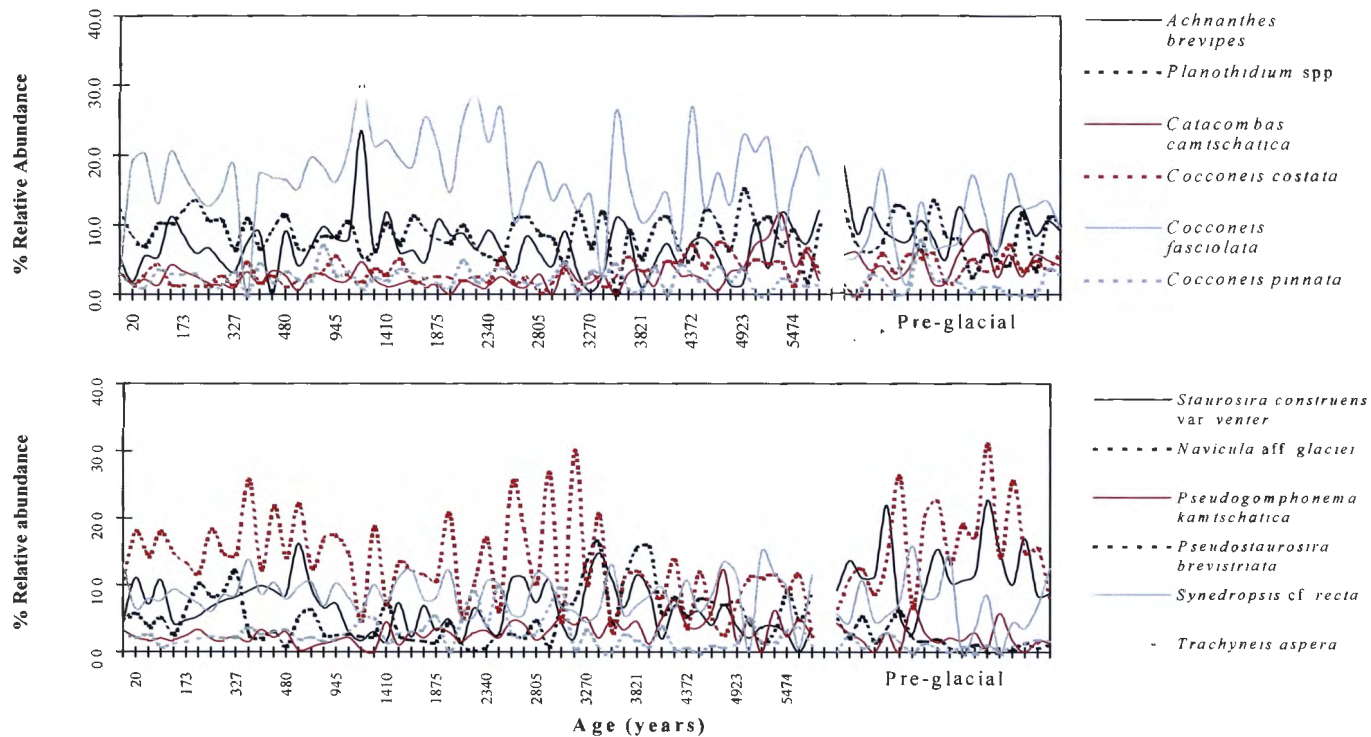


Figure 6.11 Compositional changes within a sediment core from a marine location within the Windmill Island.

All species shown attained a relative abundance >5% in at least 1 sample.

### Statistical analysis of diatom communities

Twelve species had relative abundances greater than 5%, in at least one sample. Changes in the relative abundances of these species are shown in Figure 6.11. Only 4 species had relative abundances greater than 20%; these species were *Achnanthes brevipes*, *Staurosira construens* var. *venter*, *Cocconeis fasciolata* and *Pseudostaurosira brevistriata* (Fig. 6.11). The latter species had the maximum relative abundance, reaching 31.2% during the pre-glacial period.

Although samples were collected every 5 mm over the first 120 mm of the core, and every 10 mm over the subsequent 380 mm, only alternate samples from these sections have been included in this analysis. The depths of these samples is shown in Table 6.3. Core samples were divided into three groups: samples from the top 60 cm of the core; samples from 60 to 100 cm depth in the core; and, samples which were deeper than 100 cm. These groups reflect broad changes in the sedimentology of the core, and correspond to the following age groups: samples less than  $3270 \pm 50$  yr BP; samples between  $3270 \pm 50$  and  $5888 \pm 50$  yr BP; samples which occur below the inferred disconformity, the dates of which are around  $25000 \pm 220$  yr BP and which are presumed to represent pre-glacial sediments.

Principal component analysis indicated that the first two ordination axes accounted for 29.3% of the variability within the diatom communities, whilst the first four ordination axes accounted for 47.7% of this variability. A PCA ordination (Fig. 6.12) indicates that the benthic diatoms present in the pre-glacial sediments (Group 3) plot on the RHS of the ordination. These diatom communities are relatively distinct to the benthic communities which occurred immediately after the deglaciation event (Group 2), which tend to plot on the left hand side of the ordination. The more recent diatom communities (Group 1) are much more variable and overlap both Groups 2 and 3 on the ordination.

A closer examination of the diatom communities from Group 1 reveals that those samples aged between  $1526 \pm 50$  and  $3270 \pm 50$  yr BP all plot on the right hand side of the ordination whilst younger diatom communities typically occur on the left (Fig. 6.12).

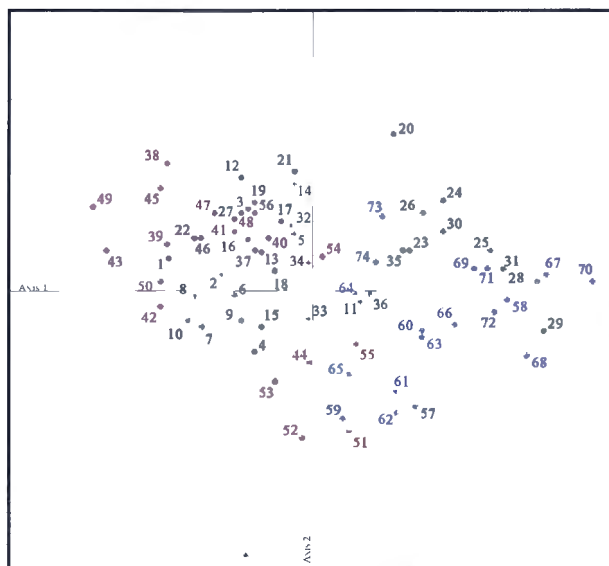


Figure 6.12(a) PCA Ordination of benthic diatom communities from core samples. Symbol colour indicates age: + indicates communities less than 3270 yr BP (Group 1), + indicates communities between 3270 and 5888 yr BP (Group 2), + indicates pre-glacial diatom communities (Group 3).

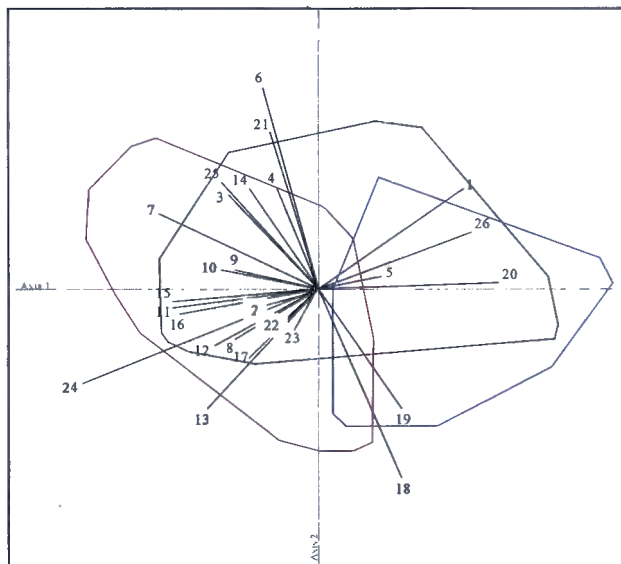


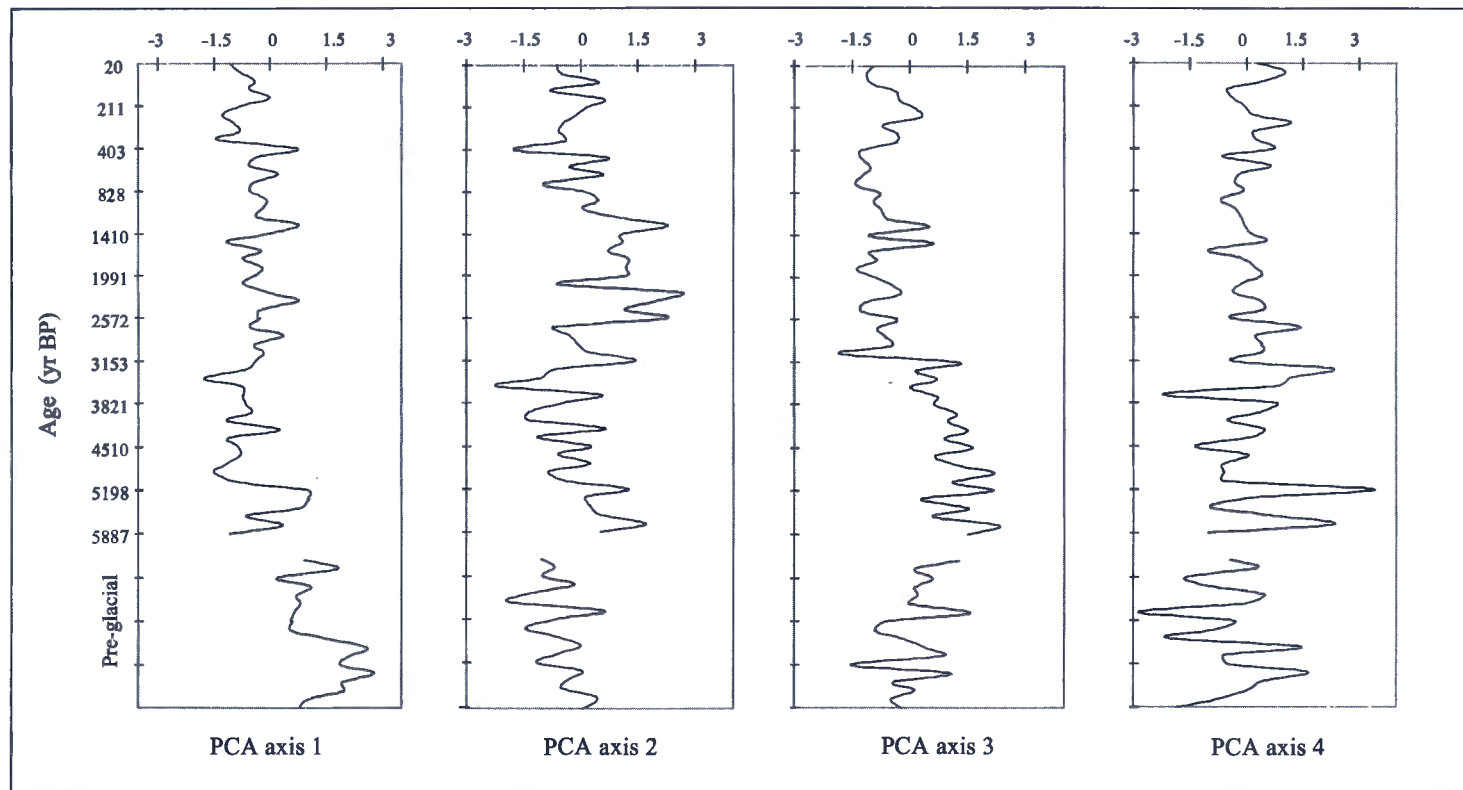
Figure 6.12 (b) Species vectors superimposed over the distributions of diatom communities of varying ages. The black line delineates the area in which benthic diatom communities from samples less than  $3270 \pm 50$  yr BP plot; the red line indicates the extent of diatom communities  $3270-5888 \pm 50$  yr BP; the blue line indicates pre-glacial benthic diatom communities. The length of the species vector indicates the strength of the correlation. Species names and numbers are shown in Table 6.4.

The relationships between species abundances and the different sample groups are shown in Figure 6.12(b). From this ordination it is apparent that the relative abundances of *Catacombas camtschatica*, *Porosira* sp. a and *Achnanthes brevipes* are higher in the pre-glacial diatom communities, than diatom communities from  $3270 \pm 50$  to  $5888 \pm 50$  yr BP. In contrast, the relative abundances of *Navicula* aff. *glaciei*, *Planothidium* spp. and *Staurosira construens* var. *venter* were higher in communities aged between  $3270 \pm 50$  and  $5888 \pm 50$  yr BP.

Table 6.4 shows the relative contribution of individual species to the ordination axes. Axis 1 has a moderate negative correlation ( $R = -0.75$ ) with *Navicula* aff. *glaciei*. Weak correlations were also observed between both *Cocconeis pinnata* ( $R = -0.51$ ) and *Catacombas camtschatica* ( $R = 0.57$ ) and this axis. Axis 2 is moderately correlated with *Cocconeis fasciolata* ( $R = 0.71$ ) and *Staurosira construens* var. *venter* ( $R = -0.67$ ). *Trachyneis aspera* was weakly correlated with this axis ( $R = 0.55$ ). *Pseudostaurosira brevistriata* and *Paralia sulcata* had weak negative correlations with Axis 3 (Table 6.4). Weak negative correlations also occurred between Axis 4 and both *Cocconeis pinnata* and *Synedropsis* cf. *recta*.

Figure 6.13 shows how the values of these axes alter over time. Benthic diatom communities from the pre-glacial sediments have higher values for Axis 1 than any of the later communities. Although the scatter plot of Axes 1 and 2 had indicated higher values relative to the communities which immediately followed the deglaciation, a large amount of overlap had appeared to occur between the more recent communities ( $> 3270 \pm 50$  yr BP) and the pre-glacial communities. Values for Axis 1 are quite variable within diatom communities younger than  $5888 \pm 50$  yr BP. This variability makes detecting trends more difficult, however there are appear to be several episodes of lower values within the post-glacial time-scale. These episodes occurred between:

0 -  $400 \pm 50$  yr BP; 1410 -  $2107 \pm 50$  yr BP; and 3270 -  $5336 \pm 50$  yr BP.



**Figure 6.13** Changes in diatom community composition, as indicated by the PCA ordination axes over time.

		Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue		0.1655	0.1143	0.0868	0.0748
Species Name and Number					
<i>Achnanthes brevipes</i>	1	0.4692	0.3533	0.0967	-0.2517
<i>Planothidium</i> spp.	17	-0.1806	-0.2291	-0.2013	0.1314
<i>Amphora libyca</i>	2	-0.048	-0.0284	-0.0859	0.002
<i>Amphora ovalis</i>	4	-0.1407	0.3595	0.0464	-0.2225
<i>Catacombas camtschatica</i>	20	<b>0.5724</b>	0.0222	0.4687	0.0437
<i>Cocconeis costata</i>	5	0.1894	0.0354	0.3788	-0.1463
<i>Cocconeis fasciolata</i>	6	-0.1843	<b>0.7071</b>	0.0776	0.0042
<i>Cocconeis pinnata</i>	7	<b>-0.5116</b>	0.2604	-0.145	<b>-0.5328</b>
<i>Cocconeis schuettii</i>	22	-0.2361	-0.1058	-0.2062	-0.0465
<i>Achnanthes</i> sp. a	8	-0.2834	-0.1894	-0.2053	0.055
<i>Staurosira construens</i> var. <i>pumila</i>	15	-0.4674	-0.0607	-0.3095	0.2981
<i>Staurosira construens</i> var. <i>venter</i>	18	0.2703	<b>-0.6761</b>	-0.335	-0.173
<i>Gyrosigma</i> sp. a	10	-0.3076	0.06	-0.3327	0.2361
<i>Paralia sulcata</i>	25	-0.3247	0.3817	<b>-0.5358</b>	-0.0909
<i>Navicula</i> sp. b	3	-0.2633	0.3165	0.1194	0.1609
<i>Navicula</i> sp. c	13	-0.365	-0.4249	0.093	-0.0198
<i>Navicula directa</i>	11	-0.4433	-0.0815	-0.1193	-0.0283
<i>Navicula</i> aff. <i>glaciei</i>	24	<b>-0.7524</b>	-0.3245	0.4074	0.1221
<i>Navicula perminuta</i>	23	-0.1308	-0.1752	0.1627	0.0818
<i>Navicula</i> sp. a	12	-0.3437	-0.2007	0.3535	-0.1875
<i>Pleurosigma elongatum</i>	14	-0.2213	0.344	-0.3	0.4436
<i>Porosira</i> sp. a	26	0.476	0.1962	-0.1011	-0.3094
<i>Pseudogomphonema kamtschatica</i>	9	-0.2718	0.0635	0.4682	0.125
<i>Pseudostaurosira brevistriata</i>	19	0.2621	-0.4261	<b>-0.6069</b>	0.38
<i>Synedropsis</i> cf. <i>recta</i>	16	-0.4691	-0.0852	-0.2946	-0.6318
<i>Trachyneis aspera</i>	21	-0.1429	<b>0.5455</b>	-0.3237	0.3409

Table 6.4 Eigenvalues of, and contributions of individual species to, the PCA axes. Significant contributions (>0.50) are shown in bold.

Axis 2 values of the pre-glacial benthic diatom communities are within the lower part of the range observed in post-glacial benthic diatom communities (Fig. 6.13). The diatom communities sampled from immediately after the inferred deglaciation event have higher values than the communities which preceded the glaciation, however the values of the post-glacial diatom communities show a trend towards decreasing values, with the lowest value recorded at  $3546 \pm 50$  yr BP. Values for Axis 2 subsequently increase, with relatively high values maintained until approximately  $829 \pm 50$  yr BP (Fig. 6.13)

At this point in time values decrease, however, values have since remained relatively constant around this lower value. Axis 3 values are quite variable but are generally slightly lower in the diatom communities from the past  $3057 \pm 50$  yr BP than in communities aged between  $3057 \pm 50$  yr BP and  $5888 \pm 50$  yr BP. The pre-glacial benthic diatom communities also exhibit some variability in Axis 3 values, however the values of this group are intermediary between those of Groups 1 and 2. The preglacial diatom communities have a wide range of Axis 4 values. This variability is also seen in the diatom communities immediately subsequent to the de-glaciation event, but is reduced within the more recent diatom communities ( $>3270 \pm 50$  yr BP) (Fig. 6.13).

The above analyses are based on the benthic diatom communities, however the relative proportion of benthic species within the entire diatom assemblage also alters quite dramatically over time (Figure 6.14). In the pre-glacial diatom assemblages, the proportion of benthic species varies between 29 and 70%. The proportion of benthic species within the diatom assemblages is less than 50% during the first 1000 years after the deglaciation event, after which values begin to increase again. Benthic diatom species comprise 35-61% of the diatom assemblages aged between  $3037 \pm 50$  yr BP and  $4800 \pm 50$  yr BP. In contrast, all diatom assemblages younger than 3037 yr consist of greater than 60% benthic species. The maximum relative abundance of benthic species (82%) was recorded  $2340 \pm 50$  yr BP.



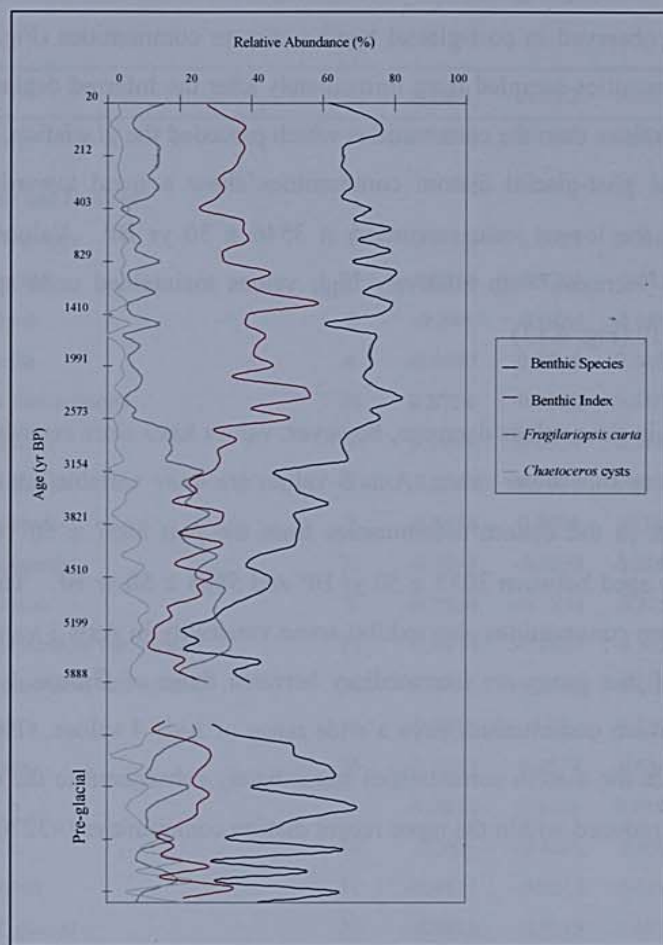
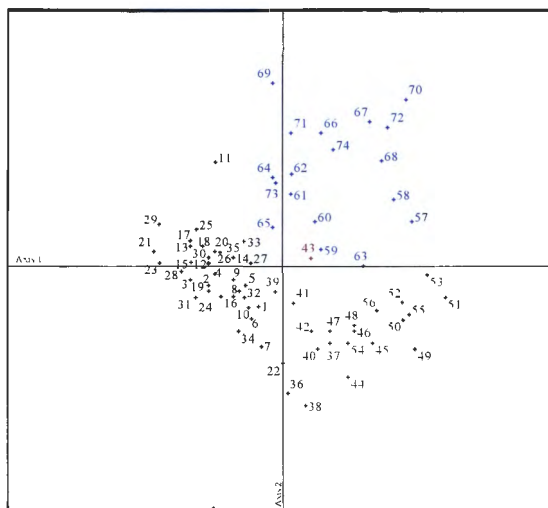


Figure 6.14 Changes in the proportion of benthic species present within the diatom assemblage, in relation to the proportion of exclusively benthic species (the benthic index) and relative abundances of *Fragilariopsis curta* and *Chaetoceros* cysts.

*Fragilariopsis curta* was the most abundant species within the total diatom assemblages, attaining a maximum relative abundance of 34%. *Pseudostaurosira brevistriata* had the second highest relative abundance, attaining a maximum of 20%. When all species (both planktonic and benthic) which attained a relative abundance greater than 2% were included, PCA analyses indicated a greater separation of diatom communities from the three age groups (Figure 6.15) than was observed in the analysis of just benthic species. In addition, Axis 1 had a much higher eigenvalue.



**Figure 6.15** PCA Ordination of entire diatom assemblages showing the differentiation between the three age groups. Symbol colour is indicative of age: • indicates communities less than 3270 yr BP (Group 1), ◐ indicates communities between 3270 and 5888 yr BP (Group 2), ◑ indicates pre-glacial diatom communities (Group 3).

The proportion of benthic species is further reduced when restricted to species which only occur in the benthos. Such species form the Benthic Index (BI) proposed by McMinn (2000) which consists of *Achnanthes* spp., *Amphora* spp., *Cocconeis* spp., *Diploneis* spp., *Hantzschia* spp., *Melosira* spp., *Podosira* spp., *Pseudogonphonema* spp. and *Trachyneis aspera*. The relative abundance of the BI generally mirrors the relative abundances of all benthic species except during the last 1000 years when the BI decreases relative to the abundance of all benthic species (Fig. 6.14).

The most recent diatom assemblages (Group 1) typically plot on the left hand side of this ordination, whilst diatom assemblages from sediments older than 3270 yr (Groups 2 and 3) tend to plot on the right (Fig. 6.15). The diatom assemblages from Group 2 typically plot in the lower half of the ordination; diatom assemblages from Group 3 typically plot in the upper half; Group 1 diatom assemblages tend to group around the middle of the vertical axis (Fig 6.15).

		Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue		0.3141	0.1270	0.0916	0.0474
Species Name and Number					
<i>Achnanthes brevipes</i>	1	-0.4625	0.3371	-0.3684	-0.059
<i>Planothidium</i> spp.	22	<b>-0.6516</b>	-0.0206	0.307	-0.3628
<i>Actinocyclus actinochilus</i>	28	-0.0228	0.3808	-0.1201	0.4713
<i>Biddulphia punctata</i>	3	<b>-0.678</b>	-0.0508	-0.1222	-0.0487
<i>Catacombas camtschatica</i>	25	0.1471	0.312	-0.2176	-0.1787
<i>Chaetoceros</i> cysts	33	<b>0.6804</b>	0.3929	0.1388	-0.3678
<i>Chrysophyte</i> cysts	32	0.0599	0.412	0.2646	<b>0.5384</b>
<i>Cocconeis costata</i>	4	-0.2426	0.2138	-0.1952	0.0868
<i>Cocconeis fasciolata</i>	5	<b>-0.5802</b>	-0.2764	-0.481	0.237
<i>Cocconeis pinnata</i>	6	<b>-0.582</b>	-0.2754	-0.1342	0.2925
<i>Eucampia antarctica</i>	7	<b>-0.5691</b>	0.0662	-0.3394	-0.0708
<i>Staurosira construens</i> var. <i>pumila</i>	18	-0.4301	-0.2462	0.2395	-0.0557
<i>Staurosira construens</i> var. <i>venter</i>	23	-0.4189	0.4485	<b>0.5808</b>	0.246
<i>Fragilariopsis curta</i>	8	<b>0.7829</b>	-0.4339	0.1643	0.0727
<i>Fragilariopsis cylindrus</i>	9	<b>0.7932</b>	-0.2905	-0.0444	0.1008
<i>Fragilariopsis kerguelensis</i>	14	<b>0.5945</b>	0.4412	-0.2679	0.0313
<i>Fragilariopsis obliquecostata</i>	10	<b>0.5999</b>	-0.3426	-0.2687	0.1594
<i>Fragilariopsis rhombica</i>	11	<b>0.556</b>	<b>-0.6297</b>	0.0174	-0.2665
<i>Fragilariopsis ritscheri</i>	13	<b>0.5855</b>	0.2299	-0.0124	0.0593
<i>Fragilariopsis sublinearis</i>	12	<b>0.6489</b>	-0.2303	-0.0862	-0.0013
<i>Gyrosigma</i> cf. <i>hudsonii</i>	16	-0.3827	-0.1779	0.0999	-0.2321
<i>Paralia sulcata</i>	29	<b>-0.7419</b>	-0.0725	-0.2674	-0.091
<i>Navicula</i> sp. b	2	-0.2986	-0.3022	-0.2107	-0.1264
<i>Navicula</i> aff. <i>glaciei</i>	27	-0.1776	<b>-0.6668</b>	0.4521	-0.002
<i>Pleurosigma elongatum</i>	17	<b>-0.5724</b>	-0.1467	-0.1663	-0.2594
<i>Porosira</i> sp. a	30	-0.4003	0.3264	-0.2173	0.0642
<i>Pseudogomphonema kamtschatica</i>	15	-0.0378	-0.4481	0.0707	-0.1482
<i>Pseudostaurosira brevistriata</i>	24	<b>-0.6838</b>	0.3399	0.4345	-0.1429
<i>Synedropsis</i> sp. b	20	-0.0395	-0.322	<b>0.5453</b>	0.2587
<i>Thalassionema gelida</i>	21	-0.2678	-0.0146	0.0722	-0.4006
<i>Synedropsis</i> cf. <i>recta</i>	19	<b>-0.6915</b>	-0.1771	0.1657	-0.0176
<i>Thalassiosira gracilis</i>	31	0.4165	0.4749	-0.1721	-0.0073
<i>Trachyneis aspera</i>	26	<b>-0.6988</b>	-0.1367	-0.3443	-0.239

Table 6.5 Contributions of individual species to, and eigenvalues of, the ordination axes. Significant contributions are shown in bold.

Table 6.5 shows the relative contribution of individual species to the ordination axis. Axis 1 is correlated with a number of species. *Fragilariopsis curta* and *Fragilariopsis cylindrus* have a strong positive correlation with this axis; *Paralia sulcata* has a strong negative correlation with Axis 1 (Table 6.5). Given the distribution of samples in the ordination diagram (Fig 6.15), it can be inferred that diatom assemblages older than 3270 have higher relative abundances of *F. curta* and *F. cylindrus* but lower abundances of *Paralia sulcata* than the more recent diatom assemblages.

Axis 2 was weakly correlated with several species, the strongest of these correlations were with *Fragilariopsis rhombica* ( $R = -0.63$ ) and *Navicula* aff. *glaciei* ( $R = -0.67$ ). Based on the ordination results, it can be concluded that diatom assemblages from Group 2 had higher relative abundances of these species than the diatom assemblages which pre-dated the glaciation (Group 3).

## Discussion

### Seasonal Variability

PCA analyses demonstrated that significant changes in composition occurred in benthic diatom communities over the 2000/01 summer season. The changes in community composition observed within Shannon Bay and the control locations were generally similar. In contrast, opposing trends were typically observed between Brown Bay and the other locations. These changes in composition were expressed as different values of both ordination Axes 1 and 2.

The relative abundances of *Navicula* species, including *N. aff. glaciei*, *N. sp. a* and *N. perminuta*, contributed significantly to observed variations in both Axes 1 and 2 values. *Navicula* aff. *glaciei* is associated both with benthic and sea-ice communities. *Navicula perminuta* is generally associated with fresh to brackish water (Cremer et al., 2001). These three species all had a positive relationship with Axis 2; with the highest values generally recorded at the start of the season.

The melting of sea-ice over Antarctic summers can lead to the stratification of the water column (Cremer et al., 2001) and thus higher salinity values within the bottom waters. It is possible that stratification of the water column early in the summer may lead to a decrease in the relative abundance of these species, but once the sea-ice has disappeared, the stratified layers become mixed by winds or storms thus allowing the abundances of these species to increase once more. Over the summer period, Axis 2 values from Brown Bay followed an opposing trend to that typically observed at other locations. In the Windmill Islands, water currents are dominantly wind-driven (Cathers et al., 1998), with winds typically blowing from the east. Brown Bay is the only study site which is not protected on the eastern side and would therefore have been subject to increased mixing of the water column. This would explain the initial increase in Axis 2 values within Brown Bay. It is possible that a larger amount of freshwater input, ie from the Thala Valley melt stream may have resulted in the stratification of the water column later in the season, explaining the observed decrease in Axis 2 values.

Axis 2 values typically start high, decline over the first sampling period, before increasing to near start levels and remaining relatively constant around this point. This may also reflect the amount of light which reaches the benthos. Light values would have been reasonably high subsequent to the melting/break out of sea-ice, reduced during the phytoplankton bloom (early January), prior to increasing once more after the phytoplankton bloom had finished. Gilbert (1991b) demonstrated that the productivity of benthic communities was related to this pattern of light availability with initially high productivity values decreasing during the phytoplankton bloom, before increasing once more. For this explanation to apply to the compositional changes observed in this study, the species contributing to Axis 2 must have relatively high requirements for light. Furthermore, although this explanation would account for the trend observed in Shannon Bay and the control bays, it does not address the opposing trend which occurred in benthic diatom communities from Brown Bay.

### Short-term variability.

Over the past five hundred years, the composition of benthic diatom communities from Sparkes Bay has remained relatively constant. In contrast, the composition of diatom communities from both Brown Bay and Shannon Bay have altered significantly during this time. Large changes in community composition were even observed over the last 100 years in diatom communities from Brown Bay Core 1.

Compositional differences observed between modern diatom communities from Sparkes Bay and either Brown Bay and Shannon Bay, have not always been so pronounced. Between 150 and 300 yr BP, the diatom communities from Brown Bay Core 2, were relatively similar to the communities of Sparkes Bay Core 2, indicated by the overlapping of these samples on the ordination plot. Similarly, diatom communities from Shannon Bay and Sparkes Bay Core 2 were more similar 300-450 yr BP than they are today. The increased differentiation between sites is due to compositional changes occurring over time to diatom communities within Brown and Shannon Bay, whilst the composition of benthic diatom communities from Sparkes Bay remained relatively static. The changes in diatom communities from Newcomb Bay are generally apparent 150 yr BP, and thus pre-date human occupation of the Windmill Islands. One exception to this is the shift in Axis 2 values observed within Brown Bay Core 2 which is most pronounced over the past 60 years. However even this pre-dates human occupation, as the first permanent research station in the Windmill Islands wasn't established until 1959.

The observed changes in the composition of benthic diatom communities from Newcomb Bay are primarily due to changes in the relative abundances of *Pseudostaurosira brevistriata*, *Staurosira construens* var. *venter*, *Cocconeis fasciolata* and several *Navicula* spp. Axis 1 is negatively correlated to *Pseudostaurosira brevistriata* but positively correlated to several *Navicula* spp. *Pseudostaurosira brevistriata* is typically found within eutrophic environments (Lowe, 1974), which would occur in the bottom layers of a stratified water column. Relative abundances of this species would therefore increase with stratification processes. The inverse relationship observed between *Pseudostaurosira brevistriata*

and *Navicula* spp within this data set therefore supports the earlier suggestion that relative abundances of *Navicula* spp. may be negatively affected by stratification of the water column.

Axis 2 is positively correlated with *Cocconeis fasciolata*, and negatively correlated with *Staurosira construens* var. *venter*. Both these species are generally found within benthic marine environments, however *Cocconeis fasciolata* is typically epiphytic (Everitt and Thomas, 1986) whilst *Staurosira construens* var. *venter* is periphytic (Lowe, 1974). It is therefore possible that Axis 2 values may correspond to a transition between periphytic and epiphytic communities. *Cocconeis fasciolata* could be present in higher abundances when macroalgae was present as a substrate; relative abundances of *Staurosira construens* var. *venter* would probably be reduced when macroalgae was present, as this would result in increased shading of the sediments, and thus lower light availability.

### Long-term variability of diatom communities

The composition of benthic diatom communities was shown to vary considerably over long-term times frames. The compositional differences were apparent as changes in values of PCA ordination axes, particularly PCA Axis 2. *Cocconeis fasciolata* had a strong positive relationship with Axis 2, whilst *Staurosira construens* var. *venter* had a negative correlation with this axis. As discussed above, *Cocconeis fasciolata* often grows as an epiphyte, whilst *Staurosira construens* var. *venter* is only found on sediments. The observed relationship between these two species suggests that Axis 2 may correspond to a transition between these two community types. High Axis 2 values may potentially indicate warmer conditions which favourable for the growth of macroalgae, and thus the epiphytic *Cocconeis fasciolata*.

Both the benthic index and the total proportion of benthic species in the assemblage varied significantly over time. The benthic index would be a more sensitive indicator of climatic changes than the proportion of all benthic species. Many of the latter are



also found in sea-ice communities, and could therefore be grow in the sea-ice during cold conditions but in the benthos during warm conditions. This may explain why the total proportion of benthic species remains high throughout the last 1000 years while the benthic index decreased 900 years ago, by about 10%, before recovering approximately 400 years ago.

High benthic index values indicate long periods of open water in summer, and less extensive sea-ice cover (McMinn, 2000). The benthic index therefore indicates short, cold summers for approximately 3000 years immediately subsequent to the deglaciation of the area. Between  $2800 \pm 50$  yr BP and  $2500 \pm 50$  yr BP temperatures generally increased with longer summers indicated by increasing benthic index values, although several small reversals are apparent on the graph. Long summers with less extensive sea-ice persisted from  $2500 \pm 50$  yr BP until ca.  $900 \pm 50$  yr BP. At this time, the summers gradually shortened and continue to do so until 400 years ago. This trend was then reversed, and open waters occurred for a longer time once again.

The benthic index indicated a warm period, which although it began ca.  $2800 \pm 50$  yr BP was most pronounced from  $2500 \pm 50$  yr BP, and that extended until  $900 \pm 50$  yr BP. This corresponds to previous estimates of when the Holocene optima occurred within the Windmill Islands. Goodwin (1993) found suggested that a Late Holocene warm period occurred between 2000 yr BP and 1000 yr BP. Cremer et al. (in prep) suggested that the warm period occurred for much longer, between 4000 and 1000 yr BP. This conflicts with the results of this study indicated cooler, shorter summers occurred until 2800 yr BP. These findings are supported by the re-advancement of the Law Dome ice margin between 4000 and 2500 yr BP (Goodwin, 1996).

The locations from which cores were collected may explain the different dates proposed for the Holocene optima. Cremer et al. (in prep) examined cores from the southern areas of the Windmill Islands, which probably reflect the influence of both the Vanderford Glacier, and Law Dome. The core examined in this study was



collected from the northern Windmill Islands, as defined by Goodwin (1993). Climate-related changes, such as deglaciation can be separated by several thousand years between the northern and southern areas of the Windmill Islands (Goodwin, 1993). Similar warm periods have previously been dated between 3000 and 1500 yr BP for the Vestfold Hills (Adamson and Pickard, 1986), 4700 and 2000 yr BP in the Bunger Hills (Melles et al., 1997) while Signy Island had a warm period between 3300 and 1200 yr BP (Jones et al., 1999).

*Fragilariopsis curta* has often been used as an indicator of climatic conditions within Antarctic regions. In open oceans, this species has been used as an indicator of past-sea-ice extent (Gersonde and Zielinski, 2000), however, in near-shore regions this species is indicative of open waters (Cremer et al., in prep), specifically, lenses of ice melt with reduced salinity (McMinn, 2000). If this species is indicative of periods of open water, then relative abundances should be positively correlated with the benthic index. Within this study, the reverse appears to be true.

High abundances of *Fragilariopsis curta* are recorded between  $3800 \pm 50$  yr BP and  $5800 \pm 50$  yr BP; values of the benthic index are very low during this time. Pidgeon Island is relatively exposed and is probably subject to oceanic currents. It is therefore unlikely that stratified waters would develop in this area during summer melt periods, thus lenses of less saline waters would not occur. At this site, relative abundances of *Fragilariopsis curta* are therefore more likely to reflect sea-ice conditions than melt conditions. This would explain the opposing behaviour observed between *Fragilariopsis curta* and the benthic index.

The ordination which included non-planktonic species had a stronger relationship with the diatom data than the benthic ordination. Differences in community composition between Groups 1 and 2 are also more apparent in the ordination of all species, rather than just benthic species. The observed change in community composition between Groups 1 and 2 occurs approximately 3270 yr BP, with a decrease in Axis 1 values potentially indicating warmer summers. A previous study

of diatom assemblages in the Windmill Islands found a major shift from a *Chaetoceros* dominated assemblage to a *Fragilariopsis* dominated assemblage was probably related to a transition from cold to warm summers (Cremer et al., 2001). This transition was dated at around 3700 yr BP, thus it seems likely that the changes observed within the Pidgeon Island core at 3270 may reflect the same environmental trend.

### Conclusion

Temporal variability was observed over each of the three scales examined. Changes in community composition were not consistent between locations, either within a season or over hundreds of years. Several *Navicula* species, including *N. sp. a*, *N. aff. glaciei*, *N. perminuta* and *N. sp. b*, contributed significantly to the variation observed within a season, and over the hundreds of years. In addition, *Navicula aff. glaciei* was predominantly responsible for the temporal variation observed in Axis 1 values over thousands of years. The abundances of these species may be related to climatic conditions. *Staurosira construens* var. *venter* and *Cocconeis fasciolata* were significant in explaining the variability of diatom community composition over hundreds of years, and over thousands of years. It is possible that high abundances of *Cocconeis fasciolata* represents conditions favourable for macroalgal growth.

### ***Is there historical evidence of human impacts on benthic diatom communities within Brown Bay?***

#### **Abstract**

Sediments of Brown Bay, near the Australian Antarctic Casey Station, have increased concentrations of petroleum hydrocarbons and several metals, including Cu, Pb, Cd and Zn, relative to reference locations. This contamination primarily results from the previous operation of a waste disposal site in Thala Valley, immediately adjacent to Brown Bay. Three sediment cores collected from Brown Bay were used to evaluate the impact of this contamination on the benthic diatom communities in relation to the naturally occurring spatial and temporal variability. Significant changes in community composition were observed contemporaneously with the operation of the waste disposal site within one contaminated core, but not within the two uncontaminated cores. Univariate analyses demonstrated that associated changes in the relative abundance of several *Navicula* species exceeded the variability observed prior to the onset of contamination, or within the two uncontaminated cores. It was therefore concluded that these compositional changes are a response to metal contamination.

#### **Introduction**

‘Before’ and ‘after’ comparisons are one method of detecting changes in biological communities which occur as a result of chemical contamination. This requires that the abundances of populations are measured before a potential impact occurs. By comparing the species composition and abundance after a potential impact event with those that occurred before the event, any changes which result from that event can be identified. If variations occurred within a population before an impact event, then impacts can be detected only if the variations resulting from the impact are greater than those observed before the stress occurred (Underwood, 1989).

In addition to providing information about current environmental conditions, the high preservation potential of diatoms means that they can be extracted from sediment cores to provide information about past environmental conditions (Dixit et al., 1992). This makes it possible to determine the naturally occurring conditions of an ecosystem, against which anthropogenic changes can be measured (Smol, 1992). Thus diatom communities can be used for before and after comparisons, even when all sampling is undertaken post-impact.

Chemical evidence (Stark et al., in press; Scouller et al., 2000) demonstrates that Brown Bay, adjacent to Casey Station in the Windmill Islands, has been contaminated with both metals and petroleum hydrocarbons as a result of the operation of the Old Casey Station and the associated waste disposal site. No information is currently available regarding the diatom communities which existed within Brown Bay prior to the establishment of this station. The aim of this study was to collect such information using sediment cores, and to examine temporal changes within these cores to determine whether any biological impact had occurred as a result of the contamination of marine sediments within Brown Bay. It was hypothesised that changes in composition or structure of the diatom communities within the cores would occur as a result of the contamination of Brown Bay, and that these changes would be greater than any temporal variations observed within the diatom communities prior to this impact.

It has previously been demonstrated (Chapters 3, 4 and 5) that the composition of diatom communities within Brown Bay is significantly different to that of diatom communities elsewhere in the Windmill Islands. Furthermore, the observed differences in diatom communities between Brown Bay and other locations have occurred for over 100 years (Chapter 6), although the magnitude of these differences has varied within this time. Consequently, diatom communities from locations outside of Brown Bay would not adequately reflect the natural variability that might be expected to occur within Brown Bay.

### Site Description

Casey Station is located at 66° 17' S, 110° 32' E and is situated on the Bailey Peninsula in the Windmill Islands (Fig. 7.1). The current Casey Station was opened in 1989 and was built to replace the previous research station, now known as "Old Casey". Old Casey was located approximately 800 m north-east of the current station at a lower elevation on the Bailey peninsula (Inset 2, Fig. 7.1).

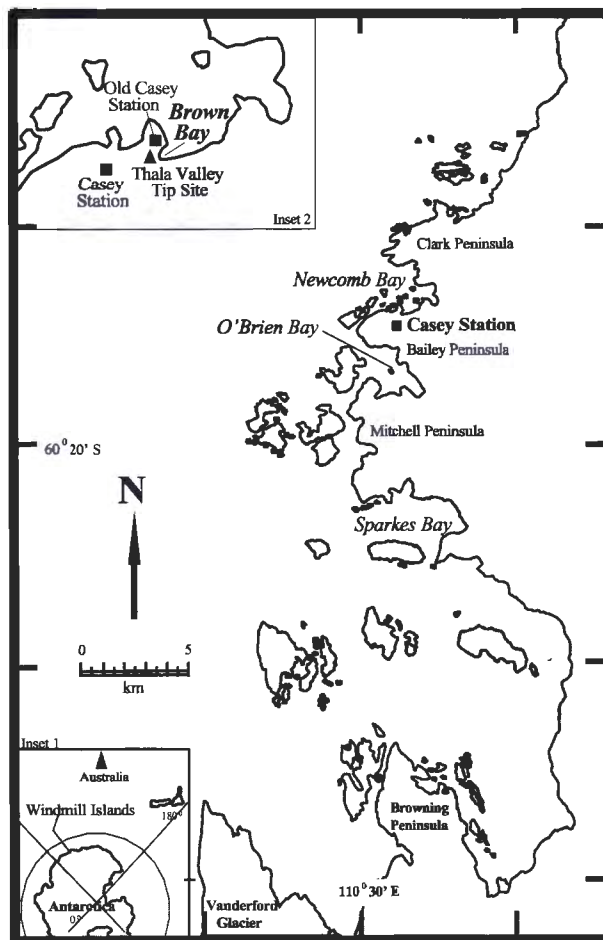
From its establishment in 1969 until a change of policy in 1986, all refuse generated by Old Casey station was dumped into the nearby Thala Valley (Deprez et al., 1999) and occasionally bulldozed onto the sea-ice in Brown Bay. The material disposed of in this manner consisted of refuse from the various mechanical workshops including engine parts, batteries, and old fuels drums, as well as domestically produced waste (Snape et al., 2001). Despite the removal of much of this waste during the 1995/96 summer season, it is estimated that up to 2500 m<sup>3</sup> of rubbish still remains (Snape et al., 1998).

In summer, a melt-stream flows through the Thala disposal site where water dissolves and entrains contaminants before entering the adjacent Brown Bay. An estimated eight cubic meters of contaminated material associated with the tip was removed by surface runoff and deposited into Brown Bay during the 1998/99 summer period (Cole et al., 2000). In addition, hydrocarbon contaminants from soils surrounding the Old Casey mechanical workshops are carried into Brown Bay by surface and sub-surface water movement (Snape et al., 2001).

Recent studies have demonstrated higher concentrations of some heavy metals and hydrocarbon in sediments collected from Brown Bay as compared to control locations (Snape et al., 2001; Scouller et al., 2000). Concentrations of some metals such as Cu, Pb, Fe, and Zn are 10 to 100 times higher than background levels (Scouller et al., 2001). Petroleum hydrocarbons, derived from lubrication oil and Special Antarctic Blend diesel fuel (SAB), are present in the surface sediments of Brown Bay at concentrations ranging between 40 and 200 mg.kg<sup>-1</sup> locations (Snape et

al., 2001). In contrast, petroleum hydrocarbons have not been detected in sediments from control locations (Snape et al., 2001).

Brown Bay is a small embayment at the southern end of Newcomb Bay, immediately adjacent to the Thala Valley tip site (Inset 2, Fig. 7.1). Aligned approximately east-west, the maximum depth of 20 m occurs at the eastern end where Brown Bay enters Newcomb Bay. Brown Bay has rocky sides which grade to a relatively homogenous



**Figure 7.1** Map of the Windmill Islands showing their location within Antarctica (Inset 1) and the station sites in relation to the study location (Inset 2).

muddy bottom (Stark, 2000), however, close to the tip site discarded material protrudes through the sediment.

### Methods

Three sediment cores were collected from the polluted Brown Bay. The cores were collected by divers inserting plastic tubes (5 mm diameter) into the sediments. These cores were frozen, intact, for return to Australia. In preparation for analysis, these cores were sliced horizontally into sections, typically 3 mm thick, and then dried. Selected sections were subsampled for one or more of the following analyses: metal concentrations,  $\text{Pb}^{210}$ , and diatom analyses. Details of which analyses were performed on individual samples are shown in Appendix 3. Preparation and sub-sampling of the core sections was undertaken by Beck Scouller of the AAD.

### Pb Analysis

The  $\text{Pb}^{210}$  samples were prepared by Rebecca Scouller of the AAD. Polonium samples were prepared according to the procedures outlined in the ANSTO instruction manual VRC-1-9-03-020; radium analyses were prepared as outlined in instruction manual VRC-1-9-03-025. Analyses were performed by a technician at ANSTO, using alpha spectrometry. The brief interpretation of the results given in this paper represent the combined work of the author and Rebecca Scouller (AAD).

The depth of the mixing layer influences the apparent age of sediments. Marine sediments typically have mixing layers 5-30 cm deep, as a result of bioturbation and physical mixing processes (McMinn et al., in press). The depth of the mixing layer influences the precision of dating techniques. In order to adjust for mixing layers of varying thickness within the core samples, the mixing model described in McMinn et al. (in press) was applied to the  $\text{Pb}^{210}$  derived ages. The age of sediments at the base of the mixing layer is determined, and this age is then subtracted from all  $\text{Pb}^{210}$  derived dates below this point. This procedure constrains the maximum age of introduction of sediments; the results produced are referred to as the "adjusted age".

## Metal Analysis

Microwave assisted acid digestion was used to prepare the sediment samples for analysis. The procedures outlined in the instruction manual VEC-1-9-01-017 (ANSTO Environmental Chemistry Analytical Laboratories) were followed for this process. All sample preparation was performed by Rebecca Scouller (AAD). Samples were then analysed by a technician from ANSTO, using either ICPMS or ICPAES. Sediment samples were analysed for Sb, As, Cd, Cu, Cr, Fe, Pb, Mn, Hg, Ni, Ag, Sn and Zn.

## Diatom preparation and identification

Organic material was removed by digestion in a 10% hydrogen peroxide solution for 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Identification was as outlined in Appendix 1, with the exception of *Cocconeis costata* and *Cocconeis fasciolata* which have been treated as one taxa in this chapter. A minimum of 400 individuals of the predominantly benthic taxa were counted per samples. The relative abundances of these taxa were then calculated and used in the statistical analyses.

## Statistical Analyses

Multivariate analyses of community composition were undertaken using non-metric multidimensional scaling (nMDS) and analysis of similarity (ANOSIM) procedures



using the PRIMER software package (Plymouth Marine Laboratories, UK). One way ANOSIMs were used to compare differences in the composition of diatom communities from the four locations. No data transformations were used in these analyses.

Similarity percentages analyses (SIMPER) were used to determine which species were responsible for compositional differences observed between diatom communities. Clarke and Warwick (1994) state that species which have a SIMPER ratio greater than 1.3 are likely to be useful for discriminating between groups. In order to determine which species were most useful the following method was used to rank species. Only species which had a SIMPER ratio above 1.3 in at least one comparison were considered. For each species, comparisons in which the ratio did not exceed 1.3 were excluded. The sum of the remaining ratios was then determined, and divided by the total number of comparisons possible. The ten species which had the highest ratio were then used in further analyses.

Natural logarithms were used to calculate Shannon-Wiener diversity ( $H'$ ) values, Simpsons' dominance index (SI), Margalef's species richness ( $d$ ) values, and Pielou's evenness ( $J'$ ) values. Collectively, these values will be referred to as the structural parameters of the diatom communities.

Single factor analyses of variance (ANOVAs) were employed to compare structural parameters, and indicator species between samples. Cochran's C test was used to check the assumption of homogeneity of variances before performing ANOVAs. Any data transformations that were necessary to fulfil this assumption are noted in the accompanying tables. Where ANOVAs indicated significant differences between samples, SNK tests were used for multiple comparisons using GMAV5 (Institute of Marine Ecology, University of Sydney, Australia). Unless otherwise stated, a significance level of  $p = 0.05$  was applied to all analyses.

## Results

### Pb dating

The Pb 210 profiles for Cores 1, 2 and 3 are given in Appendix 3.

#### Core 1

The line of best fit was calculated using the CIC model, and indicated a sedimentation rate of  $0.67 \text{ mm y}^{-1}$ . The deepest sample in this core was taken from 224.5 mm, with a resulting age of 335 years, before adjustment. The Pb<sup>210</sup> profile shows a mixing depth of 13.5 mm. Adjusted ages of samples from this core are given in Table 7.1.

#### Core 2

The Pb<sup>210</sup> data was not clearly interpretable within this core. The sedimentation rate, and mixing depth from core 1 were therefore applied, as these two cores were only separated by about 10 m. Given that the deepest sample was taken from 82.5 mm, a maximum age of 123.1 years was calculated for this core. The Pb<sup>210</sup> profile shows a mixing depth of 13.5 mm. Adjusted ages for samples were calculated according to the method described earlier, and are shown in Table 7.1.

#### Core 3

The CIC model indicated a sedimentation rate of  $0.71 \text{ mm y}^{-1}$ . This core had a depth of 179.5 mm, however values were at background levels for the three deepest samples, which were therefore disregarded. The oldest age that could therefore be used was 103.5 years. The Pb<sup>210</sup> profile indicated a mixing depth of 31.5 mm, thus the maximum adjusted age equates to 59.2 years (Table 7.1).

### Metal Analysis

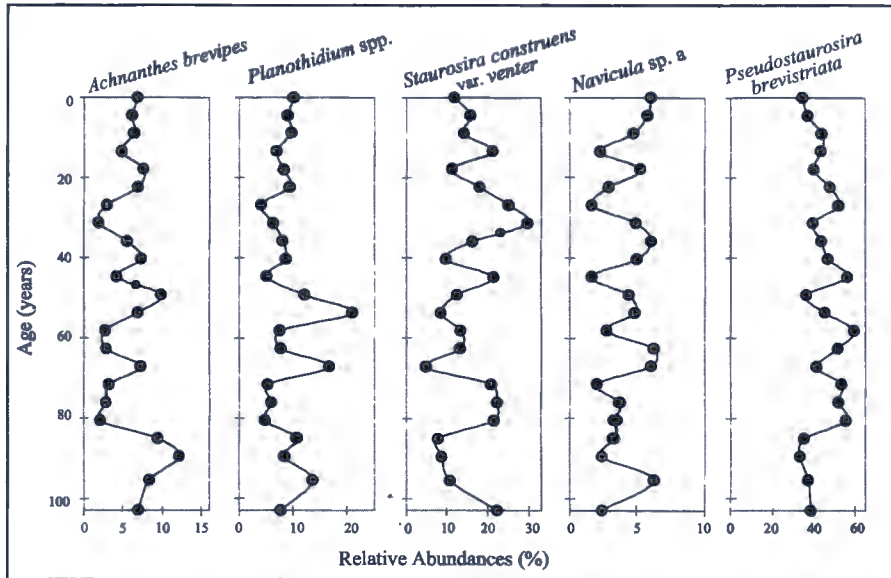
Metal concentrations in Cores 1 and 2 (Table 7.2) are similar to those measured in reference locations in the Windmill Islands (Scouller, pers. comm.). Core 3 shows some contamination, with the concentrations of several metals increasing since the operation of the Thala Valley waste disposal site. The greatest increases in metal concentrations were observed for As, Sb, Cu, Fe, and Pb (Table 7.2).

Core 1			Core 2			Core 3		
Depth (mm)	Isotope Age	Adjusted Age	Depth (mm)	Isotope Age	Adjusted Age	Depth (mm)	Isotope Age	Adjusted Age
1.5	2	mixing zone	4.5	7	mixing zone	1.5	2	mixing zone
4.5	7	↓	7.5	11	↓	4.5	6	↓
10.5	16		10.5	16		7.5	11	
13.5	20	0	13.5	20	0	10.5	15	
16.5	25	4	16.5	25	4	13.5	19	
19.5	29	9	19.5	29	9	16.5	23	
22.5	34	13	22.5	34	13	19.5	27	
25.5	38	18	25.5	38	18	22.5	32	
28.5	43	22	28.5	43	22	25.5	36	
31.5	47	27	31.5	47	27	28.5	40	↓
34.5	51	31	34.5	51	31	31.5	44	0
37.5	56	36	37.5	56	36	34.5	49	4
40.5	60	40	40.5	60	40	37.5	53	8
43.5	65	45	43.5	65	45	40.5	57	13
46.5	69	49	46.5	69	49	43.5	61	17
49.5	74	54	49.5	74	54	46.5	65	21
52.5	78	58	52.5	78	58	49.5	70	25
55.5	83	63	55.5	83	63	52.5	74	30
58.5	87	67	58.5	87	67	55.5	78	34
61.5	92	72	61.5	92	72	58.5	82	38
64.5	96	76	64.5	96	76	61.5	87	42
67.5	101	81	67.5	101	81	64.5	91	46
70.5	105	85	70.5	105	85	67.5	95	51
73.5	110	90	73.5	110	90	70.5	99	55
94.5	141	121	77.5	116	96	73.5	104	59
104.5	156	136	82.5	123	103			
114.5	171	151						
124.5	186	166						
134.5	201	181						
144.5	216	196						
160.5	240	219						
174.5	260	240						
184.5	275	255						
197	294	274						
207	309	289						
217	324	304						
224.5	335	315						

**Table 7.1** Depth (mm), Pb derived age, and the adjusted age of core samples.

Age (years)	Sb	As	Cd	Cu	Cr	Fe	Pb	Mn	Hg	Ni	Ag	Sn	Zn
<i>Core 1</i>													
4.5	0.85	25.80	1.70	14.80	23.50	11500	19.4	400.66	0.60	8.40	0.30	4.6	48.7
13.4	0.20	13.50	1.20	10.30	21.50	12400	22.8	447.51	0.30	7.60	0.20	2.1	39.8
22.4	0.20	11.20	1.20	8.50	20.00	12500	22.8	537.77	0.40	7.00	0.20	1.6	33.9
35.8	0.30	10.90	1.20	12.90	20.80	12600	20.3	494.19	0.80	7.40	0.30	1.1	48.8
49.3	0.20	9.90	1.30	9.80	22.20	12000	19.5	388.17	0.20	8.60	0.20	1.1	44.0
58.2	0.30	11.70	1.40	10.00	23.40	12300	17.7	422.96	0.80	8.40	0.30	1.3	45.0
67.2	0.30	9.40	1.30	8.80	21.00	12100	18.5	451.78	0.60	7.50	0.30	1.1	38.4
76.1	0.20	11.00	1.40	11.10	26.40	11900	21.0	403.05	0.50	8.90	0.20	1.3	43.5
85.1	0.20	7.20	1.70	9.20	21.70	12400	19.9	446.69	0.50	7.90	0.20	1.3	40.9
<i>Core 2</i>													
0.0	0.20	6.30	0.20	5.00	18.20	12700	28.7	712.86	0.70	5.30	0.20	1.7	23.6
9.0	0.25	6.40	0.30	6.20	19.70	10850	30.4	576.77	0.60	5.55	0.25	1.7	25.2
17.9	0.20	3.00	0.20	6.00	15.60	10600	27.7	614.52	0.30	4.60	0.20	1.1	25.1
26.9	0.20	4.80	0.20	5.40	18.20	12100	29.5	754.74	0.50	5.30	0.20	1.4	24.2
40.3	0.20	3.20	0.30	4.10	19.70	11800	26.5	702.30	0.30	4.30	0.20	1.2	22.3
49.3	0.30	4.60	0.40	4.00	15.70	10100	28.3	531.07	0.60	4.60	0.30	1.0	22.5
58.2	0.30	5.30	0.50	6.40	16.50	10400	25.7	570.32	0.60	5.00	0.30	0.9	26.3
67.2	0.30	4.60	0.50	6.60	19.60	11300	27.7	600.60	0.30	6.20	0.30	1.0	32.6
76.1	0.30	6.80	0.40	6.45	21.05	10550	28.5	543.70	0.50	6.35	0.30	0.8	37.4
85.1	0.30	3.20	0.40	5.60	18.20	12100	25.9	587.89	0.40	5.60	0.30	0.9	30.9
<i>Core 3</i>													
0.0	0.90	65.40	1.30	32.40	28.10	19100	102.5	470.32	0.90	7.40	0.30	23.3	66.5
12.7	0.70	57.40	1.10	36.90	31.40	18800	102.9	488.13	0.40	8.70	0.30	30.8	79.4
21.1	0.90	32.90	1.30	32.70	25.90	17500	109.9	575.67	0.90	7.00	0.40	18.7	68.8
29.6	0.50	23.10	1.20	17.10	24.40	18600	99.8	736.97	0.70	6.40	0.30	15.3	62.1
38.0	0.40	24.90	1.20	14.60	25.90	18400	82.2	584.53	0.60	7.10	0.20	13.3	46.2
50.7	0.23	14.83	0.60	11.53	27.70	16400	37.0	743.75	0.40	7.65	0.25	3.8	47.3

**Table 7.2** Metal Concentrations (ppm) in core samples from the contaminated Brown Bay, adjacent to the now defunct Thala Valley tip site, in the Windmill Islands, Antarctica. Samples which predate the tip site are shaded grey.



**Figure 7.2** Changes in the relative abundances of selected diatom species from Core 1. The core was sampled more intensively within the top section, thus accounting for the apparent increase in variability.

## Diatom Analysis

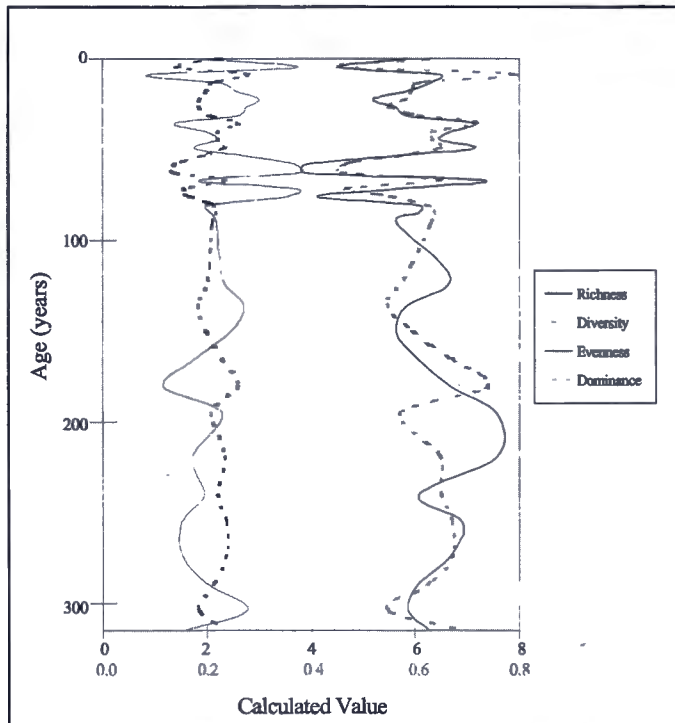
### Core 1

Twenty seven diatom sub-samples were taken from this core, however three of these samples were from within the mixing layer. *Pseudostaurosira brevistriata* was the most common species in this core; relative abundances of this species varied between 23.6% and 51.5%. *Staurosira construens* var. *venter* was also a common species in this core with relative abundances ranging between 5.4% and 37.4% (Fig. 7.2).

*Planothidium* spp. had a minimum relative abundance of 1.5%, whilst a maximum of 12% was recorded in the deepest sample. This was the only sample in which this species attained a relative abundance greater than 10% (Fig. 7.2). This was also the only sample in which *Achnanthes brevipes* attained a relative abundance greater than 10%, occurring at 10.6%. The relative abundances of this species covered a broad range, with a minimum of 0.7% recorded for this core. The relative abundances of

*Navicula* sp. c were highly variable ranging between 1 and 7.6% (Fig. 7.2). No reason for this variation was immediately apparent.

A high degree of variability was also observed in the structural parameters for this core (Fig. 7.3). Richness and diversity values for this core ranged between 3.91 to 7.6 and 1.33 to 2.72, respectively. Evenness and dominance values were varied from 0.445 to 0.793 and 0.086 and 0.376, respectively (Fig. 7.3).

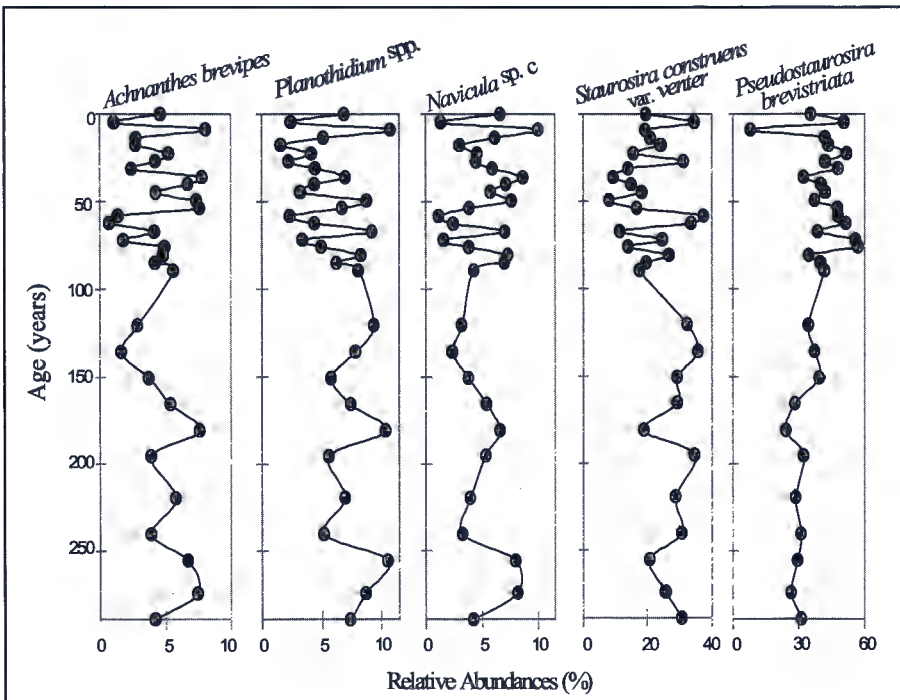


**Figure 7.3** Structural parameters of diatom communities in Core 1 over the past 318 years. Note that the different horizontal scales correspond to the line colours of the parameters. The core was sampled more intensively within the top section, thus accounting for the apparent increase in variability.

### Core 2

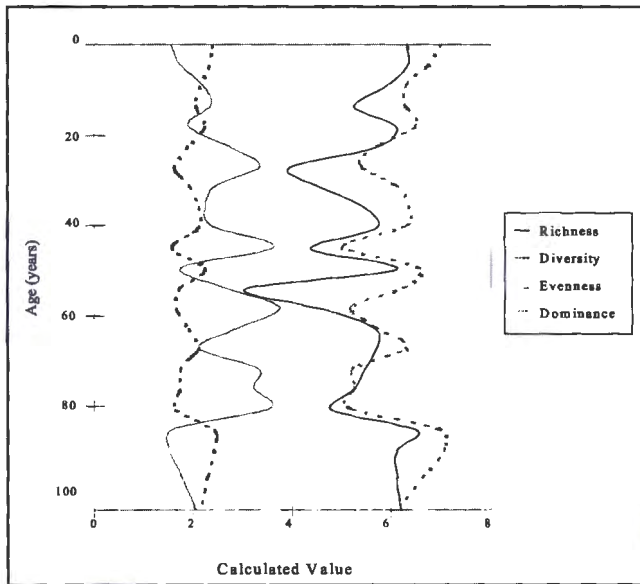
Twenty six subsamples were taken from this core for diatom analysis. This core consisted of high abundances of *Pseudostaurosira brevistriata*, with relative

abundances always exceeding 30%. The maximum relative abundance of *Pseudostaurosira brevistriata* was 59.4%, which occurred in the year 1940. No significant change in the relative abundance of this species was observed during times of human occupation of the Windmill Islands. Both *Planothidium* spp. and *Staurosira construens* var. *venter* were also abundant (Fig. 7.4), with the former attaining a maximum relative abundance of 22.4% in the deepest sample. Both these species occurred a several times at relative abundances below 5%. *Achnanthes brevipes* was another common species, attaining a maximum relative abundance of 12.1%. The minimum relative abundance recorded for this species was 1.9%. *Navicula* sp. c generally occurred at relative abundances between 1 and 5%, however in 9 samples higher relative abundances were recorded, reaching a maximum relative abundance of 6.25% (Fig. 7.4).



**Figure 7.4** Relative abundances of selected diatom species in Core 2, over the last 100 yrs.

Structural parameters were quite variable in this core (Fig. 7.5). Richness values for this core ranged between 3.04 and 6.51. Values for diversity ranged between 1.58 and 2.39 respectively (Fig. 7.5). Evenness values were between 0.495 and 0.706, whilst dominance values ranged between 0.149 and 0.374 (Fig. 7.5).



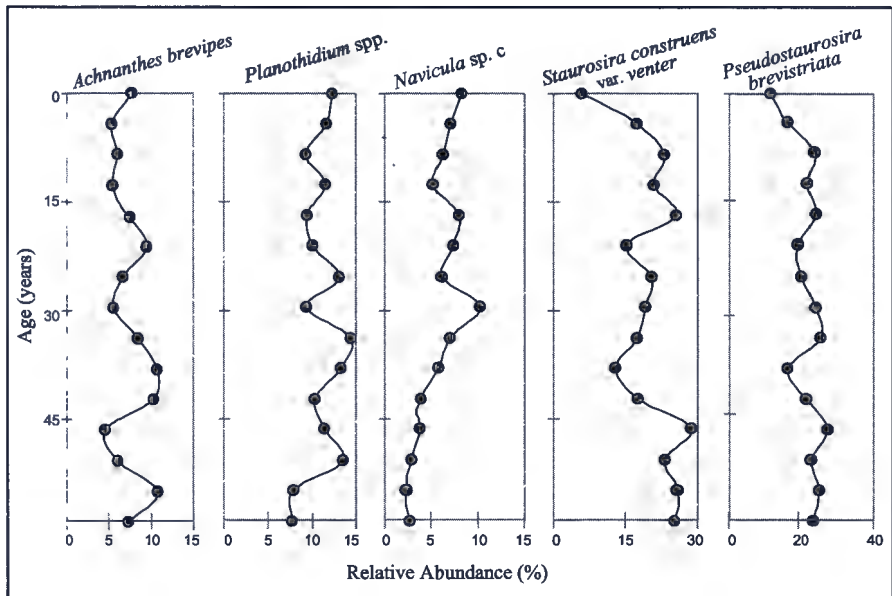
**Figure 7.5** Calculated values for structural parameters of diatom communities in Core 2. Note that the different horizontal scales correspond to the line colour used for each parameter.

### Core 3

Of the diatom sub-samples, 17 were from above the disturbed lower section, however the 5 top most samples were from within the mixing layer indicated by the  $\text{Pb}^{210}$  profile, leaving 12 viable samples. *Staurosira construens* var. *venter* and *Pseudostaurosira brevistriata* were the most abundant species in this core, with relative abundances ranging between 12.8% to 28.8% and 17.0% to 27.5%, respectively (Fig. 7.6). *Planorhynchium* spp. was another common species in this core, with relative abundances between 7.7% and 14.5%. *Achnanthes brevipes* had a relative abundance greater than 5% in all but one sample (Fig. 7.6). *Navicula* sp. c occurred at relative abundances greater than 5% in all core samples younger than 38



years, however, the relative abundances of this species in older samples only varied between 2 and 4%. *Navicula directa* also occurred at higher relative abundances in younger samples than in older samples (Fig. 7.6). Richness values for this core ranged between 4.34 and 6.95 (Fig. 7.7). Diversity values varied between 2.21 and 2.91. Evenness values were between 0.679 and 0.831. Dominance values were between 0.064 and 0.172 (Fig. 7.7).



**Figure 7.6** Changes in relative abundances of selected species from Brown Bay Core 3.

## Assessment of impact

### Core 1

The adjusted ages (Table 7.1) indicate that core samples between 13.5 mm and 31.5 mm are either contemporaneous with, or post-date the operation of the tip site, and could therefore reflect any changes associated with chemical contamination. No significant changes in any of the structural parameters occurred between these samples and those which pre-dated the Thala Valley waste disposal site, as indicated

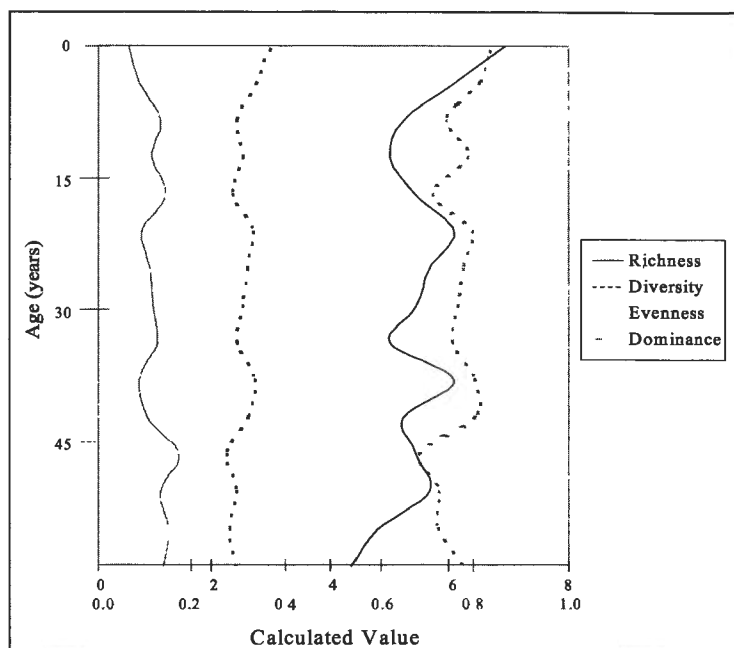


Figure 7.7 Calculated values for structural parameters of diatom communities in Core 3. Note the different horizontal scales correspond to the line colour used for each parameter.

		Within Cores			Between Cores		
		Core 1	Core 2	Core 3	All samples	Samples>	60
<b>Richness</b>	ANOVA	NS	NS	NS	0.0177	NS	
	SNK				2>1=3		
<b>Diversity</b> ( $x^3$ )	ANOVA	NS	NS	NS	<0.0001	<0.0001	
	SNK				3>1=2	3>1=2	
<b>Evenness</b> ( $x^3$ )	ANOVA	NS	NS	NS	<0.0001	<0.0001	
	SNK				3>1=2	3>1=2	
<b>Dominanc</b> (always)	ANOVA	NS	NS	NS	<0.0001	<0.0001	
	SNK				1=2>3	1=2>3	

Table 7.3 ANOVA and SNK tests (where appropriate) of structural parameters. Comparisons within cores are made between samples that pre-date the Thala Valley waste disposal site, and those that are contemporaneous with, or post-date it. NS indicates that no differences were detected at a significance level of  $p = 0.05$ . Values in () beneath each parameter indicate the transformation employed to satisfy assumptions of homogeneity. No transformation removed the heterogeneity from dominance values; therefore a lower significance level was applied.

by the ANOVA results (Table 7.3). ANOSIM analyses demonstrated that there were no significant changes in community composition (indicated by a global  $R$  value of 0.045 at a significance level of 29.6%) between samples which pre-dated the Thala Valley tip, and those that were either contemporaneous with, or post-dated it.

### Core 2

The adjusted ages (Table 7.1) indicate that core samples between 13.5 mm and 22.5 mm would be contemporaneous with any contamination resulting from the operation of the Thala Valley tip site. ANOSIM analyses demonstrated that there were no significant changes in community composition ( $R = -0.080$ ,  $p = 0.811$ ) between these samples and the remaining samples from this core. Similarly, the ANOVA results indicated no significant change in any of the structural parameters subsequent to the operation of the Thala Valley waste disposal site (Table 7.3).

### Core 3

The adjusted ages (Table 7.1) indicate that core samples between 31.5 mm and 49.5 mm are of the appropriate age to reflect any anthropogenic impacts that may have occurred during the operation of the Thala Valley tip site. ANOSIM analyses demonstrated that there was a significant shift in community composition between these and older samples from this core, with a global  $R$  value of 0.180 at a significance level of 5%. SIMPER analyses revealed that the two groups (ie. samples from before the Thala Valley tip, and sample from after the tip began operating) had a dissimilarity of 21.74 %. As with the previous cores, no significant changes in any of the structural parameters were observed between the two groups (Table 7.3).

The ten species with the highest modified SIMPER ratios were *Staurosira construens* var. *venter*, *Pseudostaurosira brevistriata*, *Navicula* sp. c, *Navicula directa*, *Navicula* aff. *glaciei*, *Navicula* sp. b, *Trachyneis aspera*, *Auricula compacta*, *Achnanthes brevipes* and *Planothidium* spp.. ANOVA results (Table 7.4) indicated that the relative abundances of only three of these species, *Auricula compacta*, *Navicula* sp. c and *Navicula directa* differed significantly between diatom communities from sediments contemporaneous, or post-dating the tip, and diatom communities which

pre-dated the tip and its associated contaminants. *Navicula* sp. a also varied significantly between pre-tip communities and more recent diatom communities ( $p = 0.05$ ).

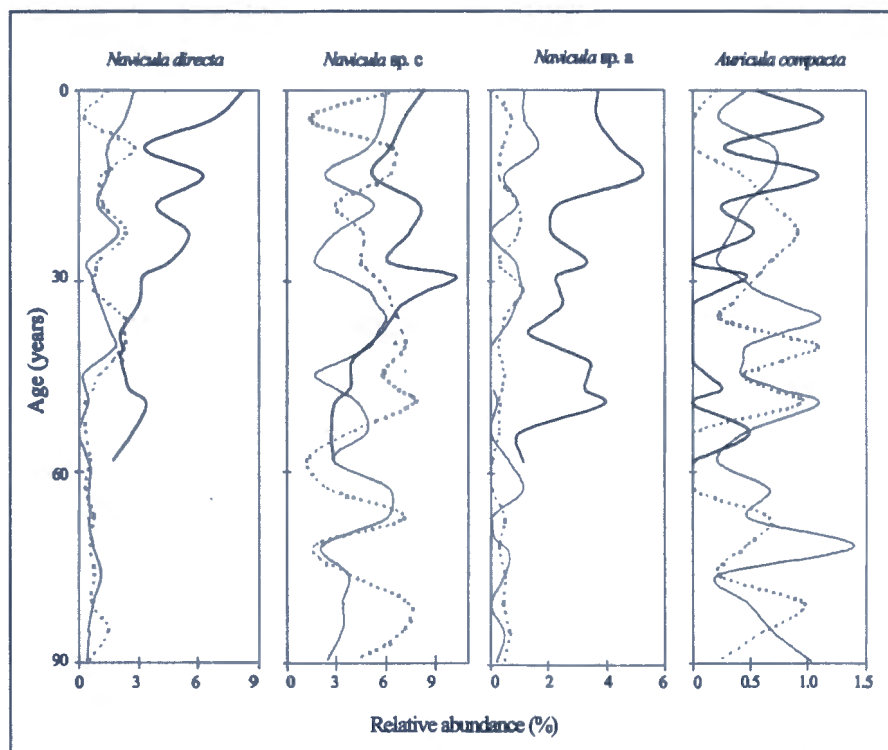
Species Name	Transformation	<i>p</i> Value	SNK
<i>Achnanthes brevipes</i>		0.1169	
<i>Planothidium</i> spp.		0.6896	
<i>Auricula compacta</i>		<b>0.0137</b>	<b>post &gt; pre</b>
<i>Staurosira construens</i> var. <i>venter</i>		0.2883	
<i>Navicula</i> sp. c		<b>0.0010</b>	<b>post &gt; pre</b>
<i>Navicula</i> sp. b		0.2628	
<i>Navicula directa</i>	<b>log (x+1)</b>	<b>0.0003</b>	<b>post &gt; pre</b>
<i>Navicula</i> aff. <i>glaciei</i>		0.1696	
<i>Navicula</i> sp. a		<b>0.050</b>	<b>post &gt; pre</b>
<i>Pseudostaurosira brevistriata</i>		0.1610	
<i>Trachyneis aspera</i>	always sig.	0.0601	

**Table 7.4** ANOVA and SNK results for comparisons of relative abundances of selected species between samples which predate the Thala Valley waste disposal site, and samples which post-date, or are contemporaneous with this site.

These latter four species all increased in abundance subsequent to the establishment of the Thala Valley tip site (Fig 7.8). The relative abundances of *Navicula directa* varied between 1.7 and 3.4% prior to the establishment of the Brown Bay tip. Subsequent to that event, relative abundances in the range of 3.3 to 8.3% were attained. *Auricula compacta* was relatively rare throughout the core, and was absent from a number of samples. Prior to the establishment of the Thala Valley tip site the relative abundances of this species ranged between 0 and 0.5%. After the establishment of the tip site, this species occurred in more samples, and at slightly higher abundances (up to 1%).

*Navicula* sp. c occurred in all samples from Core 3. Before the Thala Valley waste disposal site was established, the relative abundances of this species varied between 2.7 and 7.0%, after the establishment of the tip site relative abundances between 5.2 and 10.2% were observed (Fig. 7.8). *Navicula* sp. a also occurred in all samples.

Relative abundances between 1.0 and 3.9% were observed prior to the establishment of the tip. Since the tip was established, relative abundances of this species have varied between 2.1 and 5.2%.



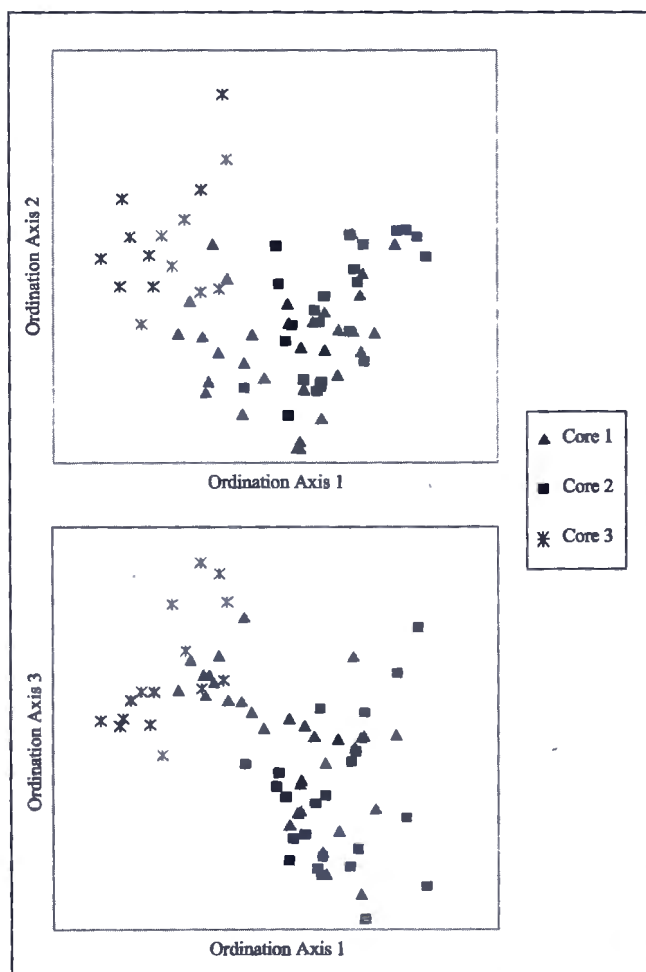
**Figure 7.8** Relative abundances of selected species within the three different cores.

Core 1 is indicated by the grey dashed line, Core 2 is represented by the continuous grey line; Core 3 is shown by the black line.

### Comparisons of diatom communities between cores.

Significant differences in diversity, evenness, dominance and richness values of the diatom communities were observed between cores (Table 7.3). Cores 1 and 2 had significantly ( $p = 0.05$ ) higher dominance values than Core 3. Significantly lower diversity and evenness values were also recorded for the first two cores, relative to Core 3. Richness values were significantly lower in Core 3 than either of the other two cores overall (Table 7.3). Core 3 is much shorter, and younger, than either of the

other two cores. When only samples less than 60 years (the maximum age of Core 3) were considered, no significant differences were observed in richness values; however, the differences observed in diversity, dominance, and evenness were still maintained (Table 7.3). Significant differences in the composition of the diatom communities were also noted between all cores, as is apparent from the nMDS ordination (Fig. 7.9).



**Figure 7.9** nMDS Ordination of samples showing the clustering of samples into cores groups. Black symbols indicate samples which post-date, or are contemporaneous with the Thala Valley waste disposal site, grey symbols represent samples that predate this.

Cores 1 and 2 were the most similar, with Cores 2 and 3 being the least similar. ANOSIM results (Table 7.5) revealed that differences between Core 3 and the other two cores were emphasised when only samples less than 60 years (the maximum age of core 3) were considered. In contrast, when only these samples were considered, the differences observed between Cores 1 and 2 were reduced (Table 7.5).

Cores Compared		All Samples	Samples < 60 years
C1	C2	$R=0.0141, p=0.0001$	$R=0.132, p=0.01$
C1	C3	$R=0.779, p=0.0001$	$R=0.830, p<0.0001$
C2	C3	$R=0.561, p<0.0001$	$R=0.746, p<0.0001$

**Table 7.5** ANOSIM results for comparisons of community composition between cores.

As they showed no evidence of metal contamination, Cores 1 and 2 can be used as indicators of the natural range of variability. Species that were found to vary significantly within Core 3 (eg. *Navicula directa*, *N. sp. c*, *N. sp. a* and *Auricula compacta*) can be compared to Cores 1 and 2 to determine whether the responses were within the range of natural variation, or due to the presence of contaminants. Figure 7.4 shows the relative abundances of these species within each core. From this diagram it is apparent that there are significant differences in the relative abundances of several of these species, both between cores, and as a result of contamination within core.

The relative abundances of *Navicula directa* and *Navicula sp. a* within Core 3 appear to be higher than in either of the control cores. *Navicula sp. c* occurs at similar abundances in samples which predate the tip in all three cores. The relative abundances increase in Core 3 during the last 30 years, however this trend is not observed within either of the control cores. *Auricula compacta* also increases in abundance over the last 30 years in Core 3; however, this appears to be within the

range of natural variability for this species, as evidenced by the relative abundances in Cores 1 and 2.

Univariate analyses (Table 7.6) revealed that the relative abundances of *Navicula directa*, *N. sp. a* and *N. sp. c* occur at significantly higher abundances within the contaminated sediments from Core 3, than in either of the other two cores. The relative abundances of both *Navicula directa* and *Navicula sp. a* were also higher in the pre-impact sediments from Core 3 than in either of the other two cores. Univariate analyses (Table 7.6) also supported the observation that the relative abundances of *Auricula compacta* in samples contemporaneous with the tip associated contamination were within the range of variability seen in Cores 1 and 2, despite being significantly higher than the pre-tip samples from Core 3.

The relative abundances of several other species also varied between Core 3 and Cores 1 and 2. *Navicula perminuta* had higher relative abundances in Core 3 than in either of the other two cores. In contrast, *Pseudostaurosira brevistriata* occurred at lower abundances in Core 3 than in Cores 1 and 2. The relative abundances of *Staurosira construens* var. *venter* were highly variable within Cores 1 and 2, but were generally higher than those observed in Core 3.

Species Name	Trans.	p-value	Relative abundances
<i>Auricula compacta</i>		$p = 0.05$	$1 = 2 = 3 > 4$
<i>Navicula sp. c</i>	always sig.	$p = 0.01$	$3 > 1 = 2 = 4$
<i>Navicula directa</i>	$\sqrt{X+1}$	$p = 0.01$	$3 > 1 = 2 = 4$
<i>Navicula sp. a</i>		$p = 0.01$	$3 > 1 = 2 = 4$

**Table 7.6** SNK results for the comparison of relative abundances of selected species between Cores 1 (1) and 2 (2), Core 3 samples which are contemporaneous with the Thala Valley waste disposal site (3), and Core 3 samples which pre-date this (4). Transformations used to satisfy assumptions of homogeneity of variance are shown; when heterogeneity was always significant, a lower significance level was used.



## Discussion

Diatom communities from Core 3 demonstrated compositional changes related to the operation of the tip; this could be related to chemical contamination. Within this core, significant differences were observed between diatom communities contemporaneous with the Thala Valley tip, and the diatom communities which pre-date the tip. These differences were apparent in the multivariate analyses and, to a lesser extent, in the univariate analyses. The ANOSIM results indicated that the species composition of the diatom communities significantly altered after the Thala Valley tip commenced operation. In contrast, the univariate analysis indicated that the relative abundances of only a few species varied significantly. Despite observed changes in species composition, no significant differences in diversity, evenness, richness or dominance occurred, suggesting that the species composition of diatom communities is a more sensitive indicator of disturbance resulting from the tip operation than the structure of these communities.

Distinguishing between natural variation occurring over time, and biological impacts is a major difficulty associated with the use of historical data as an assessment or monitoring technique (Underwood, 1989). Whilst there is evidence of changes in the composition of diatom communities subsequent to the operation of the Thala Valley tip site, care must be taken to separate between the effects of natural temporal variation, and differences that resulted from tip-associated contamination. Many natural populations have considerable temporal and spatial variability. The detection of an impact requires not that the abundance has changes at some place at some time, but that the observed change in abundance is larger than can normally be expected to occur, given the processes that are already stressing the population (Underwood, 1989). In order to demonstrate that an impact results from chemical contamination, the variations observed within Core 3 would need to exceed that which naturally occur. Comparisons with control cores would need to be undertaken in order to enable this to be established.

The selection of appropriate control cores is somewhat problematic within the Windmill Islands. Previous sampling (Chapter 4) has demonstrated that diatom communities vary significantly between the higher order bays within the region (ie between Newcomb Bay, O'Brien Bay and Sparkes Bay). Hence, cores from O'Brien Bay and Sparkes Bay would not be representative of the naturally occurring diatom communities from Brown Bay, which is situated within Newcomb Bay. Within Newcomb Bay, areas of relatively homogenous fine-grained sediments, such as that seen in Brown Bay, are limited to Shannon Bay and Brown Bay. Given that Shannon Bay is another potentially impacted site, with elevated levels of heavy metals previously recorded (Scouller et al., 2000; Morris et al., 2000), this bay would therefore not be appropriate as a control location. Two of the cores collected from Brown Bay were uncontaminated, presumably because they were collected at a greater distance from the tip site than Core 3. These cores can therefore be used as control cores.

Changes over time in the species composition of these two uncontaminated cores can therefore be regarded as the naturally occurring temporal variation. No significant differences were observed in the community composition of these cores between samples which pre-date the establishment of the tip, and those that post-date it. This implies that the compositional changes result from chemical contamination, or some other environmental factor that may be acting in parallel with this.

It is therefore possible to determine whether changes observed in relative abundances of diatom species before and after contamination, exceed the variation that would naturally be expected. The abundance of several species increased significantly in Core 3 subsequent to the operation of the Thala Valley tip; the magnitude of these increases was demonstrated to exceed that which occurred within the other two cores. These results have been interpreted as indicating that the compositional changes observed in Core 3 result from the operation of the Thala Valley tip site, and most probably from the associated chemical contamination. Several species, namely *Navicula directa*, *Navicula* sp. c, and *Navicula* sp. a, may therefore be suitable

indicators of biological impact resulting from anthropogenic contamination of the marine environment around Casey Station.

*Navicula* has previously been described as a pollution tolerant genus (Palmer, 1969), however this was specifically related to organic enrichment. Small species of this genus have previously been shown to be more tolerant of pollution, both organic (Kelly and Whitton, 1995) and metal (Ivorra et al., 1999) than larger *Navicula* species. Within this study, pollution tolerance does not appear to be related to size. *Navicula* sp. a, a relatively small species (20-55  $\mu$ m in length) did appear to be pollution tolerant, however, *Navicula directa*, a large species (70-120  $\mu$ m in length) responded to metal contamination in a similar manner.

### Conclusions

Significant changes in the composition of diatom communities were related to the operation of the Thala Valley tip site, and are tentatively linked to chemical contamination resulting from this. These changes exceed what might be expected from the natural spatial and temporal variability observed within Brown Bay. The relative abundances of several *Navicula* species increased significantly as a result of this contamination; these species would be good candidates for further investigations of indicators of anthropogenic contamination within the region.

***Is the distribution of benthic diatom communities within Brown Bay related to concentrations of heavy metals?***

**Abstract**

Redundancy analysis was used to explore the relationship between the distribution of benthic diatom communities and heavy metal concentrations within the contaminated Brown Bay. This direct gradient ordination technique indicated that 63.8% of the variation observed in diatom abundances could be explained by metal concentrations, however, when highly correlated metals were removed from the data set the variation explained decreased to 48%. Concentrations of Sn and Zn explained a total of 33.6% (16.3% and 17.3%, respectively) of the variation in diatom abundances, whilst the concentrations of Cu and Cd each explained a further 5.3% of this variation.

**Introduction**

It is well established that high concentrations of some metals can have toxic effects on diatoms (Fisher and Frood, 1980). These effects include reduced photosynthetic ability (Rijstenbil et al., 1994), reduced growth rate (Cid et al., 2001), the cessation or interruption of cell division and deformation of the diatom frustule (Braeck and Jensen, 1976). Studies which examine the effects of metal toxicity on diatoms are typically laboratory based experiments involving either a single diatom species exposed to several metals at varying concentrations, or several different diatom species exposed to varying concentrations of the one metal (Mason et al., 1995). Whilst a large amount of such work has been undertaken with marine diatoms, these have almost exclusively been planktonic taxa (Payne and Price, 1999; Rijstenbil et

al., 1994). Scant information is available on the toxicity of metals to benthic marine diatoms.

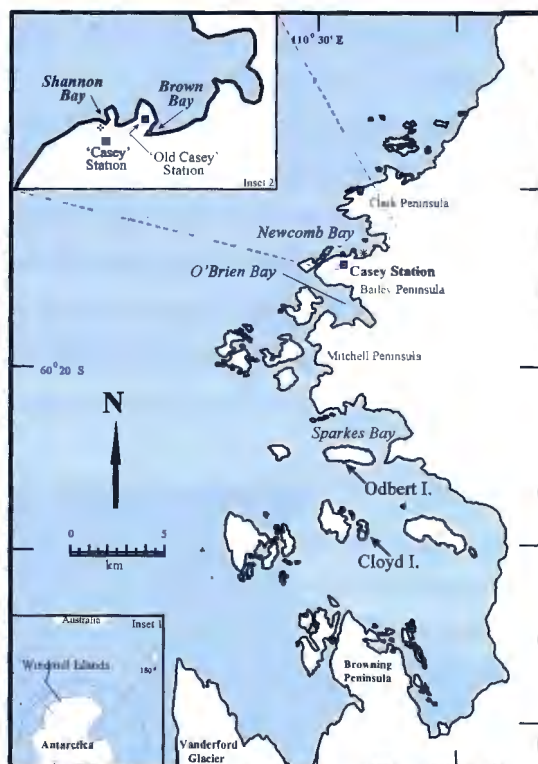
Previous studies have inferred that the marine sediments of Brown Bay, near Casey Station in the Windmill Islands, have been contaminated as a result of station activities, including the operation of a waste disposal site (Snape et al., 2001; Stark et al., in press). The contaminants consist of both hydrocarbons and metals, such as lead, zinc, copper and tin. Metal concentrations within the sediments of Brown Bay are 10-100 times the concentrations in sediments from control locations (Snape et al., 2001; Scouller et al., 2000). It has previously been shown that the metal contaminants present within Brown Bay have a significant impact on the diatom communities within this bay (Chapter 7). The purpose of this paper was to further examine the relationship between the metal contaminants, and the diatom communities within Brown Bay. It was hypothesised that the diatom data would be strongly related to the concentrations of the various metals present.

## **Methods**

### **Site description**

The Windmill Islands cover an area of approximately 75 km<sup>2</sup> in Wilkes Land, Antarctica. Casey Station is situated at 66° 17' S, 110° 32' E, on Bailey Peninsula in the Windmill Islands (Fig. 8.1). Casey Station is the third permanent research station to operate in the Windmill Islands. Its immediate predecessor, "Old Casey" was also located on Bailey Peninsula, approximately 800 m northwest of the current Casey Station (Inset 2, Fig 8.1).

Since its establishment in 1969 until a change of policy in 1986, all refuse generated by the Old Casey Station was dumped into the nearby Thala Valley (Deprez et al., 1999) and occasionally bulldozed onto the sea-ice in Brown Bay. The dumped waste consisted of waste from the science laboratories, and from the various mechanical workshops, such as engine parts, batteries, and old fuel drums (Snape et al., 2001),



**Figure 8.1** Map of the Windmill islands showing the location of Casey Station and Brown Bay (\*). Inset 1 shows the location of the Windmill Islands on the Antarctic continent. Inset 2 shows the details of the station location, including the sewage outfall (+). Note the proximity of Brown Bay to the Thala Valley tip site (▲).

as well as domestically produced waste. Despite an earlier attempt to clean up this site during the 1995/96 summer season, it is estimated that up to 2500 m<sup>3</sup> of rubbish still remains (Snape et al., 1998).

In summer, a melt-stream flows through the Thala Valley tip site where water dissolves and entrains contaminants before runoff enters into the adjacent Brown Bay. An estimated eight cubic meters of contaminated material associated with the tip was removed by surface runoff and deposited into Brown Bay during the 1998/99 summer period (Cole et al., 2000). Higher concentrations of some heavy metals and petroleum hydrocarbons have been recorded in sediments collected from Brown Bay, relative to control locations. Concentrations of some metals, including copper, lead,

iron and zinc, are 10 to 100 times higher than background levels (Scouller et al., 2000, Stark et al., in press).

Brown Bay is a small embayment aligned approximately east-west at the southern end of Newcomb Bay, immediately adjacent to the Thala Valley tip site (Fig. 8.2). The maximum depth of 20 m occurs at the eastern end where Brown Bay enters Newcomb Bay. Brown Bay has rocky sides which grade to a relatively homogenous muddy bottom (Stark, 2000); close to the tip site, discarded material protrudes through the sediment.

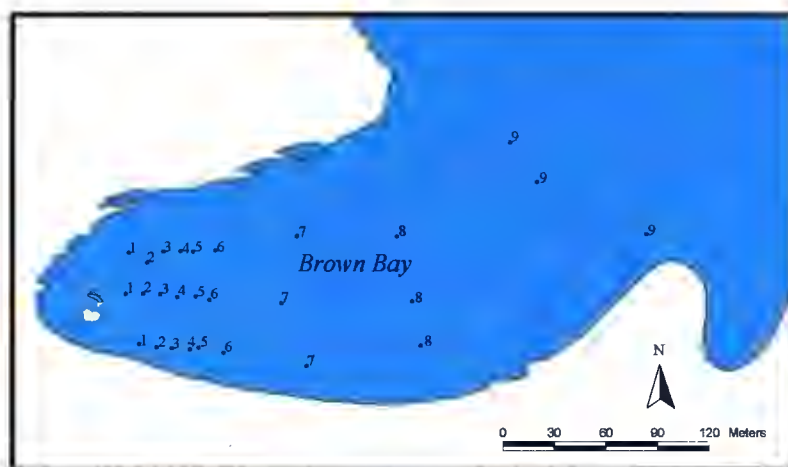


Figure 8.2. Sample locations within Brown Bay

### Sampling Design

A series of sediment samples were collected from within Brown Bay. Nine samples were collected at intervals along each of three parallel transects. The transects were aligned approximately W-E, and thus consecutive samples represent increasing distance from the tip-site (Fig. 8.2). A fourth transect was established just outside of Brown Bay, and consisted of four sampling points. Samples were collected by divers inserting small (5 cm diameter) PVC tubes into the sediments. Once inserted into the sediments, the top was capped and the tube retrieved. The top 5 cm of each core were homogenised and used for both the metal and diatom analyses.



## **Sediment Analysis**

Sediment samples were analysed for thirteen different metals, and total organic carbon (TOC). In preparation for these analyses, the sediment samples were wet-sieved through plastic 2 mm grids, and dried at 50 °C. Sediment samples were extracted under moderate acid conditions: 1 M HCl at room temperature on shaker for 1 hour, with 0.45 m cellulose nitrate filtration. Extract volume was determined using a ratio of 20:1 extract: sediment. Sample preparation was undertaken by Scott Stark (AAD). Metal concentrations were determined using ICP-MS. Both the metal and TOC analyses were performed by AGAL, in Pymble, N.S.W.

## **Diatom preparation and identification**

Organic material was removed by digestion in a 10% hydrogen peroxide solution for 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. The final solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Identification was as outlined in Appendix 1. A minimum of 400 individuals of the predominantly benthic taxa was counted for each sample. The relative abundances of these taxa were then calculated and used in the statistical analyses. Only taxa which had a relative abundance of 2% in at least one sample were included in the analysis. Exclusion of rare taxa is on the basis that they may be allocthanous.

## **Statistical Analyses**

A direct gradient ordination was used to examine the relationships between diatom abundances and measured environmental variables, and to determine which variables



were directly responsible for the variations observed in the diatom abundances. A preliminary canonical correspondence analysis (CCA) was performed to determine which type of analysis was most appropriate for the data. This revealed that the maximum length of the ordination axes was 1.6 standard deviations, thus a linear response model was most applicable (ter Braak, 1987). Redundancy analysis (RDA) was therefore selected as the preferred ordination method.

All of the environmental variables examined had skewed distributions, and were therefore  $\log(x+1)$  transformed prior to analysis. Species data was also transformed in this manner. All ordinations were performed using CANOCO version 3.12 (ter Braak, 1988, 1990).

Constrained RDAs were used to estimate the relative importance of individual variables in explaining the species data. Multiple collinearity between environmental variables was examined using variance inflation factors (VIFs). Large VIFs ( $>20$ ) indicate that a variable is highly correlated with other variables, and thus contributes little information to the ordination (ter Braak, 1998). Preliminary ordinations revealed that high VIFs were common within the data set, indicating that many variables were highly correlated with each other. Further preliminary ordinations were undertaken to determine which combination of variables explained the greatest amount of the variation observed in the species data, without incorporating environmental variables which had high VIFs. The selected variables were used as active variables, whilst the remainder were incorporated as passive variables. Correlation scores were used to determine which variables were highly correlated ( $>0.90$ ).

Redundancy analysis was performed using the selected variables. Ordination scores were scaled for covariance biplots, as this maximises interpretation of the relationship between species (ter Braak, 1987-92). Intra-set correlations were used to examine the relative contribution of the environmental variables to the separate ordination axis. Eigenvalues indicate the importance of an ordination axis in

explaining variation within the species data. The significance of the first and second ordination axes were determined using unrestricted Monte Carlo permutation tests (99 permutations). The significance of the overall effect of the environmental variables on the species was determined by using the trace statistic, instead of an ordination axis, in these tests. Graphical representation of the ordination results was undertaken using CANODRAW (Smilauer, 1992).

## Results

The geographical and chemical data pertaining to the samples is given in Table 8.1. Large variations in the concentrations of many metals were observed between samples. The greatest variation was observed in the concentration of tin, which increased 100 fold, ranging between 0.24 and 37 mg.kg<sup>-1</sup>. Iron was the most abundant metal with some sediment samples containing more than 10,000 mg.kg<sup>-1</sup>, however, concentrations as low as 216 mg.kg<sup>-1</sup> were also recorded (Table 8.1). Antimony and mercury occurred at concentrations below the method detection limits in the majority of samples (Table 8.1) and were excluded from the analysis.

Twenty one diatom species had a relative abundance greater than 2% in at least one sample. The relative abundances of the diatom species in the different samples is shown in Table 8.2. In general, the diatom communities had relatively high abundances of *Achnanthes brevipes*, *Planothidium* spp., *Cocconeis costata/fasciolata* and *Staurosira construens* var. *venter*.

An ordination of the thirty one sites, and associated diatom and chemical data, indicated that the first four ordination axes accounted for a total of 63.8% of the variance in the diatom data. Although this ordination accounted for a high degree of the variation in diatom data, collinearity between environmental variables was pronounced with only arsenic and manganese having VIFs below 20. The correlation scores (Table 8.3) indicated that the chemical variables could be grouped into three broad categories. The first category consisted of copper, iron lead and tin, all of which were highly correlated (0.919-0.975). The second category consisted of metals

Sample	Sample No	Sb	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Ag	Sn	Zn	TOC	Eastng	Northng
Transect 1, Sample 1	1	0.1590	14.513	1.431	6.402	77.535	14910.5	168.99	7.753	0.0099	2.783	0.497	31.809	97.416	26500	479407.8	2648779.8
Transect 1, Sample 2	2	0.0192	4.808	0.404	1.288	9.808	1615.4	28.85	5.000	<0.002	0.712	0.135	5.192	19.231	5190	479418.5	2648774.1
Transect 1, Sample 3	3	0.0865	17.872	1.038	3.786	24.986	4707.6	92.25	7.111	0.0144	1.951	0.413	13.163	50.928	21400	479427.8	2648780.5
Transect 1, Sample 4	4	0.1373	19.020	1.235	3.176	27.451	4705.9	119.61	5.686	0.0118	1.961	0.412	14.706	72.549	21800	479437.9	2648780.7
Transect 1, Sample 5	5	<0.02	2.132	0.291	0.523	1.938	329.5	5.81	5.039	<0.002	0.368	0.058	0.795	6.977	2470	479458.0	2648781.2
Transect 1, Sample 6	6	<0.02	7.160	0.334	0.878	4.387	849.3	10.31	3.915	<0.002	0.535	0.105	1.833	8.396	4590	479505.6	2648789.4
Transect 1, Sample 7	7	0.0198	19.841	1.607	1.825	5.754	615.1	14.48	4.960	0.0040	2.183	0.278	1.627	33.730	27400	479563.5	2648789.3
Transect 1, Sample 8	8	<0.02	4.902	0.706	0.569	2.353	184.3	3.33	4.118	<0.002	0.686	0.137	0.373	11.961	5210	479629.4	2648844.1
Transect 1, Sample 9	9	<0.02	28.141	1.166	1.849	5.628	623.1	13.67	4.020	0.0040	1.990	0.241	1.950	19.497	31600	-	-
Transect 2, Sample 1	10	<0.02	3.824	0.382	0.707	7.075	707.5	22.94	4.207	<0.002	0.669	0.096	3.250	15.870	4380	479406.1	2648755.9
Transect 2, Sample 2	11	0.1761	12.916	1.018	3.366	35.225	8023.5	125.24	5.284	0.0117	1.722	0.548	19.178	62.622	17700	479416.2	2648756.1
Transect 2, Sample 3	12	0.0575	9.579	0.575	1.762	11.686	1494.3	34.48	4.406	0.0057	0.900	0.211	4.598	26.820	8150	479426.1	2648755.5
Transect 2, Sample 4	13	0.0794	10.218	1.042	2.816	25.795	5158.9	78.36	6.049	0.0050	1.756	0.357	13.788	49.593	15100	479435.8	2648754.0
Transect 2, Sample 5	14	0.0796	41.791	0.657	3.423	33.831	4975.1	89.55	5.970	0.0080	1.592	0.338	13.731	49.751	17900	479454.6	2648752.3
Transect 2, Sample 6	15	<0.02	16.473	0.426	1.124	6.008	794.6	16.86	4.457	0.0039	0.814	0.155	2.519	13.760	8010	479496.4	2648750.4
Transect 2, Sample 7	16	0.0197	21.675	1.970	1.813	6.897	571.4	13.99	6.305	0.0039	2.562	0.296	1.557	45.320	28000	479572.4	2648751.5
Transect 2, Sample 8	17	<0.02	7.443	0.992	0.592	3.244	209.9	5.15	3.817	<0.002	0.859	0.134	0.573	14.504	9520	479645.0	2648821.1
Transect 2, Sample 9	18	<0.02	9.009	1.508	0.921	3.428	254.6	2.25	4.994	<0.002	1.655	0.147	0.294	22.517	12410	-	-
Transect 3, Sample 1	19	0.1949	18.519	1.150	3.548	27.290	5848.0	87.72	6.823	0.0136	2.144	0.370	37.037	54.581	14400	479413.8	2648726.6
Transect 3, Sample 2	20	0.0392	9.214	0.617	1.703	12.934	1891.7	46.09	5.384	0.0029	0.989	0.196	6.565	31.377	6680	479423.9	2648724.9
Transect 3, Sample 3	21	<0.02	9.038	0.538	1.442	11.154	1307.7	36.34	4.615	0.0019	0.808	0.192	5.577	23.077	5770	479432.6	2648724.2
Transect 3, Sample 4	22	<0.02	11.776	0.425	1.429	8.301	810.8	27.03	5.019	0.0058	0.618	0.174	4.054	16.023	5760	479443.3	2648723.6
Transect 3, Sample 5	23	0.0490	18.281	0.821	2.188	18.672	2053.0	62.55	6.542	0.0039	1.437	0.244	8.894	39.105	12600	479462.8	2648721.5
Transect 3, Sample 6	24	<0.02	10.405	0.617	1.098	6.744	732.2	23.12	5.010	0.0039	0.944	0.154	2.697	23.121	7510	479511.1	2648714.1
Transect 3, Sample 7	25	0.0193	8.317	0.812	0.948	4.255	309.5	10.25	5.029	<0.002	1.025	0.135	1.373	18.569	7200	479577.5	2648725.6
Transect 3, Sample 8	26	<0.02	23.940	0.858	1.636	6.783	917.7	16.96	4.389	0.0040	1.337	0.239	2.594	21.945	16460	479668.0	2648790.3
Transect 3, Sample 9	27	<0.02	7.753	1.909	1.014	3.777	258.4	1.85	5.368	<0.002	1.650	0.179	0.239	25.845	16930	-	-
Transect 4, Sample 1	28	<0.02	0.369	0.097	0.380	13.133	544.2	6.10	1.497	<0.002	0.175	<0.02	1.250	6.060	520	-	-
Transect 4, Sample 2	29	<0.02	0.394	0.118	0.296	1.617	414.2	4.93	2.170	<0.002	0.178	<0.02	1.045	2.959	1220	-	-
Transect 4, Sample 3	30	<0.02	2.165	0.335	0.394	1.831	216.5	3.35	3.937	<0.002	0.413	0.039	0.768	5.709	2280	-	-
Transect 4, Sample 4	31	<0.02	24.000	1.780	2.040	9.000	1020.0	17.80	6.000	0.0060	2.800	0.220	2.800	30.000	32990	-	-

**Table 8.1** Chemical and geographical data for sediment samples.

Species Name and Number	Transect 1										Transect 2										Transect 3										Transect 4									
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4									
<i>Achnanthes brevipes</i>	1	10.0	8.0	5.7	8.4	6.9	4.9	6.4	4.0	6.1	7.6	7.8	10.5	10.7	5.7	7.3	13.7	5.9	6.2	6.3	8.0	4.3	5.7	6.8	5.7	3.8	6.2	6.4	8.5	4.1	1.9	3.3								
<i>Achnanthes</i> sp. a	8	2.0	1.3	1.1	0.4	0.4	1.2	0.8	0.4	0.4	1.1	0.3	0.0	0.4	1.1	1.5	0.0	0.0	0.8	1.1	0.4	1.5	1.5	1.0	1.1	0.9	1.6	0.0	9.2	14.6	4.2	2.5								
<i>Amphora pediculus</i>	3	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	1.1	0.4	0.4	0.0	2.1	1.2	0.8	0.0	0.4	0.4	0.0	0.3	0.0	0.4	0.8	0.4	0.0	0.0	0.0	0.0								
<i>Catacomba comstachica</i>	4	0.8	0.4	0.0	0.0	0.4	0.0	0.0	0.8	0.8	0.4	0.7	0.4	3.6	2.5	0.7	1.1	0.0	0.0	0.4	0.4	0.7	0.0	0.7	1.5	0.9	0.4	0.8	0.4	0.0	0.0	0.4								
<i>Cocconeis costata</i>	5	1.2	1.8	1.1	1.5	0.4	0.8	0.8	0.4	0.4	0.0	0.7	1.8	1.6	2.5	0.7	1.1	0.4	0.0	0.4	2.0	0.0	1.5	0.0	1.1	0.0	0.4	0.0	1.1	0.8	0.4	0.4								
<i>Cocconeis fauvelata</i>	6	6.8	8.0	5.7	5.5	6.9	4.9	13.3	2.4	8.6	7.6	8.1	9.8	13.4	8.2	6.5	20.0	11.8	10.0	6.9	6.0	5.6	11.7	8.2	5.3	6.0	5.4	8.7	7.4	4.1	8.8	5.8								
<i>Cocconeis schuetti</i>	7	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.4	0.0	0.3	1.1	2.0	1.1	0.7	1.1	0.0	0.8	0.0	0.4	0.7	0.8	0.0	0.4	1.3	0.4	0.0	0.4	0.4	0.4	0.0								
<i>Ctenophora pulchella</i>	9	1.6	1.3	3.8	0.4	0.0	0.0	0.0	0.4	0.0	0.8	0.3	0.4	1.2	1.4	0.7	0.0	0.0	0.0	2.9	1.2	1.9	0.4	1.0	0.4	0.4	0.0	0.0	4.2	3.3	0.4	0.0								
<i>Navicula</i> aff. <i>glaciel</i>	15	4.8	4.0	7.3	1.1	1.2	4.9	0.8	0.4	0.8	0.4	5.4	0.7	2.8	3.6	1.5	1.1	1.6	0.0	8.0	2.8	5.6	4.5	3.8	1.5	1.7	0.0	0.4	10.2	15.9	1.9	3.3								
<i>Navicula directa</i>	14	0.8	4.4	1.9	0.7	0.8	1.2	0.0	0.4	0.0	0.4	2.7	4.6	2.8	1.1	3.6	1.1	0.8	0.8	4.0	2.0	1.9	3.0	2.4	0.8	0.0	0.8	0.4	0.4	0.0	0.4	0.0								
<i>Navicula</i> sp. a	16	0.8	0.4	1.5	1.1	0.0	1.6	0.0	0.8	0.0	0.8	3.4	0.4	0.8	1.1	0.7	0.0	0.4	0.4	2.2	2.0	1.1	0.8	1.4	0.4	1.3	0.4	0.8	3.5	2.4	0.0	1.2								
<i>Navicula</i> sp. b	13	1.6	3.5	1.9	2.9	0.0	0.4	0.8	1.6	0.4	3.8	0.0	2.5	1.2	1.1	0.4	3.2	0.8	0.0	1.8	1.6	1.9	0.8	3.4	0.8	0.4	0.4	1.1	0.0	0.8	0.4	0.8								
<i>Navicula</i> sp. c	12	2.4	1.3	2.7	1.8	2.3	2.0	4.8	0.8	1.2	2.7	2.0	2.8	1.2	2.5	2.9	5.3	6.7	0.0	4.3	4.8	1.9	2.3	2.1	4.9	3.0	0.4	1.1	3.2	2.8	0.4	0.0								
<i>Pinnularia quadratarea</i>	17	0.0	0.4	1.5	0.7	0.4	0.0	0.8	0.4	0.4	0.0	0.7	1.1	2.0	0.4	0.0	1.1	0.0	0.0	0.4	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4								
<i>Planorhithidium</i> spp.	2	14.8	15.0	12.3	12.4	12.4	5.7	10.0	5.2	10.2	7.6	13.2	14.0	6.7	7.1	8.7	17.9	11.0	4.1	13.8	5.2	11.6	10.2	13.7	8.3	10.6	2.7	11.4	9.5	12.6	10.3	8.3								
<i>Pseudostaurastrum brevistrata</i>	18	0.8	2.1	1.0	3.2	3.8	2.9	3.0	6.1	4.6	3.5	2.1	1.8	0.8	1.4	3.2	12.4	2.3	4.1	1.9	2.6	2.0	1.4	2.1	3.8	6.2	5.5	4.5	1.2	1.2	4.3	4.3								
<i>Stauroneis wislizenii</i>	19	0.8	1.3	4.2	0.0	0.4	0.4	0.0	0.0	0.0	0.4	1.4	0.4	0.0	0.7	0.4	0.0	0.0	0.0	3.3	0.8	1.1	0.8	0.3	0.0	0.0	0.0	0.0	3.9	3.7	0.0	0.4								
<i>Stauroneis construens</i> var. <i>pumila</i>	10	0.4	0.0	1.5	2.2	0.4	0.4	0.4	0.0	0.0	1.1	1.0	0.0	0.0	2.1	0.4	0.0	2.0	0.4	1.1	0.8	0.4	0.4	1.4	1.1	0.0	0.8	0.0	3.5	6.5	1.5	2.1								
<i>Stauroneis construens</i> var. <i>venter</i>	11	2.8	9.7	3.4	10.6	18.1	17.1	12.0	29.4	18.0	9.5	6.8	7.0	1.6	8.9	16.4	47.3	9.8	24.9	1.4	6.0	8.2	7.5	7.5	13.6	10.2	31.1	15.9	2.1	6.9	22.9	26.0								
<i>Trachyneis aspera</i>	20	2.4	1.8	1.9	2.9	0.8	0.4	1.6	1.2	2.5	3.1	2.4	4.2	7.1	3.6	1.5	6.3	2.8	2.1	1.4	0.8	1.1	3.8	3.1	3.4	1.7	0.4	2.7	0.7	0.0	0.4	1.2								
Unknown pennate sp. a	21	0.0	0.4	1.1	0.0	0.0	0.4	0.0	0.4	0.4	0.8	0.0	0.0	0.0	0.4	0.0	2.1	0.0	0.0	0.4	0.0	0.0	0.0	0.7	0.0	1.3	0.4	0.4	0.4	0.0	0.0	0.0								

Table 8.2 Relative abundances of diatom species used in RDA ordination.

Constrained RDAs were used to identify the importance of individual variables in explaining the species data (ter Braak, 1998). The ratio of the eigenvalue of the first constrained axis to the eigenvalue of the second unconstrained axis identifies the relative importance. Ratios greater than 0.50 indicate there is a significant relationship between the diatom data and that particular variable (Dixit et al., 1991). Copper, lead, tin and iron all had ratios equal to, or greater than 0.5. As an individual variable, tin made the greatest contribution to explaining the variation in species data (0.617).

As	1.000												
Cd	0.667	1.000											
Cr	0.739	0.541	1.000										
Cu	0.491	0.260	0.892	1.000									
Fe	0.475	0.184	0.899	0.951	1.000								
Pb	0.539	0.151	0.873	0.919	0.958	1.000							
Mn	0.729	0.636	0.755	0.522	0.550	0.588	1.000						
Ni	0.817	0.917	0.798	0.547	0.506	0.479	0.754	1.000					
Ag	0.732	0.626	0.951	0.820	0.823	0.802	0.722	0.818	1.000				
Sn	0.464	0.150	0.874	0.930	0.975	0.965	0.574	0.471	0.795	1.000			
Zn	0.774	0.707	0.921	0.813	0.761	0.772	0.816	0.866	0.930	0.747	1.000		
TOC	0.910	0.874	0.745	0.438	0.430	0.450	0.779	0.942	0.787	0.397	0.824	1.000	
	As	Cd	Cr	Cu	Fe	Pb	Mn	Ni	Ag	Sn	Zn	TOC	

**Table 8.3 Correlation coefficients between metal variables within Brown Bay.**

Preliminary analyses indicated that the combination of cadmium, copper, nickel, tin, silver, zinc and TOC explained the greatest amount of variation in the diatom data, without incorporating variables with high VIFs ( $>20$ ). The first four ordination axes explained a cumulative total of 47.5% of the variation in the diatom data. An unrestricted Monte Carlo permutation test of the trace statistic indicated that the species abundance is significantly related to these variables ( $p = 0.01$ ). Despite the high correlation between tin and copper (0.929), the VIFs remained below twenty and the exclusion of either decreased the amount of variation in the diatom data that was explained by the selected environmental variables.

The first two ordination axes explain 31.2% and 11.0% of the variation in diatom abundances respectively. The diatom-environment correlations for Axis 1 (.903) indicate a strong relationship between the diatom taxa and these metals while the diatom-environment correlations for Axis 2 (.766) indicate a moderately strong relationship. Unrestricted Monte Carlo permutation tests indicated that the species abundances were significantly related to Axis 1 ( $p = 0.01$ ), which is correlated with copper (Table 8.4). Axis 2 is correlated to several metals; the strongest correlation was with zinc, however copper, silver and tin were also correlated with this axis. Unrestricted Monte Carlo permutation tests indicated that diatom abundances were significantly related ( $p=0.01$ ) to Axis 2 (with Axis 1 as a co-variable). Diatom abundances were not significantly related to subsequent ordination axes ( $p = 0.05$ ).

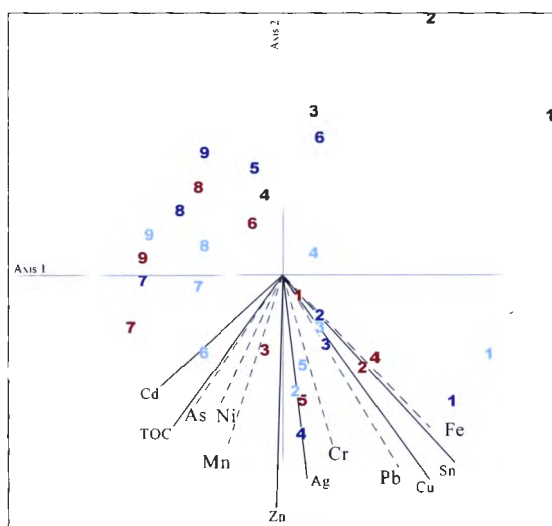
	Axis 1	Axis 2	Axis 3	Axis 4
Cadmium	-0.408	-0.308	0.474	-0.006
Copper	0.469	<b>-0.587</b>	0.210	0.125
Silver	0.095	<b>-0.573</b>	0.247	0.240
Tin	<b>0.514</b>	<b>-0.562</b>	0.001	0.136
Zinc	0.016	<b>-0.679</b>	0.258	0.084
TOC	-0.373	-0.438	0.297	0.171

**Table 8.4** Intra-set correlations between active environmental variables and ordination axes. Significant correlations are shown in bold.

Forward selection identified 2 environmental variables which accounted for approximately 70.1% of the variance explained by the 6 active variables. Unrestricted Monte Carlo permutation tests confirmed the significance of these two variables

( $p = 0.01$ ). Tin accounted for 34.0% of the variance explained by the active variables and zinc accounted for a further 36.1% of this variance. Copper ( $p = 0.05$ ) and cadmium ( $p = 0.03$ ) each explained a further 10.6% of the variation in diatom abundances that was related to the active variables. The remaining variables did not individually explain any additional significant percentage of the variance observed within the diatom data ( $p = 0.05$ ).

The relationships between samples and the environmental variables are shown in Figure 8.3. The first ordination axis, from left to right, corresponds to a gradient of increasing concentrations of tin (and correlated metals). The sampling locations that were closest to the tip site typically plot on the RHS of this ordination (Fig 8.3),

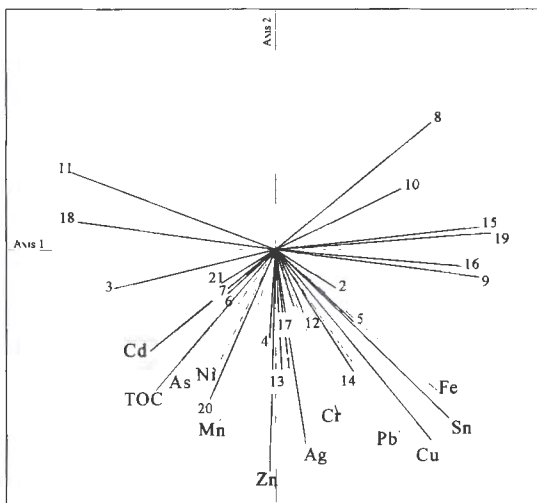


**Figure 8.3** RDA ordination showing the relationship between diatom communities and environmental variables (metal concentrations) within the contaminated Brown Bay. Active variables are shown by a solid black line, passive variables are indicated by a grey dashed line. Transects 1-4 are indicated by the colours dark blue, brown, light blue and green respectively. The numbers 1-9 indicate sample order within each transect, and correspond to increasing distance from the tip site.

reflecting their high concentrations of these metals. Conversely, samples collected further from the tip site plot on the LHS of the ordination, indicating lower concentrations of these metals. Axis 2 was correlated primarily with zinc, with concentrations increasing from top to bottom. No relationship between these variables and the sampling locations was apparent (Fig 8.3).

High concentrations of tin are associated with increased abundances of *Cocconeis costata* and *Planothidium* spp., indicated by the angle between environmental variables and species vectors in the ordination plot (Fig. 8.4). Similarly, increased abundances of *Navicula directa* and *Navicula* sp. c were associated with increasing copper concentrations. In contrast, *Pseudostaurosira brevistriata* and *Staurosira construens* var. *venter* are negatively correlated with both these metals.

Increasing abundances of *Achnanthes brevipes*, *Navicula* sp. b, and *Catacombas camtschatica* are strongly correlated with increasing concentrations of zinc.



**Figure 8.4** RDA ordination showing approximate correlations between species and environmental variables, indicated by the angle between the different vectors. Small angles indicate a high correlation; right angles indicate no correlation whilst angles approaching 180 ( indicate high negative correlations. Active environmental variables are depicted with a solid red line. Passive variables are indicated with a dashed grey line. Species names (and numbers) are given in Table 8.2.



*Trachyneis aspera* appears to correlate with increasing levels of nickel and manganese. Increased concentrations of cadmium and TOC are correlated with increased abundances of *Cocconeis fasciolata* and *Cocconeis schuettii* but negatively correlated with *Achnanthes* sp. a and *Staurosira construens* var. *pumila*.

### Discussion

The results clearly demonstrate that diatom composition is strongly related to varying concentrations of metals within Brown Bay. The chemical contaminants explained a large proportion of variation observed in the diatom communities. Tin and zinc were both highly significant, each explaining more than a third of the variation due to the environmental variables. Toxic effects of zinc primarily result from inhibition of the uptake of nutrients (Santana-Casiano et al., 1997; Sunda and Hunstman, 1996). Zinc has previously been shown to have detrimental effects on microphytobenthos, with changes in both community composition and structure observed (Ivorra et al., 2000).

Tin concentrations were highly correlated ( $>0.90$ ) with copper, iron and lead. The individual influence of these four metals can not be distinguished, thus the observed relationship between diatom composition and tin may actually result from the effects of copper, lead, or iron. Of these four metals, the toxic effects of copper on diatom communities have been most studied. Copper can interfere with the action of the oxidising site on PSII and has an inhibitory effect on photosynthesis (Cid et al., 1995). Copper can also produce toxic effects through its inhibition of the uptake of manganese (Sunda and Huntsman, 1998). Copper concentrations of  $0.1 \text{ mg l}^{-1}$  and  $0.5 \text{ mg l}^{-2}$  reduce growth and photosynthetic rates of the marine diatom *Phaeodactylum tricornutum* by 50% (Cid et al., 1995). Comparisons of copper, zinc and cadmium have shown copper to be the most toxic (Fisher and Frood, 1980). What little information is available on lead toxicity relates to fish and invertebrates. Acute toxicity values range between 1 and  $480 \text{ mg Pb l}^{-1}$ , however this is strongly related to the amount of  $\text{CaCO}_3$  present in the water (Helliwell, 1986). Although very little data exists on the toxicity of tin to organisms, it appears to be low

(Helliwell, 1986). Insufficient information exists regarding the toxicity of iron on organisms for comparative assessments to be made. Based on current data, it most likely that the concentrations of copper are producing the observed effects on diatom abundances, however future investigations of lead, iron and tin may demonstrate similar toxic effects.

Cadmium explained 10% of variation in the diatom abundances that related to the environmental variables. Cadmium can be highly toxic at low doses as it accumulates within the organisms and is thought to damage ion-regulating mechanisms (Helliwell, 1986). Experimental studies of cadmium toxicity found that cadmium concentrations of  $2 \mu\text{g l}^{-1}$  reduced the growth rate of the diatom *Asterionella formosa* by an order of magnitude, and  $10 \mu\text{g l}^{-1}$  resulted in the cessation of growth (Conway, 1978). Field studies have shown that concentrations of cadmium as low as  $0.2 \mu\text{g l}^{-1}$  significantly reduced photosynthesis and primary production by planktonic communities (Marshall and Mellinger, 1980).

TOC contributed significantly to the variation in diatom data that was explained by the environmental variables. TOC is a measure of the total organic carbon present in the sediments. Whilst studies investigating the influence of this variable on the toxicity of metals are not known to the author, many studies have demonstrated that dissolved organic carbon (DOC) complexation can ameliorate metal toxicity on phytoplankton (Riseng et al., 1991). It is possibly that TOC acts in a similar manner, thus concentrations of this variable may influence the apparent response of diatom communities to concentrations of metals.

Several contaminants explained similar percentages of the variation within the diatom communities. This can occur either when the distribution of several metals are highly correlated, or when different metals have similar effects on the diatom communities. Antagonistic, synergistic and over-additive responses have all been observed when the toxic effects of 2 or more metals have been examined. The metal pairs of copper-zinc, and copper-cadmium both exhibit antagonism when applied to

the diatoms *Phaeodactylum tricornutum* and *Skellontonema costatum*, clone Skel 0, but acted in a synergistic manner when applied to the diatom *Thalassiosira pseudonana* (Braek et al., 1980). The antagonism observed between metals is hypothesised to result from competition for uptake sites (Braek et al., 1980). Manganese also competes with copper, zinc, and cadmium for uptake sites in *Phaeodactylum tricornutum* and it is likely that many divalent cations compete for uptake via the same route in this species (Braek et al., 1980). Common uptake mechanisms have previously been found in many different organisms (Braek et al., 1980). It is conceivable that a common uptake mechanism may contribute to the observed inter-changeability of some metals, with regard to explaining variation in the diatom data.

The difficulties associated with identifying the individual effects of environmental variables highlights the need for multiple variables to be measured. If only arsenic, cadmium, copper, manganese and TOC had been measured, then the data would have indicated that copper, and copper alone was predominantly responsible for the observed variation in diatom data. By measuring an increased number of variables, the accuracy of the results is increased (Underwood and Peterson, 1988).

This study demonstrated a strong relationship between metal concentrations and diatom community composition, however, it cannot yet be concluded that metal concentrations are causing the observed patterns in diatom communities. Correlations are only conclusive if it is known that no other factor has a similar pattern as that of the perturbation (Underwood and Peterson, 1988). Not all environmental factors have been sufficiently defined within Brown Bay for such a conclusion to be drawn. One obvious omission from this study is grain-size data. Not only can grain-size influence diatom community composition (Chapter 5) but metals are often associated with fine-grained sediments (Goldberg et al., 1975). The relationship between sediment grain-size and metal concentration is a primary focus of the research currently being undertaken by Rebecca Scouller and has therefore not been considered in this study.

Several of the *Navicula* species included in this investigation had a positive correlation with metal concentrations. As metal concentrations increased, so did the relative abundances of *Navicula directa*, *Navicula* sp. c, and *Navicula* sp. b. This indicates that these species are metal tolerant, and can exploit conditions where less tolerant species are reduced. These results further suggest that *Navicula* may be metal tolerant as a genus, although the relative abundances of *Navicula* aff. *glaciei* and *Navicula* sp. a were not significantly correlated with the metals examined. In this study, *Pseudostaurosira brevistriata*, *Staurosira construens* var. *venter*, *Staurosira construens* var. *pumila* and *Amphora pediculus* all appear to be metal sensitive, reducing in abundance when metal concentrations are increased. This is consistent with previous reports of *Staurosira construens* being sensitive to metal pollution (Ruggiu et al., 1998). The relative abundances of these species may therefore be of use in the assessment of potentially impacted sites within Antarctica, however, further research would be required to examine whether these responses are maintained in different locations.

Direct gradient techniques, such as those used in this study, facilitate the development of transfer functions which predict the value of an environmental variable based on observed diatom community compositions. Diatom-based transfer functions have previously been used to predict a variety of variables including water depth (Campeau et al., 1999), salinity (Roberts and McMinn, 1998; Sylvestre et al., 2001), pH (Stevenson et al., 1989; ter Braak, and Van Dam, 1989) nutrients (Reavie and Smol, 2001) and chlorophyll *a* (Jones and Juggins, 1995). The strong relationships observed between the diatom abundances and metal concentrations in this study indicate the feasibility of reconstructing past metal concentrations within Brown Bay.

### Conclusions

The abundance patterns of diatom species within Brown Bay are significantly related to the concentrations of various heavy metals within this bay. Zinc and tin appear to be the most significant factors in determining diatom community composition.

However, copper, iron and lead are all highly correlated with tin, thus it cannot be determined which of these metals is responsible for the observed effects. Should interactions between grain-size, metal concentrations and diatom abundances be clarified, the development of diatom based transfer functions for monitoring purposes could be undertaken.

*Navicula* species were generally found to be pollution tolerant, occurring at high abundances in samples which contained high concentrations of metal contaminants, particularly tin. In contrast, *Pseudostaurosira brevistriata*, *Staurosira construens* var. *venter* and *Amphora pediculus* were shown to be sensitive to pollution. These species may prove to be a useful indicator of metal contamination within Antarctic regions, however, further verification of this would be required.

### ***A preliminary assessment of the relationship between hydrocarbon concentrations and the composition of benthic diatom communities within Brown Bay.***

#### **Abstract**

Redundancy analysis was used to assess the relationship between total purgeable hydrocarbon (TPH) fractions (C6-C9, C10-C14, C15-28 and C29+) and diatom abundances within a contaminated bay adjacent to Casey Station in the Windmill Islands, Antarctica. *Achnanthes brevipes*, *Navicula directa* and *Trachyneis aspera* were positively correlated with concentrations of TPH. *Staurosira construens* var. *pumila* and *Achnanthes* sp. a had strong negative correlations with TPH concentrations. Diatom abundances were significantly related to both the chemical variables overall (as indicated by the trace statistic) and the first ordination axis at a significance level of 10%.

#### **Introduction**

Petroleum hydrocarbons have previously been shown to have a significant impact on diatom communities. Compositional differences, with marked changes in the presence or absence of species, were observed between control communities and those exposed to either light crude oil, or diesel based oil-cuttings (Plante-Cuny et al., 1993). More subtle compositional differences have also been recorded, with pollution sensitive species inhibited, as a result of hydrocarbon contamination (Morales-Los and Goutz, 1990). Typically, marine species are more sensitive to hydrocarbon contamination than their freshwater counterparts (Kusk, 1991). Pennate diatoms may be more tolerant than centric diatoms, with one study (Siron et al., 1996) reporting an increase in the relative abundances of pennate species, in treatments exposed to dispersed, but not absorbed, oil.

Previous studies have demonstrated that the marine sediments of Brown Bay, near Casey Station in the Windmill Islands, have been contaminated with petroleum hydrocarbons as a result of station activities, (Cole et al., 2000). Petroleum hydrocarbons are present in the sediments of Brown Bay at concentrations of up to 200 mg TPH kg<sup>-1</sup> (Snape et al., 2001). No petroleum hydrocarbons have been detected at control locations in the Windmill Islands (Snape et al., 2001).

It has previously been shown that the composition of diatom communities in Brown Bay is both spatially and temporally related to the occurrence of metals within the sediments (Chapters 6 and 8). The purpose of this paper is to examine the distribution of both hydrocarbons and diatom communities and to assess if they are related. If the concentrations of hydrocarbons present within Brown Bay have impacted the diatom community, it would be expected that a high correlation would be observed in the distributions.

## **Methods**

### **Site description**

The Windmill Islands cover an area of approximately 75 km<sup>2</sup> in Wilkes Land Antarctica. "Casey Station" is situated at 66° 17' S, 110° 32' E, on Bailey Peninsula in the Windmill Islands. Casey Station is the third permanent research station to operate in the region. Its immediate predecessor, Old Casey, was also located on Bailey Peninsula, approximately 800 m northeast of the current Casey Station.

Several fuels spills have occurred in the immediate area of Casey and Old Casey Stations. In 1982, approximately 38,000 litres of diesel fuel leaked from the storage farm adjacent to the wharf and entered Newcomb Bay, resulting in an oil slick (Deprez et al., 1994). In 1990, a temporary storage tank, also adjacent to the wharf, leaked approximately 59,000 litres of fuel (Deprez et al., 1994). A further 16,000 litres of fuel was spilt at the upper fuel farm in 1999, the majority of which entered Brown Bay via Thala Valley (Deprez et al., 1999). A number of smaller fuel spills

around the Old Casey mechanical workshop have resulted in this area having the highest petroleum-hydrocarbon levels ( $47,600 \text{ mg TPH kg}^{-1}$ ) that were recorded in soils around Casey Station (Snape et al., 2001). Approximately twenty sites in the immediate vicinity of the Old Casey Station have been identified as either contaminated, or potentially contaminated (Deprez et al., 1994; Deprez et al., 1999). These sites include the Old Casey mechanical workshop, the Old Casey powerhouse, and the now-abandoned Thala Valley tip site.

The mobility of contaminants from the above sites increases the potential for environmental impacts. Petroleum hydrocarbons have been traced from the area surrounding the Old Casey mechanical workshop, through the Thala Valley catchment area, and into Newcomb Bay (Guille et al., 1997; Cole et al., 2000). The processes responsible for this movement have yet to be fully clarified with both surface run-off (Guille et al., 1997) and the movement of groundwater (Cole et al., 2000) implicated. Petroleum hydrocarbons, derived from lubrication oil and Special Antarctic Blend diesel fuel (SAB) are present in the surface sediments of Brown Bay at concentrations ranging between 40 and  $200 \text{ mg THP kg}^{-1}$ . In contrast, no petroleum hydrocarbon contaminants were detected in sediments from control locations (Snape et al., 2001).

Brown Bay is a small embayment at the southern end of Newcomb Bay, immediately adjacent to the Thala Valley tip site (Fig. 9.1). Aligned approximately east-west, the maximum depth of 20 m occurs at the eastern end where Brown Bay enters Newcomb Bay. The rocky sides grade to a relatively homogenous muddy bottom (Stark, 2000), however, close to the tip site discarded material protrudes through the sediment.

### **Sampling Design**

A series of sediment samples were collected from within Brown Bay (Fig 9.1). Nine samples were collected at intervals along each of three parallel transects. Transect 1 was located on the southern side of the bay, Transect 2 in the centre of Brown Bay, and Transect 3 on the northern side. The transects were aligned approximately E-W,



and thus consecutive samples represent increasing distance from the tip-site. A fourth transect was established just outside of Brown Bay, and consisted of four sampling points. Sediment samples for diatom analyses were collected by divers inserting a small (5 cm diameter) PCV core tube into the sediments. This was capped, and the core removed from the sediment. On removal, the remaining end was also capped. Sediment samples for hydrocarbon analyses were collected by divers inserting small (5 cm diameter) glass jars into the sediment to a depth of 5 cm. On removal from the sediment, the jars were tightly capped with foil lined lids. All sediment samples were frozen at -20 (C for return to Australia.

### **Sediment Analysis**

Sample preparation was undertaken by Scott Stark (AAD). Twenty two sediment samples were analysed for total purgeable hydrocarbons (TPH), and the following fractions: C06-C09, C10-C14, C15-28, C29+. Metal concentrations were determined using GC-FID. Analyses were performed by technicians at the Sandy Bay Laboratory of Analytical Services Tasmania.

### **Diatom preparation and identification**

The top 5 cm of the sediment cores were homogenised and used for the diatom analyses. Organic material was removed from the sediment by digestion in a 10% hydrogen peroxide solution for 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Identification was as

described in Appendix 1. A minimum of 400 individuals of the predominantly benthic taxa was counted for each sample. The relative abundances of these taxa were then calculated and used in the statistical analyses. Only taxa which had a relative abundance of 2%, in at least one sample, were included in the analyses. Exclusion of rare taxa is on the basis that they may be allocthanous, for example, an exclusively freshwater species, *Luticola muticopsis*, was recorded in the sediment of Brown Bay, but was probably derived from the meltstream which enters Brown Bay.

### Statistical Analyses

A direct gradient ordination technique was used to examine the relationships between diatom abundances and TPH fractions, and to assess whether the distribution of any of these fractions explained a significant proportion of the variation observed in the diatom abundances. Although thirty one samples were collected, only those which were analysed for TPH were incorporated into the ordination. A preliminary CCA was performed to determine which type of analysis was most appropriate for the data. This revealed that the length of the ordination axes was less than 2 standard deviations, thus a linear response model was most applicable (ter Braak, 1987). Redundancy analysis (RDA) was therefore selected as the ordination method.

Both the species data and hydrocarbon concentrations were  $\log(x+1)$  transformed prior to analysis. All ordinations were performed using CANOCO version 3.12 (ter Braak, 1988, 1990). Multiple collinearity between environmental variables was examined using variance inflation factors (VIFs). Large VIFs ( $>20$ ) indicate that a variable is highly correlated with other variables, and thus contributes little information to the ordination (ter Braak, 1998).

Redundancy analysis was performed using the selected variables. Ordination scores were scaled for covariance biplots, as this maximises interpretation of the relationship between species (ter Braak, 1987-92). Eigenvalues indicate the importance of an ordination axis in explaining variation within the species data. The significance of the first ordination axis was determined using unrestricted Monte

Carlo permutation tests (99 permutations). The significance of the overall effect of the environmental variables on the species was determined by using the trace, instead of an ordination axis, in these tests.

## Results

### Chemical analysis

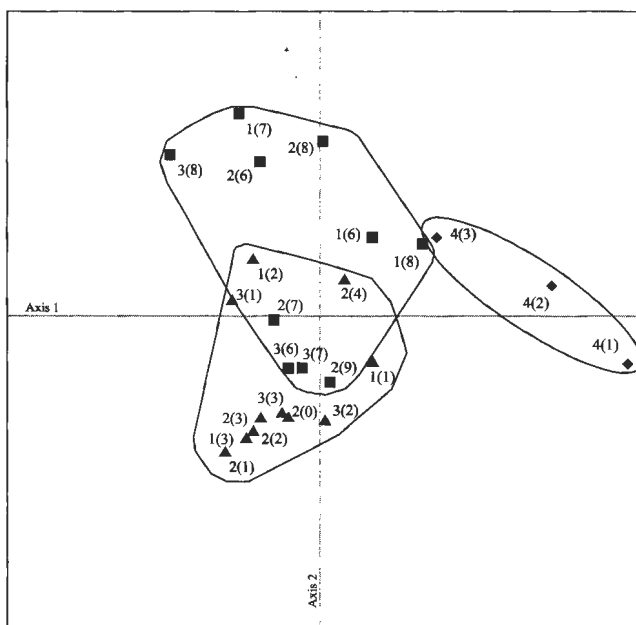
TPH fractions were quite variable within the sediments of Brown Bay (Table 9.1). The maximum value of 976 mg TPH kg<sup>-1</sup> was recorded in Sample 3 from Transect 1, the minimum recorded value of 23 mg TPH kg<sup>-1</sup> occurred in Sample 1 from Transect 4. These values exceed the range which have previously been reported for sediments from Brown Bay, namely 41-200 mg TPH kg<sup>-1</sup> (Snape et al., 2001). Samples from Transect 4 all had low concentrations of TPH, ranging between 23 mg kg<sup>-1</sup> and 63 mg kg<sup>-1</sup>. Only two other samples had TPH concentrations <100 mg kg<sup>-1</sup>; these samples represented the outermost samples from Transect 1.

Sample	TPH	C06-09	C10-14	C15-28	C29+
1 (1)	325	10	33	163	120
1 (2)	291	15	51	212	14
1 (3)	976	27	77	554	318
1 (6)	331	9	23	260	39
1 (7)	67	9	39	18	4
1 (8)	57	6	20	30	4
2 (0)	588	16	64	312	197
2 (1)	752	20	103	378	251
2 (2)	674	18	81	332	243
2 (3)	544	26	70	381	67
2 (4)	380	10	31	289	50
2 (6)	145	13	37	91	4
2 (7)	314	15	54	221	24
2 (8)	192	10	23	152	7
2 (9)	251	14	47	160	31
3 (1)	311	18	65	211	17
3 (2)	371	14	52	213	92
3 (3)	575	16	64	277	218
3 (6)	479	23	48	353	54
3 (7)	222	16	52	133	21
3 (8)	726	21	55	624	26
4 (1)	23	4	8	12	4
4 (2)	34	4	11	18	4
4 (3)	63	6	18	38	4

**Table 9.1** Concentrations (mg kg<sup>-1</sup>) of TPH, and fractions thereof, in sediment samples from the contaminated Brown Bay in the Windmill Islands, Antarctica. The sample number indicates transect with the sample position shown in brackets.

## Diatom analyses

Twenty one species attained a relative abundance greater than 2%, in at least one sample. The relative abundances of these species per sample are shown in Table 9.2. The relationships between samples, based on their diatom composition, is shown in Figure 9.2. The sampling locations that were closest to Thala Valley typically plot in the lower portion of this ordination (Fig. 9.2). Samples which were collected further from Thala Valley are located higher in the ordination. Samples from the fourth transect, just outside of Brown Bay, plot on the right hand side of the ordination.



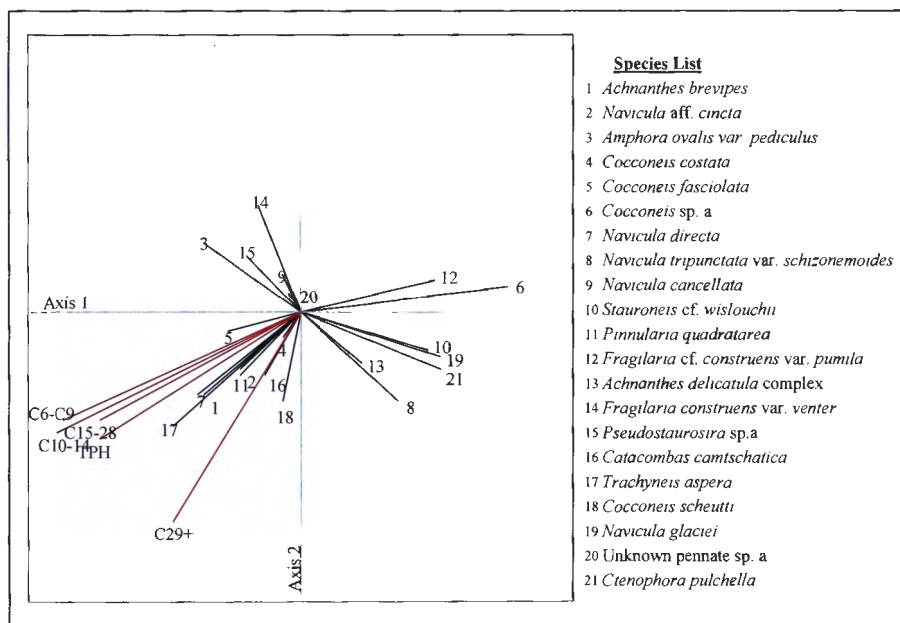
**Figure 9.2** Scatter plot showing the distribution of samples based on their diatom distribution. Samples are represented by the transect number, followed by the sample number in ( ). ▲ indicates samples close to the tip, ■ indicates samples collected further from the tip, ◆ indicates samples from the fourth transect, just outside of Brown Bay.

Species Name and Number	1 (1)	1 (2)	1 (3)	1 (6)	1 (7)	1 (8)	2 (0)	2 (1)	2 (2)	2 (3)	2 (4)	2 (6)	2 (7)	2 (8)	2 (9)	3 (1)	3 (2)	3 (3)	3 (6)	3 (7)	3 (8)	4 (1)	4 (2)	4 (3)	
<i>Achnanthes brevipes</i>	1.0	8.0	5.7	8.4	4.9	6.4	4.0	7.6	7.8	10.5	10.7	5.7	7.3	13.7	5.9	6.2	8.0	4.5	5.7	5.7	3.8	6.2	8.5	4.1	1.9
<i>Navicula</i> sp. b	2.0	3.5	1.9	2.9	0.4	0.8	1.6	3.8	0.0	2.5	1.2	1.1	0.4	3.2	0.8	0.0	1.6	1.9	0.8	0.8	0.4	0.4	0.0	0.8	0.4
<i>Amphora ovalis</i> var. <i>pediculus</i>	3.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	1.1	0.4	0.4	0.0	2.1	1.2	0.8	0.4	0.4	0.0	0.0	0.4	0.8	0.0	0.0	0.0
<i>Cocconeis costata</i>	4.0	1.8	1.1	1.5	0.8	0.8	0.4	0.0	0.7	1.8	1.6	2.5	0.7	1.1	0.4	0.0	2.0	0.0	1.5	1.1	0.0	0.4	1.1	0.8	0.4
<i>Cocconeis fasciolata</i>	5.0	8.0	5.7	5.5	4.9	13.3	2.4	7.6	8.1	9.8	13.4	8.2	6.5	20.0	11.8	10.0	6.0	5.6	11.7	5.3	6.0	5.4	7.4	4.1	8.8
<i>Achnanthes</i> sp. a	6.0	1.3	1.1	0.4	1.2	0.8	0.4	1.1	0.3	0.0	0.4	1.1	1.5	0.0	0.0	0.8	0.4	1.5	1.5	1.1	0.9	1.6	9.2	14.6	4.2
<i>Navicula directa</i>	7.0	4.4	1.9	0.7	1.2	0.0	0.4	0.4	2.7	4.6	2.8	1.1	3.6	1.1	0.8	0.8	2.0	1.9	3.0	0.8	0.0	0.8	0.4	0.0	0.4
<i>Navicula tripunctata</i> var. <i>schizonemoides</i>	8.0	0.4	1.5	1.1	1.6	0.0	0.8	0.8	3.4	0.4	0.8	1.1	0.7	0.0	0.4	0.4	2.0	1.1	0.8	0.4	1.3	0.4	3.5	2.4	0.0
<i>Navicula</i> sp. c	9.0	1.3	2.7	1.8	2.0	4.8	0.8	2.7	2.0	2.8	1.2	2.5	2.9	5.3	6.7	0.0	4.8	1.9	2.3	4.9	3.0	0.4	3.2	2.8	0.4
<i>Stauroneis</i> cf. <i>wislouchii</i>	10.0	1.3	4.2	0.0	0.4	0.0	0.0	0.4	1.4	0.4	0.0	0.7	0.4	0.0	0.0	0.0	0.8	1.1	0.8	0.0	0.0	0.0	3.9	3.7	0.0
<i>Pinnularia quadratarea</i>	11.0	0.4	1.5	0.7	0.0	0.8	0.4	0.0	0.7	1.1	2.0	0.4	0.0	1.1	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.0	0.4	0.4	0.4
<i>Staurosira construens</i> var. <i>pumila</i>	12.0	0.0	1.5	2.2	0.4	0.4	0.0	1.1	1.0	0.0	0.0	2.1	0.4	0.0	2.0	0.4	0.8	0.4	0.4	1.1	0.0	0.8	3.5	6.5	1.5
<i>Achnanthes delicatula</i>	13.0	15.0	12.3	12.4	5.7	10.0	5.2	7.6	13.2	14.0	6.7	7.1	4.7	17.9	11.0	4.1	5.2	11.6	10.2	8.3	10.6	2.7	9.5	12.6	10.3
<i>Staurosira construens</i> var. <i>venter</i>	14.0	9.7	3.4	10.6	17.1	12.0	29.4	9.5	6.8	7.0	1.6	8.9	16.4	47.3	9.8	24.9	6.0	8.2	7.5	13.6	10.2	31.1	2.1	6.9	22.9
<i>Pseudostaurosira</i> sp. a	15.0	2.1	1.0	3.2	2.9	3.0	6.1	3.5	2.1	1.8	0.8	1.4	3.2	12.4	2.3	4.1	2.6	2.0	1.4	3.8	6.2	5.5	1.2	1.2	4.3
<i>Catacombas camtschatica</i>	16.0	0.4	0.0	0.0	0.0	0.0	0.8	0.4	0.7	0.4	3.6	2.5	0.7	1.1	0.0	0.0	0.4	0.7	0.0	1.5	0.9	0.4	0.4	0.0	0.0
<i>Trachyneis aspera</i>	17.0	1.8	1.9	2.9	0.4	1.6	1.2	3.1	2.4	4.2	7.1	3.6	1.5	6.3	2.8	2.1	0.8	1.1	3.8	3.4	1.7	0.4	0.7	0.0	0.4
<i>Cocconeis schuetti</i>	18.0	0.0	0.0	0.0	0.0	0.4	0.0	0.3	1.1	2.0	1.1	0.7	1.1	0.0	0.8	0.4	0.7	0.8	0.4	1.3	0.4	0.4	0.4	0.4	0.4
<i>Navicula</i> aff. <i>glaciei</i>	19.0	4.0	7.3	1.1	4.9	0.8	0.4	0.4	5.4	0.7	2.8	3.6	1.5	1.1	1.6	0.0	2.8	5.6	4.5	1.5	1.7	0.0	10.2	15.9	1.9
Unknown pennate sp. a	20.0	0.4	1.1	0.0	0.4	0.0	0.4	0.8	0.0	0.0	0.0	0.4	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.4	0.4	0.0	0.0
<i>Ctenophora pulchella</i>	21.0	1.3	3.8	0.4	0.0	0.0	0.4	0.8	0.3	0.4	1.2	1.4	0.7	0.0	0.0	0.0	1.2	1.9	0.4	0.4	0.4	0.0	4.2	3.3	0.4

Table 9.2. Relative abundances of diatom species within sediment samples.

### Direct gradient analysis

The correlations between species and concentrations of TPH and the fractions are shown in Figure 9.3. Several species appear to be positively correlated with hydrocarbon concentrations, as indicated by the close angle between vectors. The vector length indicates that *Trachyneis aspera* has the most significant positive correlation with TPH concentrations, followed by *Achnanthes brevipes* and *Navicula directa*. Strong negative correlations were observed between hydrocarbon concentrations and the abundances of *Staurosira construens* var. *pumila* and *Achnanthes* sp. a. High vector angles ( $\sim 90^\circ$ ) indicate that the relative abundances of many species were not correlated with TPH concentrations. These species include *Navicula* sp. a, *Navicula* aff. *glaciei*, *Amphora pediculus*, *Ctenophora pulchella* and *Staurosira construens* var. *venter*.



**Figure 9.3** Biplot showing approximate correlations between species (black lines) and environmental variables (red lines), indicated by the angle between the different vectors. Small angles indicate a high correlation; right angles indicate no correlation whilst angles approaching  $180^\circ$  indicate high negative correlations. The length of the vectors indicates the significance of the correlation.

Redundancy analysis indicated that the chemical variables accounted for 27.1% of the variation in the diatom data, however this included collinear variables. Both total TPH and the fraction C15-28 had VIFs greater than 20, however removing total TPH from the active data set reduced the VIF of the fraction C15-28 to below 20. A subsequent analysis explained 23.3% of the variation in diatom data, with Axes 1 and 2 accounting for a total of 20% (15.4% and 4.6% respectively). These axes captured a total of 85.7% of the variance in the species-environment relationship.

Interset correlations (Table 9.3) indicate that Axis 1 is significantly correlated to all TPH fractions other than C29+. No significant correlations occurred between the environmental variables and Axis 2. Forward selection indicated that each of the TPH fractions C6-C9 ( $p = 0.01$ ) and C10-14 ( $p = 0.02$ ) could individually explain 60.9%

	Axis 1	Axis 2	Axis 3	Axis 4
TPH C6-C9	<b>-0.647</b>	0.122	0.129	-0.120
TPH C10-C14	<b>-0.666</b>	0.142	-0.025	0.041
TPH C15-28	<b>-0.547</b>	0.133	-0.092	-0.322
TPH C29+	-0.371	0.370	-0.154	-0.143

Table 9.3. Interset correlations showing the correlation between environmental variables and RDA ordination axes. Significant correlations ( $>0.50$ ) are shown in bold.

of the variation in diatom abundances which could be explained by the environmental variables. Once either of these variables had been selected, no other variables individually explained a significant proportion of the variation observed in the diatom data. Unrestricted Monte Carlo permutation tests (99 permutations) indicated the trace was significant at a  $p$ -value of 0.09. Axis 1 was significant at a  $p$ -value of 0.07.

## Discussion

The concentrations of TPH and TPH fractions in the sediments of Brown Bay were significantly related to the diatom abundances only at a significance level of 10%. Measuring TPH, and fractions thereof, does not allow discrimination between naturally occurring hydrocarbons and anthropogenically derived contaminants (Cripps and Priddle, 1991). It is possible that the presence of naturally occurring hydrocarbons may be adding "noise" to the data set, thus increasing the error. This may explain the higher significance level observed between the environmental variables and diatom abundances, however more detailed data, specifically the individual concentrations of natural and anthropogenic hydrocarbons, would be required to verify this.

Naturally occurring hydrocarbons are usually present in Antarctic marine sediments at concentrations ranging between 0.1 - 9.3 mg TPH kg<sup>-1</sup> (Cripps and Priddle, 1991), however, values up to 48 mg TPH kg<sup>-1</sup> have been reported from anoxic fjords near Davis Station (Green and Nichols, 1995). TPH concentrations measured from two sediment cores in Sparkes Bay, a control location in the Windmill Islands, ranged from <20 mg TPH kg<sup>-1</sup> to 195 mg TPH kg<sup>-1</sup> (unpublished data). All samples from Transect 4 had TPH concentrations at the lower end of this range, as did the two outermost samples from Transect 1. Two samples from Transect 2 had TPH concentrations within the higher end of this range; these samples were among those collected from the outer regions of Brown Bay. This suggests that petroleum contaminants within Brown Bay are predominantly restricted to sediments in close proximity to Thala Valley. Petroleum hydrocarbon contamination is also very localised at Signy Island (Cripps, 1992), South Georgia (Cripps, 1994) and McMurdo Station (Lenihan et al., 1990), despite total purgeable hydrocarbons concentrations up to 4500 mg kg<sup>-1</sup> at the latter (Lenihan et al., 1990).

Despite the higher significance level (10%), the relative abundances of several diatom species were correlated with TPH concentrations. The two species which were negatively correlated with TPH fractions, namely *Staurosira construens* var.



*pumila* and *Achnanthes* sp. a, were also found to be negatively associated with total organic carbon (TOC) (Chapter 8), probably reflecting the relationship between these environmental variables. *Achnanthes brevipes*, *Trachyneis aspera* and *Navicula directa* were all positively correlated with TPH concentrations. These three species were also positively correlated with metal concentrations (Chapter 8); both *Achnanthes brevipes* and *Trachyneis aspera* increased with increasing Mn and Ni, while *Navicula directa* increased with Cu concentrations. This suggests that either that the species are generally pollution tolerant, or that the concentrations of TPH and these metals are correlated. Further analyses would be required to verify this.

In addition to a possible correlation between metal and TPH concentrations, it is possible that other environmental variables, such as grain-size, could also be correlated with the observed distribution of TPH fractions within the sediment. The proportion of fine sediments (<63  $\mu$ m) accounts for a significant proportion of variability in diatom abundances (Chapter 5). As hydrocarbons typically enter subtidal sediments in association with fine particular matter, it is likely that the distribution of hydrocarbons would therefore be related to the proportion of fine sediments. This relationship is currently being examined by Rebecca Scouller, and is therefore not assessed within this project. If a relationship between petroleum hydrocarbon contamination and diatom abundances was to be demonstrated, the influence of such environmental variables would first need to be allowed for.

The first two ordination axes explained 23.3% of the variation in the diatom data, capturing 85.7% of the species-environment relationship. These values are higher than many used to as the basis of a transfer function. Campeau et al. (1999) based a water-depth transfer function on ordination axes which explained 17.7% of the variation in diatom data, and captured 61% of the diatom-environmental relationship while Roberts and McMinn (1998) based a salinity transfer function on data which explained 19.6% of the variation in diatom abundances. Should the observed relationship between petroleum hydrocarbon contamination and diatom abundances be maintained after potential interactions with grain-size and metals is resolved, it

would then be feasible to construct a transfer function based on this data. This would enable the concentration of petroleum hydrocarbons to be determined given a known diatom composition, and would therefore be a viable option for future monitoring of contaminants within Brown Bay.

### **Conclusions**

Although diatom abundances and concentrations of TPH fractions were shown to related at a 10% significance level, it is recommended that further investigations be undertaken to discriminate between naturally occurring hydrocarbons and those that are anthropogenic contaminants. The distribution of TPH fractions explained 23.3% of the variability in diatom abundances. Should potential interactions between the distribution of TPH fractions and other environmental variables, such as grain-size and metal concentrations, be sufficiently quantified, it would be possible to construct transfer functions which would be applicable for monitoring purposes.

## Chapter 10

### ***The effects of heavy metal and hydrocarbon contamination of sediments on the development of benthic diatom communities***

#### **Abstract**

A manipulative field experiment was used to assess the influence of sediment contamination on the development of diatom communities near Casey Station. Both contaminated and uncontaminated (control) sediments were deployed at several locations for a twelve month period. Two of these locations are potentially impacted, having been contaminated with heavy metals. It was only within one of these potentially impacted locations that significant differences in community composition between contaminated and uncontaminated sediments were observed. No structural differences were detected between diatom communities which developed on contaminated sediments and those that developed on control sediments.

#### **Introduction**

The benthic microflora of Antarctic regions consists almost entirely of diatoms (Gilbert, 1991). Diatoms have been shown to have narrow tolerance ranges for many environmental variables, and respond rapidly to environmental change, making them ideal bioindicators (Reid et al., 1995). Contaminants can affect the growth rate and species composition of diatom communities, with subsequent implications for organisms higher in the foodchain (Stronkhurst et al., 1994). The terrestrial environment surrounding past and present research stations in the Windmill Islands has been contaminated with heavy metals and hydrocarbons (Deprez et al., 1999). Several marine bays immediately adjacent to these stations have also been contaminated (Snape et al., 2001; Scouller et al., 2000).

Current data suggests that the composition of diatom communities in these bays has been affected by chemical contaminants. Both Shannon Bay and Brown Bay showed different patterns of spatial variability in diatom communities than control locations within the Windmill Islands (Chapter 4). The species composition of benthic diatom communities around Casey Station differs significantly between Brown Bay and uncontaminated sites further away from the station (Chapters 3, 4 and 5). Furthermore, the composition of diatom communities of Brown Bay appears to be correlated with metal concentrations in the sediments (Chapter 8).

The effects of sediment contamination on diatom communities are not well understood. This study is one of the first to examine how chemical contamination of marine sediments affects the microphytobenthos which inhabit them. The majority of work examining the sensitivity of diatoms to pollution has been based on phytoplankton (eg. Hsiao, 1978). Whilst the use of periphyton for pollution monitoring has increased in recent years, this has typically been related to water quality (eg. Ivorra et al., 1999) and not sediment contamination. This chapter examines diatom community response to sediment contamination at levels similar to those which currently occur within Brown Bay.

A manipulative field experiment was used to examine differences in the composition and structure of diatom communities which developed on contaminated sediments from Brown Bay relative to those which developed on uncontaminated sediments. Manipulative field experiments are the most appropriate means of demonstrating causal relationships between environmental factors, such as contamination, and observed biological patterns (Underwood, 1989). Manipulative experiments using benthic microalgae are very scarce (Ivorra et al., 1999), but generally consist of the translocation of diatom communities between sites. One problem associated with this approach is that the environmental factors examined are typically associated with the sites, and may not necessarily be independent of other processes acting at these sites. By deploying both contaminated and control sediments at several locations, the effects of sediment contamination can be observed within each location. If

differences in the community composition are observed between control and contaminated sediments within one or more sites, this can be attributed directly to the sediment type.

## **Methods**

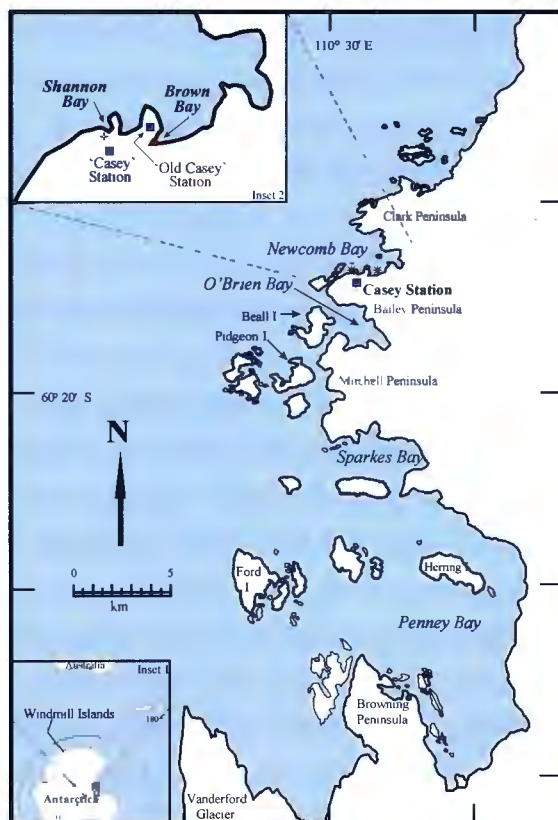
### **Site description**

The Windmill Islands are a small deglaciated oasis in Wilkes Land, Antarctica (Fig. 10.1) which cover an area of approximately 75 km<sup>2</sup>. The Windmill Islands represent the only large area of seasonally snow-free terrain for over 400 km of coastline, either east or west (Murray and Luders, 1980). The ANARE research station, Casey is situated within this region, and is located at 66° 17' S, 110° 32' E. Casey is the third research station to have been built within the area and was opened in 1989. The first station, Wilkes, was established in 1959 but was succeeded by "REPSTAT" (now known as "Old Casey") in 1969. All three stations have been located on peninsulas surrounding Newcomb Bay.

Heavy metal and hydrocarbon contamination of the terrestrial environment surrounding all three stations has previously been reported (Deprez et al., 1999; Snape et al., 2001). Some of these contaminants have also entered the marine environment immediately adjacent to Casey Station. Brown Bay is the worst affected with some heavy metals (including copper, lead, iron and zinc) at concentrations 10 to 100 times higher than background levels, whilst Shannon Bay also has elevated concentrations of many of these metals (Snape et al., 2001). Elevated levels of ammonia, total phosphorous and bacteria have also been recorded near the station sewage outfall in Shannon Bay (Morris et al., 2000). Petroleum hydrocarbons, derived from lubrication oil and Special Antarctic Blend diesel fuel (SAB) are present in the surface sediments of Brown Bay at concentrations ranging between 40 and 200 mg kg<sup>-1</sup>, whereas no petroleum hydrocarbons occur in sediments from control locations (Snape et al., 2001).

### Brown Bay

Brown Bay is a small embayment in the southern region of Newcomb Bay, immediately adjacent to an abandoned tip site (Inset 2, Fig. 10.1). During summer, a melt stream runs down Thala Valley, through the tip site and into Brown Bay, transporting contaminants into the bay. Concentrations of heavy metals in marine sediments from Brown Bay are 10-100 times higher than from equivalent control sediments (Scouller et al., 2000). High concentrations of petroleum hydrocarbons have been recorded in sediments from this bay, however none have been detected in sediments from control locations (Snape et al., 2001).



**Figure 10.1** Map of the Windmill Islands, showing Casey Station and experiment locations (\*). Inset 1 shows the position of the Windmill Islands relative to Australia. Inset 2 shows the surrounds of Casey Station, including the sewage outfall (+), and the now defunct Thala Valley tip site (▲).

The rocky sides of this bay grade to a sediment covered bottom. Close to the tip site, patches of sediment occur between boulders, discarded tip material and areas of bare rock. Further away from the tip, areas of fine sediments are more extensive and relatively homogenous (Stark, 2001), but are still occasionally interrupted by large boulders. The maximum depth of 20 m occurs at the junction with Newcomb Bay. Brown Bay is typically ice free for 1-2 months a year, generally between January and February. Brown Bay is aligned with the dominant wind direction, thus the sea-ice in Brown Bay is rarely blown out during the winter period.

### *Shannon Bay*

Shannon Bay is a small embayment within the south-western corner of Newcomb Bay, approximately 800 m west of Brown Bay. Shannon Bay is bordered by 2-15 m ice cliffs, with the sewage outfall situated 30 m landward of the eastern cliff (Inset 2, Fig. 10.1). The input of treated waste-water from the present Casey station has resulted in elevated levels of ammonia, total phosphorous and bacteria within Shannon Bay (Morris et al., 2000; in prep). Preliminary sampling of Shannon Bay also indicated elevated concentrations of heavy metals (Scouller et al., 2000).

The subtidal sides of this bay consist of steeply sloping rock and boulder fields below which is a relatively homogenous muddy sand (Stark, 2000). A maximum depth of 32 m was recorded at the mouth of this bay. This bay is generally ice free for a longer period than Brown Bay, with open water occurring between December and March.

### *O'Brien Bay*

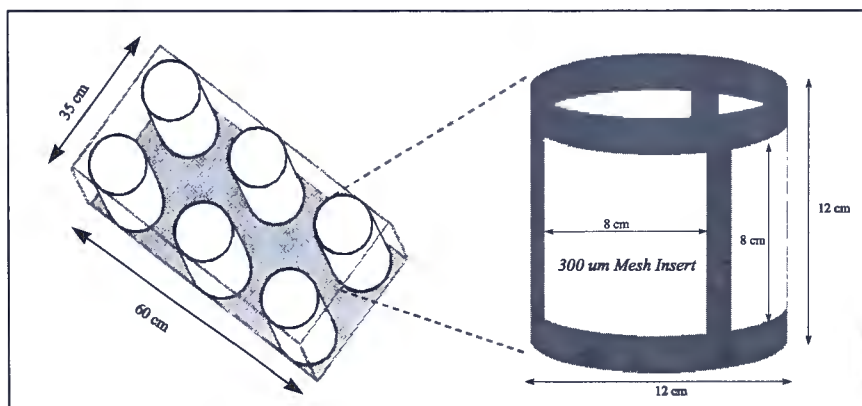
This bay is located several kilometers south of Casey Station. The margins of this bay primarily consist of ice cliffs dropping vertically into deep water and steep rocky shorelines. The eastern end of this bay generally has a year-round cover of sea-ice, although this breaks out in exceptionally warm summers. This bay was chosen as a control because it is unlikely to be contaminated by human activity, and is easily accessible. The two locations used in this experiment were both on the northern side of this bay, as the southern side of the bay consists predominantly of steep cliffs and exposed rock. The sites selected consisted of steeply sloping boulder fields as well

as more gently inclined rocky banks. Patches of poorly mixed mud and sand, interspersed between gravel, cobbles and boulders formed the bottom sediments of this area (Stark, 2000).

### Experimental Methods

Contaminated and control sediments were used for the experiment. Contaminated sediments were collected from Brown Bay while control sediments were collected from the unpolluted O'Brien Bay. The sediments were collected by Van Veen grab or divers using polyethylene buckets. The sediments were frozen at  $-20^{\circ}\text{C}$  for 48 hours. The thawed sediments were then sieved through a 500  $\mu\text{m}$  mesh to remove the fauna with the coarser material discarded to reduce grainsize differences between the two sediment types. Each sediment type was then thoroughly mixed to promote homogeneity.

Cylindrical plastic flower pots (12 cm diameter x 12 cm height) were used as receptacles for the sediments. Prior to the sediments being added, three 8 x 8 cm holes were cut into the sides, and a hole of 9 cm diameter was cut into the base of each flower pot, all of which were then covered with a 300  $\mu\text{m}$  mesh (Fig. 10.2).



**Figure 10.2** Diagram of the modified flower pots, and the tray in which they were deployed.



These mesh inserts permit water to permeate through the container in an attempt to reproduce more natural conditions. Six pots of the one treatment were placed in a tray, with two trays of each treatment being placed at each of four locations. Two of these locations were within the unpolluted O'Brien Bay, and are referred to as O'Brien Bay 1, and O'Brien Bay 2. The other locations were the two contaminated bays, namely Shannon Bay and Brown Bay.

After a deployment period of twelve months the trays were retrieved. Some sample loss did occur, namely both control sediment trays from O'Brien Bay 2, and one tray of control sediments from Brown Bay. Four pots from each tray were used for studies on the recruitment of soft-sediment infauna (Stark et al., submitted). Diatoms were sampled by taking a 3 cm long by 0.5 cm deep scrape from the surface of the remaining two pots. It was assumed that by sampling only the top 0.5 cm, this would restrict the diatoms sampled to predominantly living diatoms, and not those that may have been present in the sediment before deployment. These sample were then preserved in glutaraldehyde. The remaining sediments from these two pots were frozen at -20 °C for later analysis of heavy metals in the sediments. A full description of the methods used for the geochemical analyses is given in Stark et al. (submitted).

This experiment was designed and implemented by Jonathan Stark (AAD). Samples for heavy metal analyses were prepared by Beck Scouller (AAD); the analyses were performed by a technician from ANSTO. The diatom analyses and the subsequent interpretation were undertaken by the author.

### **Diatom Preparation and Identification**

Organic material was removed from the sediments by digestion in a 10% hydrogen peroxide solution for 72 hours. Excess liquid was decanted off, and the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in distilled water (volume = 10 ml). The centrifuging process was repeated twice more.

Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom valves was undertaken using a Zeiss KF2 light microscope with 1000x magnification, and phase contrast illumination. Identification was based on Hasle and Syverston (1996) and Medlin and Priddle (1990). A minimum of 1000 individuals was counted for each sample. The relative abundances of predominantly benthic taxa were then calculated and used in the statistical analyses.

### **Statistical Analyses**

Multivariate analyses of community composition were undertaken using non-metric multidimensional scaling (nMDS) and analysis of similarity (ANOSIM) procedures using the PRIMER software package (Clarke and Warwick, 1994). One way ANOSIMs were used to compare the effects of both treatment and location. In ANOSIMs, the R value indicates the dissimilarity between groups, with scores of -1 or +1 indicating that the groups have no similar characteristics, whilst a score of 0 would indicate the groups were identical. The significance level indicates the likelihood of the observed groupings occurring by chance; a low value indicates a low probability of the groups being due to random processes. No data transformation was used. Similarity matrixes were calculated using the Bray-Curtis similarity measure.

Similarity percentages analyses (SIMPER), were used to determine which species were responsible for compositional differences observed between the communities. Groups used for SIMPER analyses consisted of all samples, both control and contaminated, that were deployed at the individual locations.

Overall variability was determined using Relative Dispersal values (Clarke and Warwick, 1994) whilst direct comparisons between two groups were undertaken using the Index of Multivariate Dispersal (IMD). Natural logarithms were used to calculate Shannon-Wiener diversity ( $H'$ ) values, Simpsons' dominance index (SI),

Margalef's species richness ( $d$ ) values, and Pielou's evenness ( $J'$ ) values. Collectively, these values will be referred to as the structural parameters of the diatom communities. Single factor analyses of variance (ANOVA) were employed for global comparisons. Where ANOVAs indicated significant difference, SNK tests were performed to determine differences between individual locations. Both ANOVAs and SNK tests were performed using GMAV 5 (Institute of Marine Ecology University of Sydney, Australia). Unless otherwise stated, a significance level of  $p = 0.05$  was applied to all analyses.

## **Results**

### **Sediment Analyses**

Concentrations of heavy metals were significantly higher in the polluted treatment than the control treatment. At the end of the experiment the concentrations of heavy metals had decreased in polluted treatments deployed at control locations (Stark et al., in prep), resulting in comparatively lower final concentrations than in the Brown Bay polluted treatments (Fig. 10.3).

### **Influence of Sediment Contamination on Diatom Communities**

The two trays of control sediment that were deployed at O'Brien Bay 2 were not recovered. Comparisons between control and contaminated treatments were therefore not possible at this location, as a result this location has been excluded from all analyses. Only one tray of control sediment was recovered from Brown Bay. The reduced sample number increased the likelihood of errors within the analyses, resulting in a minimum  $p$  value of 6.7% for comparisons of treatments within this location. Any analyses which had this value were consequently regarded as significant.

The presence of contaminants within the sediments had little influence on the species composition of the diatom communities overall, as indicated by ANOSIM results (global  $R$  of 0.068 at a significance level of 14.5%). Pairwise comparisons (Table 10.1 indicate that it was only within Brown Bay that the two treatments resulted in

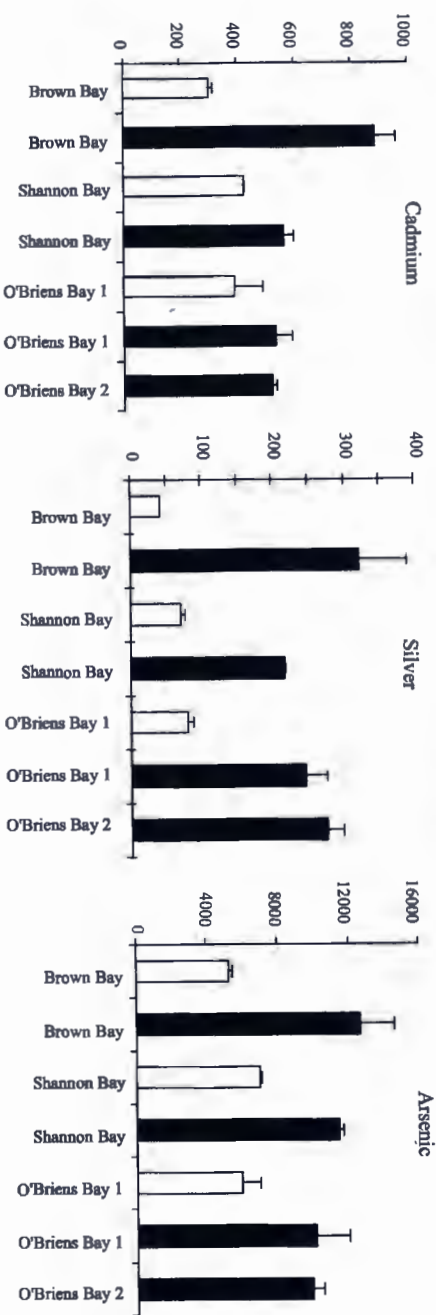
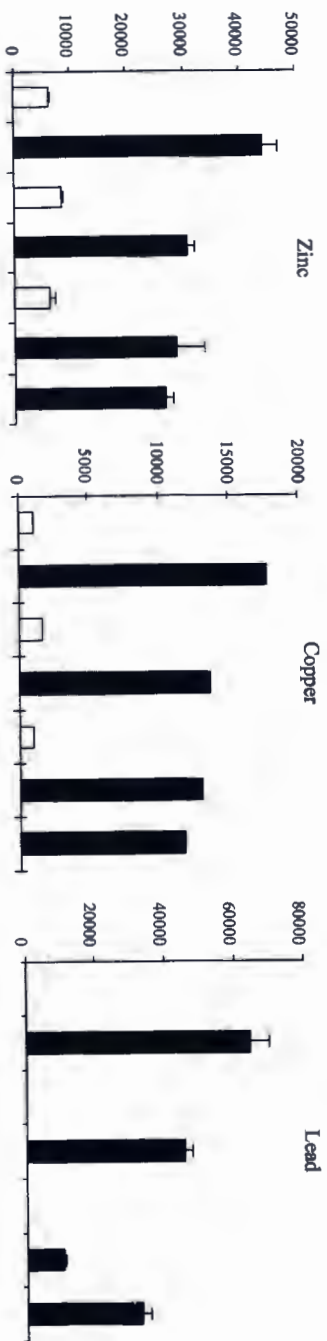


Figure 10.3 Heavy metal concentrations ( $\mu\text{g kg}^{-1}$ ) in control (white bars) and contaminated (black bars) sediments at the end of the experiment.

significantly different community compositions. Comparisons of the two treatment types within Brown Bay, indicated that they were different ( $R = 0.500$ ) at a 6.7% significance level (Table 10.1). No differences in structural parameters of diatom communities were detected between treatment types overall, or within the individual locations (Table 10.2).

Location	R value	Sig. Level	IMD Value (Control v Polluted)
All locations	0.068	14.5%	0.287
Shannon Bay	0.167	17.1%	0.556
<b>Brown Bay</b>	<b>0.500</b>	<b>6.7%</b>	<b>-1.000</b>
O'Brien Bay	0.073	22.9%	0.056

**Table 10.1** ANOSIM results for comparison of community composition between control and polluted treatments both overall, and within the three different locations in the Windmill Islands. Significant differences are shown in **bold**. IMD values show the relative difference in multivariate variability between treatments, both overall and within each of the three locations.

	Location	Treatment	Interactions
Diversity	<b><math>p = 0.0267</math></b> <b><math>B &gt; S = 0</math></b>	$p = 0.8048$	$p = 0.0802$
Dominance	$p = 0.0731$	$p = 0.8208$	$p = 0.1973$
Evenness	<b><math>p = 0.0340</math></b> <b><math>B = S &gt; O = S</math></b>	$p = 0.6628$	$p = 0.1152$
Richness	$p = 0.2128$	$p = 0.8326$	$p = 0.7879$

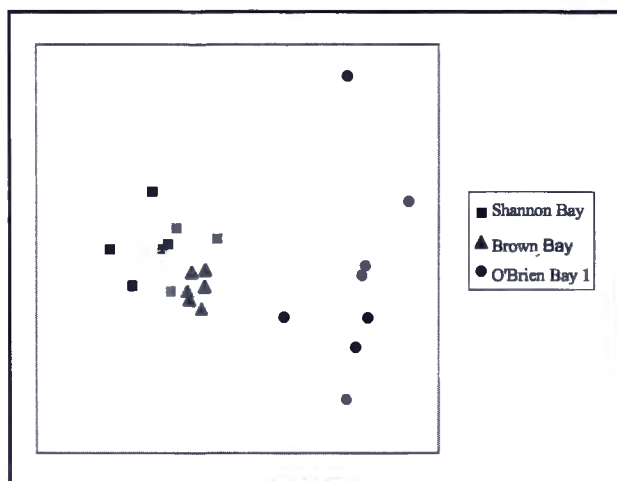
**Table 10.2** ANOVA and SNK results for comparisons of structural parameters of diatom communities. Interactions refers to potential interaction terms between location and treatment. Significant results are shown in **bold**.

Diatom communities which developed on the contaminated treatments were, overall, more variable than those which developed on the control treatments. Differences in the overall variability of diatom communities between control and polluted treatments were emphasised in the two polluted locations (Table 10.1). Within the control location, O'Brien Bay, the differences between these treatments were reduced (0.056) compared to the overall result. Differences in the variability of diatom

communities recruiting to control and polluted sediments were location specific. Within Brown Bay, the communities which recruited to polluted sediments were more variable than those which recruited to control sediments, however the reverse was true in Shannon Bay. The diatom communities which recruited to control and polluted treatments within O'Brien Bay had similar values for multivariate dispersal.

### Influence of Location on Diatom Communities

The nMDS ordination (Fig. 10.4) indicates that samples grouped according to location. This was confirmed by the ANOSIM of location groups which had a global  $R$  value of 0.56 at a significance level  $< 0.01\%$ . Significant differences occurred between all bays, demonstrated by the pairwise results (Table 10.3). These ANOSIM results indicate that the two polluted locations are the most alike, with the two control locations having the next highest degree of similarity. On the nMDS ordination, the Brown Bay samples almost appear to fall within the range of the Shannon Bay samples, both of which are closer to the O'Brien Bay 2 samples than the O'Brien Bay samples.



**Figure 10.4** nMDS ordination showing separation of diatom communities into location groups (Stress = 0.13). Control sediments are shown in black, contaminated sediments are shown in grey.

The compositional differences observed between locations were most apparent in the polluted treatments. ANOSIM results indicated that the composition of diatom communities which recruited to the polluted treatments were significantly different between all four locations, whilst the composition of diatom communities which recruited to control treatments were only significantly different between O'Brien Bay and Shannon Bay (Table 10.3). Even allowing for the higher significance level, the diatom communities which recruited to Brown Bay control sediments were not compositionally distinct from those which recruited to similar sediments deployed in O'Brien Bay or Shannon Bay.

Locations Compared		R value	Sig. Level
<i>Overall</i>			
Shannon Bay	Brown Bay	0.372	0.7%
Shannon Bay	O'Brien Bay	<b>0.854</b>	<b>0.0%</b>
Shannon Bay	O'Brien Bay 2	0.647	0.2%
Brown Bay	O'Brien Bay	0.708	0.0%
Brown Bay	O'Brien Bay 2	0.726	0.5%
O'Brien Bay	O'Brien Bay 2	0.540	0.2%
<i>Control Treatments</i>			
Shannon Bay	Brown Bay	0.321	20%
Shannon Bay	O'Brien Bay	<b>0.833</b>	<b>2.9%</b>
Brown Bay	O'Brien Bay	0.393	20%
<i>Polluted Treatments</i>			
Shannon Bay	Brown Bay	0.552	2.9%
Shannon Bay	O'Brien Bay	<b>0.896</b>	<b>2.9%</b>
Shannon Bay	O'Brien Bay 2	0.792	2.9%
Brown Bay	O'Brien Bay	<b>0.885</b>	<b>2.9%</b>
Brown Bay	O'Brien Bay 2	0.563	2.9%
O'Brien Bay	O'Brien Bay 2	<b>0.854</b>	<b>2.9%</b>

Table 10.3 ANOSIM results for comparison of diatom communities which developed in the different locations, both overall and within each treatment type. Significant results are shown in bold.

Changes in the relative abundances of species, rather than the presence or absence of individual species, were predominantly responsible for the observed differences between locations. Similarity percentages indicated that the presence or absence of species accounted for a maximum of 6% of compositional differences observed between localities (Table 10.4). Only seven species (*Biddulphia punctata*, *Entomoneis* sp. b, *Pleurosigma* sp. c, *Gyrosigma* sp. a, *Licomorpha* sp. b, *Pinnularia quadratarea* var. *constricta* and *Pleurosigma* sp. a weren't present at all locations (Table 10.4).

Only one taxon was present in abundances greater than 5% at all four locations, namely *Planothidium* spp. (Table 10.4). In samples from O'Brien Bay, *Achnanthes brevipes*, *Eucampia antarctica* and *Synedropsis* cf. *recta* all had a relative abundance greater than 5%. The first two species were observed at these relatively high abundances only within O'Brien Bay, whilst *Synedropsis* cf. *recta* was present at greater than 5% in all locations apart from Shannon Bay. In contrast, *Cocconeis fasciolata* had an average abundance greater than 5% only in Shannon Bay (Table 10.4). *Pseudostaurosira brevistriata* attained abundances greater than 5% only within the two polluted locations, whilst *Navicula* sp. a exceeded the 5% abundance only within Brown Bay.

Both diversity and evenness varied significantly between locations (Table 10.2). SNK tests revealed that diatom communities from Brown Bay were more diverse than communities from either Shannon Bay or O'Brien Bay. Higher evenness values were also recorded in communities from Brown Bay, relative to communities from O'Brien Bay (Table 10.2). These differences were maintained within each of the sediment types, thus no interaction effects were observed between treatment and location (Table 10.2).

Differences in the variability of the developing diatom communities were also observed between locations. Brown Bay had the least amount of variation between samples, reflected in the tight clustering of these samples in the nMDS ordination



	Average Abundance			% Dissimilarity		
	Shannon	Brown	O'Brien 1	Shannon v Brown	Shannon v O'Brien 1	Brown v O'Brien 1
<i>Achnanthes brevipes</i>	2.50	3.23	5.28	2.05	3.88	3.23
<i>Planothidium</i> spp.	8.27	6.22	5.92	5.11	4.59	2.76
<i>Actinocyclus actinochilus</i>	0.28	0.20	0.36	0.62	0.28	0.47
<i>Amphora libyca</i>	2.25	1.77	1.50	1.45	1.21	1.1
<i>Amphora</i> sp. a	0.42	0.87	0.74	1.31	0.88	0.88
<i>Ampohora ovalis</i>	0.75	1.25	0.80	1.43	0.91	1.42
<i>Parlibella</i> sp. a	0.03	0.04	0.06	0.12	0.11	0.12
<i>Auricula compacta</i>	0.00	0.31	0.48	0.67	0.67	0.59
<i>Biddulphia punctata</i>	0.13	0.00	0.00	0.27	0.18	0
<i>Catacombas camtschatica</i>	0.00	0.08	0.06	0.17	0	0.17
<i>Cocconeis costata</i>	1.52	1.10	0.80	2.19	1.54	0.97
<i>Cocconeis fasciolata</i>	5.05	3.53	2.62	3.33	3.34	1.37
<i>Cocconeis pinnata</i>	0.45	0.20	0.18	0.74	0.49	0.32
<i>Cocconeis schuettii</i>	0.20	0.12	0.09	0.5	0.31	0.17
<i>Achnanthes</i> sp. a	2.21	0.94	4.46	3.26	4.03	5.32
<i>Ctenophora pulchella</i>	2.22	1.80	0.24	2.58	2.71	2.35
<i>Cymbella</i> sp. a	0.15	0.12	0.12	0.38	0.25	0.22
<i>Dactylisolen antarcticus</i>	0.28	0.04	0.11	0.56	0.33	0.18
<i>Diploneis splendida</i>	0.25	0.20	0.09	0.48	0.28	0.29
<i>Entomoneis</i> sp. a	0.63	0.43	5.20	1.11	6.33	6.94
<i>Entomoneis</i> sp. b	0.05	0.00	0.03	0	0.09	0.04
<i>Eucampia antarctica</i>	2.67	2.16	9.78	2.69	10.8	11.87
<i>Staurorsira construens</i> var. <i>pumila</i>	2.17	1.71	3.25	3.76	2.87	2.44
<i>Staurorsira construens</i> var. <i>venter</i>	2.41	2.21	0.38	2.3	2.83	2.67
<i>Gonphonema</i> sp. a	0.00	0.23	0.09	0.49	0.12	0.38
<i>Gyrosigma</i> sp. a	0.18	0.00	0.00	0.37	0.24	0
<i>Nitzschia dubis</i> var. <i>australis</i>	0.34	0.31	0.17	0.96	0.52	0.5
<i>Licomorpha antarctica</i>	0.78	0.24	0.15	1.54	0.95	0.42
<i>Licomorpha</i> sp. b	0.15	0.00	0.00	0.32	0.2	0
<i>Navicula</i> sp. c	2.51	3.71	1.32	4.12	1.83	3.66
<i>Navicula</i> sp. b	0.43	1.57	1.67	2.43	1.84	1.19
<i>Navicula directa</i>	2.83	3.62	1.92	3.41	2.11	2.58
<i>Navicula</i> aff. <i>glaciei</i>	5.61	6.12	4.05	5.66	3.29	4.62
<i>Luticola muticopsis</i>	0.00	0.12	2.11	0.25	2.87	2.92
<i>Navicula perminuta</i>	1.79	1.21	0.62	2.65	2.08	1.2
<i>Navicula</i> sp. a	3.09	5.69	2.22	5.56	2.25	5.06
<i>Nitzschia</i> sp. b	0.00	0.63	0.15	1.34	0.21	0.85
<i>Nitzschia</i> sp. a	0.54	0.55	3.47	1.01	4.33	4.59
<i>Pinnularia quadratarea</i>	0.35	0.67	0.71	1.16	0.95	0.96
<i>Pinnularia quadratarea</i> var. <i>constricta</i>	0.16	0.00	0.06	0.35	0.25	0.09
<i>Pleurosigma elongatum</i>	0.24	0.71	0.23	1.17	0.32	0.82
<i>Pleurosigma</i> aff. <i>obscurum</i>	1.50	0.59	1.83	2.41	2.12	2.1
<i>Pleurosigma</i> sp. a	0.25	0.00	0.00	0.52	0.34	0
<i>Porosira</i> sp. a	0.29	0.39	0.78	0.71	0.84	0.88
<i>Pseudogomphonema kamtschatica</i>	0.60	0.36	0.03	0.92	0.81	0.49
<i>Pseudostaurorsira brevistriata</i>	6.55	5.14	1.15	4.28	6.46	5.84
<i>Stauroneis wislouchii</i>	0.54	2.08	2.83	3.53	3.42	2.39
<i>Thalassionema gelida</i>	0.53	0.78	0.43	1.04	0.67	0.94
<i>Synedropsis</i> cf. <i>recta</i>	4.59	6.91	5.94	6.47	4.99	4.71
<i>Trachyneis aspera</i>	1.16	2.55	1.97	2.96	1.78	1.99
<i>Trigonium arcticum</i>	1.04	0.24	0.06	2.08	1.38	0.38
Unknown pennates	2.03	3.11	0.68	5.07	2.84	4.51

Table 10.4 Relative abundances of species within each treatment, and SIMPER results showing the amount individual species contributed to the overall dissimilarity between treatments

(a)				
Location		Overall	Control	Polluted
Brown Bay		0.28	0.05	0.37
Shannon Bay		1.10	1.34	0.98
O'Brien Bay		1.38	1.32	1.48

(b)				
Locations Compared		Overall	Control	Polluted
Shannon Bay	Brown Bay	0.933	1.000	0.778
Shannon Bay	O'Brien Bay	-0.355	0.000	-0.772
Brown Bay	O'Brien Bay	-0.995	-1.000	-1.000

**Table 10.5** Comparisons of variability between diatom communities. (a) Relative Dispersal values provide the global analysis. (b) IMD values allow pairwise comparisons. Negative values indicate less variation occurred in diatom communities from the first location.

(Fig. 10.3). O'Brien Bay showed the greatest degree of variability between samples, followed by Shannon Bay, reflected in the larger dispersion of these samples on the nMDS ordination. The relative dispersal values confirm these differences, indicating that Brown Bay was the least variable location, followed by Shannon Bay with O'Brien Bay as the most variable location (Table 10.5). The largest differences in variability occurred between Brown Bay and O'Brien Bay, whilst the smallest difference in variability was observed between Shannon Bay and O'Brien Bay.

The presence of contaminants also influenced the variability observed within each location. No significant differences were observed in the variability of diatom communities recruiting to control sediments deployed in Shannon Bay and O'Brien Bay. The variability of these diatom communities was as different as possible (ie.  $IMD = 1$  or  $-1$ ) from the variability observed within Brown Bay communities, with communities from Brown Bay having a much lower relative dispersal value (Table 10.6). The same trend was noted between communities which recruited to the polluted treatments in O'Brien Bay and Brown Bay. Differences in variability of the diatom communities recruiting to polluted sediments deployed in Brown Bay and

	Control		Polluted	
	Tray 1	Tray 2	Tray 1	Tray 2
Shannon Bay	1.00	1.43	0.43	1.29
Brown Bay	0.14	-	0.29	0.57
O'Brien Bay	0.86	1.86	1.57	1.71

**Table 10.6** Relative dispersal values for comparisons of multivariate dispersal between diatom communities within the Windmill Islands.

Shannon Bay were reduced in the polluted sediments, relative to the control sediments. Differences in variability between diatom communities recruiting to the polluted samples deployed in Shannon Bay samples and O'Brien Bay samples were greater than those seen in the control treatments from these bays (Table 10.5).

In order to determine if the low variability of diatom communities from the control sediments deployed in Brown Bay resulted from the reduced sample number, sample numbers were standardised by comparing individual trays (2 samples per tray). The previous findings were maintained, as the Brown Bay control treatments had a lower relative dispersal value than both polluted treatments from Brown Bay and all other control treatments (Table 10.6).

## Discussion

Location of deployment was clearly the dominant influence on the recruitment of diatom communities during this experiment, influencing species composition, species diversity, evenness, dominance and even the variability of developing communities. This is consistent with the large differences in location previously observed in the Windmill Islands (Chapters 3, 4 and 5). Previous research has demonstrated that differences in grain-size, light availability and depth can all contribute to compositional differences observed between diatom communities within the Windmill Islands (Chapter 5). Within this experiment, grain-size and depth were constant between locations, thus of the above parameters only light availability could explain compositional differences between locations. It is possible that other factors such as sea-ice thickness and freshwater input, may also have contributed to differences observed in community composition between locations.

The use of structural parameters to infer stress levels is somewhat ambiguous. High levels of disturbance usually result in decreased species richness, decreased evenness, decreased diversity and increased dominance values (Clarke and Warwick, 1994). However, low levels of stress reduce competition between species, thus resulting in increased diversity, evenness and richness but reduced dominance values (Connell, 1978). Fortunately, because the levels of pollution are known for both the locations and treatments, it is easier to interpret the structural responses. For example, Brown Bay had higher diversity and evenness values with lower dominance values than O'Brien Bay. These structural parameters could either indicate severe disturbance in O'Brien Bay with none occurring in Brown Bay or, alternatively, intermediate disturbance within Brown Bay. As O'Brien Bay is a control site, and Brown Bay is known to be polluted, it is likely that the structural parameters are indicating intermediate disturbance of the diatom communities within Brown Bay.

Despite comparatively high levels of heavy metals, the overall composition and numerical structure of diatom communities which developed on polluted sediments originally collected from Brown Bay, were not significantly different from communities that developed on control sediments from O'Brien Bay. Previous studies have demonstrated significant changes in the composition and structure of diatom communities resulting from a wide range of heavy metal concentrations. Marked changes in the composition of diatom communities, including the disappearance of several species, occurred when copper concentrations in the waters of Lake Orta exceeded 5000 ppm (Ruggiu et al., 1998). Lower levels of contaminants can also have significant impacts on diatom communities. Increased aqueous copper and zinc concentrations (from 14 ppb to 25 ppb and 25 ppb to 1238 ppb, respectively) reduced both the species richness and diversity of benthic diatom communities (Crossey and Point 1988). Similarly, mixtures of cadmium, copper and zinc at concentrations of 0.55 ppb, 6 ppb and 55 ppb respectively, resulted in significant differences in species composition, richness and diversity of periphytic diatom communities in laboratory experiments (Medley and Clements, 1998).

Correlations with field data, however, indicated that distinct community responses were observed at monitoring sites when the zinc concentrations in water exceeded 200 ppb, while at moderately polluted sites (<200 ppb zinc) no significant effects on the diatom communities were observed (Medley and Clements, 1998).

The metal concentrations in this experiment (ie. copper 1 ppm in control sediment, and 18.5 ppm in polluted sediment) fall within the range for which significant impacts have previously been described, however, this experiment is concerned with sediment contamination, whilst the previous studies have examined contaminants within the water column. Sediment contamination has previously been shown to have a more muted effect on diatom communities than contaminants in the water column (Cattaneo et al., 1995) but no data is available on the levels of sediment contamination that produce an observable effect on diatom communities.

The polluted treatment of Brown Bay had higher diversity and lower dominance values than the control treatment of the same bay, implying a low level disturbance to the diatom communities. It was only within this highly polluted site that any structural differences between control and polluted treatments occurred. There are several possible explanations for this. Firstly, the pollution history of Brown Bay could be influencing the development of diatom communities. Communities in areas already stressed (ie. polluted) may be more susceptible to the influence of further stressors than communities from control locations (Underwood, 1989). Thus, the susceptibility of the Brown Bay diatom communities to the sediment contamination imposed by this experiment may be increased by the pre-existing pollution in this bay.

Alternatively the presence of heavy metal contaminants within the water column of Brown Bay may be acting in concert with contaminants within the experimental sediments. A synergistic effect between existing contaminants and the polluted sediments could also explain why the Shannon Bay polluted treatment had a lower relative dispersal value than the control. It would also explain why the Shannon Bay

polluted treatment has a lower variability compared to the equivalent O'Brien Bay treatment, given that both of these bays had the same degree of variability in control treatments.

Variability of the recruiting diatom communities was significantly different between the treatments overall. Clarke and Warwick (1994) reported that in a range of environmental studies the variability among samples collected from impacted areas was much greater than that from control sites. Our results did not follow this pattern. The diatom communities recruiting to the most polluted site, Brown Bay, were much less variable than those recruiting elsewhere. Furthermore, the polluted sediments were, overall, less variable than the control sediments, however these results were not maintained at all locations studied. At Brown Bay, the communities recruiting to polluted sediments were more variable than those recruiting to control sediments. In contrast, in Shannon Bay, the communities recruiting to the polluted sediments were more variable than in the control sediments. This suggests that either there is a threshold of contamination which must be exceeded before it causes increased variability of recruiting communities, and that the concentrations used in this experiment did not reach this threshold, or that the effect of pollution on biological variability may be different at different locations. A much more detailed study, and greater understanding of the processes involved would be required before variability could be used as an indicator of pollution within the Windmill Islands.

### **Conclusions**

Chemical contamination of sediments can significantly affect the composition, variability and structure of benthic diatom communities. This study demonstrated a causal link between chemical contamination and the composition and structure of diatom communities within Brown Bay. Diatom communities from other locations in the Windmill Islands were not significantly affected by similar levels of chemical contamination, indicating that other processes occurring within Brown Bay are modifying the response of the diatom communities to chemical contamination.



### ***The influence of heavy metals and petroleum hydrocarbons on benthic diatom communities in the Windmill Islands: an experimental assessment***

#### **Abstract**

The effects of heavy metals and petroleum hydrocarbons on benthic marine diatom communities were studied using a manipulative field experiment at Casey Station, Antarctica. Uncontaminated, metal contaminated, and petroleum hydrocarbon contaminated sediments were deployed for an eleven-week period over the 1999 austral summer. The treatments were deployed at three different locations: Brown Bay, which is known to have elevated levels of anthropogenic contaminants, and two reference locations, Sparkes Bay and O'Brien Bay. No anthropogenic contaminants have been detected at the reference locations, however, Sparkes Bay has naturally occurring high concentrations of some heavy metals.

At each of the three locations, significant differences between the composition of diatom communities recruiting to control and petroleum hydrocarbon contaminated treatments were observed. *Navicula directa* occurred at lower abundances in the petroleum-hydrocarbon contaminated treatments, than in the control treatments. In contrast, *Navicula* sp. a occurred at higher relative abundances in both the metal contaminated and petroleum hydrocarbon contaminated treatments, than in the control treatment.

Significant interactions between treatment and location were also observed for several species including *Navicula* aff. *glaciei* and *Staurosira construens* var. *venter*. It was only within Brown Bay that the diatom communities which developed on metal contaminated sediments were significantly different to communities which developed on either hydrocarbon contaminated sediments, or control sediments. Location of deployment also had a significant influence on the composition of developing diatom communities. *Achnanthes brevipes* occurred at higher abundances in the reference locations than in Brown Bay. In contrast, *Navicula* sp. b reached higher relative abundances within Brown Bay, than in either of the reference locations. Benthic diatom communities were demonstrated to be sensitive to sediment contamination, and would be suitable for future monitoring work within the region and other areas of Antarctica.

## **Introduction**

Antarctica is widely regarded as the last remaining wilderness; however, the integrity of this environment is threatened by human activities. Increases in chemical contaminants have been recorded in the marine environments around many of the permanent research stations (eg. Lenihan et al., 1990). Detailed information on the extent of such contamination is available for only a few sites, including McMurdo Station (Crockett, 1997; Kennicutt et al., 1995), and Casey Station (Snape et al., 2001; Stark et al., in press). Information on the biological effects of such contamination is also limited to a few studies most of which have examined the effects on faunal communities (eg. Lenihan and Oliver, 1995; Stark, 2000).

The benthic microflora of Antarctic regions consists almost entirely of diatoms (Gilbert, 1991). Diatoms have been shown to have narrow tolerance ranges for many environmental variables, and respond rapidly to environmental change, making them ideal bioindicators (Reid et al., 1995). Contaminants can affect the growth rate and species composition of diatom communities, with subsequent implications for organisms higher in the foodchain (Stronkhurst et al., 1994).

Recent studies (Snape et al., 2001; Scouller et al., 2000; Stark et al., in press) have demonstrated higher concentrations of some heavy metals and petroleum hydrocarbons in sediments collected from bays adjacent to Casey Station compared to locations further away. This contamination has been linked to both the operation of a waste disposal site, and hydrocarbon spills (Deprez et al., 1999). Brown Bay, adjacent to the waste disposal site, is the worst affected with some heavy metals (including copper, lead, iron and zinc) occurring in the sediments at concentrations 10 to 100 times higher than background levels (Scouller et al., 2000). Petroleum hydrocarbons, derived from lubrication oil and Special Antarctic Blend diesel fuel (SAB) are present in the surface sediments of Brown Bay at concentrations ranging between 40 and 200 mg kg<sup>-1</sup>, whereas petroleum hydrocarbons were not detected in sediments from reference locations (Snape et al., 2001). Seawater collected from Brown Bay also contained elevated concentrations of copper, cadmium, lead and zinc (Deprez et al., 1999; Snape et al., 2001).



The species composition of diatom communities around Casey Station differs significantly between Brown Bay and uncontaminated sites further away from the station (Chapters 3, 4 and 5). Environmental factors, including grain-size (Chapter 4) and total organic content of the sediments, also vary between these locations (Stark et al., in press). Subsequently, the observed differences in diatom communities between Brown Bay and reference locations cannot be unequivocally linked to contamination by heavy metals and petroleum hydrocarbon.

Manipulative field experiments are the most appropriate means of demonstrating causal relationships between environmental factors, such as contamination, and observed biological patterns (Underwood and Peterson, 1988). Manipulative experiments using microbenthic algae are very scarce (Ivorra et al., 1999), and generally consist of the translocation of diatom communities between sites. One problem associated with this approach is that the environmental factors examined are typically associated with the sites, and may not necessarily be independent of other processes acting at these sites. Artificially contaminating sediments enables the influence of the contaminants to be isolated from other sources of variability between sites. Within this study, artificially contaminated sediments were used to examine the effects of metal contamination, and petroleum hydrocarbon contamination, on benthic diatom communities.

The purpose of this study was to assess whether benthic diatom communities can be used as an indicator of environmental impacts within coastal regions of Antarctica. The following objectives were identified:

1. To determine if a causal relationship between differences in diatom community composition and contamination by petroleum hydrocarbons and/or heavy metals could be demonstrated. It was hypothesised that the diatom communities which developed on contaminated sediments would be different than those in control, uncontaminated sediment.

2. To study the influence of location on the development of diatom communities and, in particular, the impact of contaminants in Brown Bay on these communities. It was hypothesised that there would be compositional differences between diatom communities which developed at the three locations.
3. To examine whether the response of the diatom communities to experimental contamination would vary between the locations, specifically whether an increased response would occur in diatom communities from Brown Bay. It was hypothesised that there would be significant interactions between location and contamination.

A secondary aim was to assess the sensitivity of diatom communities to relatively low levels of chemical contamination, and thus determine their suitability for future monitoring work within Antarctica.

## **Methods**

### **Location description**

Casey Station is located at 66° 17' S, 110° 32' E in the Windmill Islands. Casey Station is the third station to have been built in the region. The first station, Wilkes, was built in 1957 on the edge of the Clarke Peninsula, but was superseded in 1969 by what is now known as 'Old Casey'. Old Casey is located on Bailey Peninsula, 2 km south of Wilkes, and 800 m east of the present Casey Station (Figure 11.1).

Refuse from the first two stations accumulated at local waste disposal locations prior to a change of policy in 1986, subsequent to which waste was either incinerated on station or returned to Australia. The Thala Valley disposal site received waste material from Old Casey Station between 1969 and 1986. This material included domestic waste as well as waste from the mechanical workshop such as batteries and fuel drums (Deprez et al., 1999). Despite an earlier clean-up effort, approximately

2500 m<sup>3</sup> of the waste generated by Old Casey station still remains in Thala Valley (Deprez et al., 1999; Snape et al., 2001).

In summer, a melt-stream flows through the Thala Valley tip site where water dissolves and entrains contaminants before entering the adjacent Brown Bay. An estimated eight cubic meters of contaminated material associated with the tip was removed by surface and ground waters and deposited into Brown Bay during the 1998/99 summer period (Cole et al., 2000). Petroleum hydrocarbons are also transported from soils surrounding the 'Old Casey' mechanical workshops into Brown Bay by the movement of surface and subsurface waters (Snape et al., 2001). Hydrocarbon contamination of Brown Bay may also result from a number of small spills which have occurred during refuelling operations.

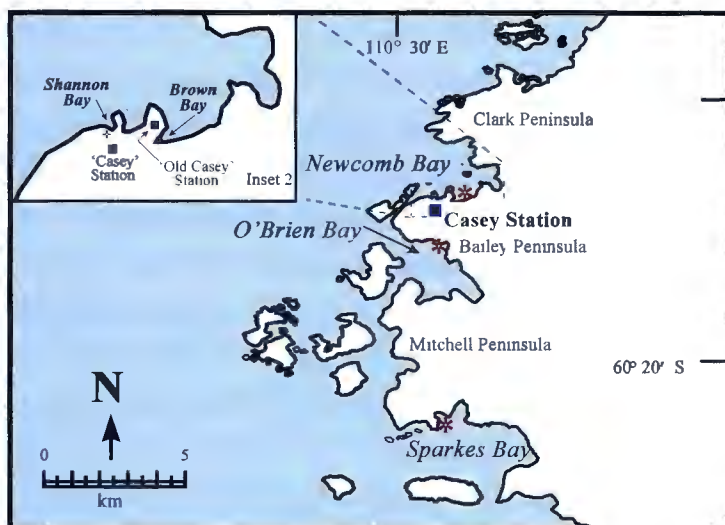


Figure 11.1 Map of the Windmill Islands, showing station locations (■) and locations where experimental sediments were deployed (\*).

Brown Bay is a small embayment at the southern end of Newcomb Bay. Brown Bay has a maximum depth of approximately 20 m with rocky sides grading to a muddy bottom (Stark, 2000). Close to the tip site, patches of sediment occur between boulders, discarded tip material and areas of bare rock. Further away from the tip, areas of fine sediments are more extensive and relatively homogenous (Stark, 2001),

but are still occasionally interrupted by large boulders. Brown Bay is typically ice free for 1-2 months a year, generally between January and February. Sea-ice is generally present within Brown Bay throughout the autumn and winter periods with prevailing winds typically blowing ice into the bay.

O'Brien Bay and Sparkes Bay are large bays situated several kilometers south of Casey Station. These bays have a variety of environments; ice cliffs dropping vertically into deep water, steep rocky shorelines, as well as shallower sediment-dominated areas. These bays were chosen as reference locations as they were unlikely to be contaminated by human activity, and because they are relatively accessible. Naturally elevated levels of some heavy metals have been recorded within Sparkes Bay (Stark et al., in press).

Within these large bays, sampling locations were selected with regard to shared physical characteristics, such as sea-ice cover, with Brown Bay. A small embayment on the northern side of Sparkes Bay was used as a reference location as it has a very similar bathymetry to that of Brown Bay with the rocky sides sloping down to a muddy bottom, and a depth range between 3 and 20 m (Stark, 2001). The reference location in O'Brien Bay was also situated on the northern side of the bay. The sides consisted of steeply sloping boulder fields as well as more gently inclined rocky banks. Patches of poorly mixed mud and sand, interspersed between gravel, cobbles and boulders formed the bottom sediments of this area (Stark, 2000).

Little data is available on hydrodynamic conditions within the region, although Cathers et al. (1998) found currents to be wind-dominated, with little tidal influence. Resuspension of bottom sediments is common within near-shore regions of Antarctica. Everitt and Thomas (1986) found that benthic diatoms consistently formed a high proportion of species recorded in planktonic communities at inshore localities near Davis Station. Within this study, it has been assumed that sufficient resuspension of the sediment occurs to allow the colonisation of sediments 12 cm above the natural substrate.

## **Experimental method**

Sediment was collected from O'Brien Bay by a van Veen grab sampler and divers using polyethylene buckets. The sediment consisted of very poorly sorted sands of which 20–40% was less than 63  $\mu\text{m}$  (Stark et al., in press). This sediment is uncontaminated (Snape et al., 2001) whilst the total organic carbon content varied between 1.5 and 3% (Stark et al., in press). The sediment was frozen at  $-20^\circ\text{C}$  for 48 hours, defrosted, and then sieved through a 500  $\mu\text{m}$  mesh to remove fauna, with material coarser than 500  $\mu\text{m}$  discarded (on average  $\sim 11\%$  of sediment). The remaining sediment was thoroughly mixed to ensure homogeneity, and then divided into three portions, each approximately 75 kg. One portion, the control treatment, was not further manipulated. One portion was contaminated by adding contaminated fine-grained tip material, whilst the third portion was contaminated by adding petroleum hydrocarbons.

An analogue for metal contamination of marine sediments, such as that found in Brown Bay, was created by mixing material from the Thala Valley waste disposal site with clean marine sediment from O'Brien Bay. Approximately 50 kg of highly contaminated waste disposal soil was sieved through a 500  $\mu\text{m}$  mesh, the coarse material discarded, and the fine material homogenised then added in a ratio of 1:100 to the O'Brien Bay sediment.

The hydrocarbon contaminated treatment was created by adding a mixture of 25 ml of lubricating oil, 50 ml of SAB and 15 l of clean sea-water to the sediment, forming a wet slurry. This was thoroughly mixed and left to equilibrate for 12 hours. The excess fluid was then siphoned off to remove any excess hydrocarbons that would have dispersed into the marine environment immediately on deployment. This treatment was intended to approximate petroleum hydrocarbon concentrations currently observed within Brown Bay.

Cylindrical plastic flowerpots (12 cm diameter  $\times$  12 cm height) were used as receptacles for the sediments. Three 8  $\times$  8 cm holes were cut into the sides, and a

hole of 9 cm diameter was cut into the base of each flowerpot; these holes were then covered with a 300  $\mu$ m mesh (Fig. 11.2). These mesh inserts allowed exchange of water through the container to better simulate natural conditions. Six pots were placed in a tray (60 cm x 35 cm x 12 cm) in a 2 x 3 arrangement, thus the pots were separated from each other by approximately 10 cm (Fig. 11.2). The pots were then secured to the tray using plastic cable ties.

The pots were filled with sediment on site immediately prior to deployment. In all three locations, three trays of each of the three treatments were deployed randomly within a roughly circular area (radius approximately 5 m). In every location, the experimental trays were placed onto muddy substrates. Within Brown and Sparkes Bay the experimental trays were deployed at 12 m water depth, whilst in O'Brien Bay the experiment trays were deployed at 12 to 15 m water depth.

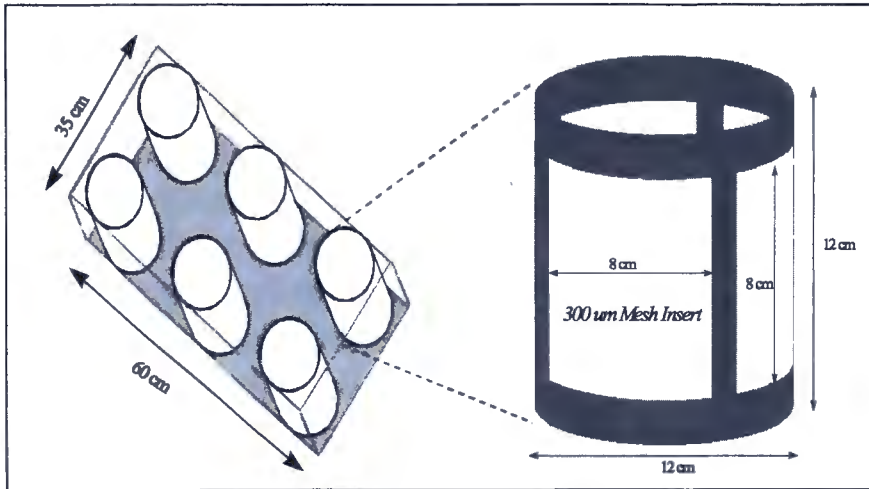


Figure 11.2 Diagram of the modified flower pots, and the tray in which they were deployed. These pots were filled with experimental sediments and deployed for an 11 week period.

Prior to deployment, sediment samples were taken from each treatment, for all three locations. These samples were frozen at -20°C for later analysis of metal and hydrocarbon concentrations. In addition, the composition of the diatom communities already present in the experimental sediments was determined for two samples from each location, and for each treatment type within Sparkes Bay.

After a deployment period of eleven weeks the trays were retrieved by scuba divers. Four pots from each tray were used for studies on the recruitment of soft-sediment infauna (Stark et al., submitted). Two scrapes (3 cm long by 0.5 cm deep) of sediment were taken from the surface of the pots; the position of these scrapes was not pre-determined and varied between pots. These sediment scrapes were preserved in glutaraldehyde and later used for diatom analyses. The remaining sediments from these two pots were frozen at -20°C for later analysis of heavy metals and hydrocarbons in the sediments. A full description of the methods used for the geochemical analyses is given in Stark et al. (submitted). Within this paper, metal and hydrocarbon concentrations presented represent those within the top 1 cm of sediment.

### **Diatom preparation and identification**

Excess organic material was removed from the sediment by digestion in 10% H<sub>2</sub>O<sub>2</sub> for 72 hours. Excess liquid was decanted off, with the remaining slurry transferred to a centrifuge tube. Distilled water was added so that the volume of each tube was 10 ml. The samples were then centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted off, and the pellet was resuspended in 10 ml of distilled water. The centrifuging process was repeated twice more. Following the third treatment, the pellet was once again resuspended in distilled water. This solution was diluted to approximately 10% and pipetted onto coverslips. After air-drying, the coverslips were mounted onto slides using Norland 61.

Examination of diatom taxa was undertaken using a Zeiss KF2 light microscope with 1000x magnification and phase contrast illumination. Identification was primarily based on Hasle and Syverston (1996), Roberts and McMinn (1999) and Medlin and Priddle (1990). In an attempt to ensure that the diatoms included within the investigation were exposed to the treatment types, species generally present only within planktonic, or sea-ice communities were excluded from the data set. Subsequent to this, a minimum of 400 valves was counted for each sample. The exact number of frustules counted varied slightly between samples, with a maximum



of 520 benthic diatoms counted in any one sample. The relative abundances of the benthic taxa were then calculated and used in the statistical analyses.

### **Statistical analyses**

Multivariate analyses of community composition were undertaken using non-metric multidimensional scaling (nMDS) and analysis of similarity (ANOSIM) procedures using the PRIMER software package (Plymouth Marine Laboratory, UK). A 2-way crossed ANOSIM (with replication) was used to determine the overall influences of both the treatments and the locations. Individual one-way ANOSIMs were used to examine the effects of treatment within each location, and the effects of location within each treatment type. This allowed any interactions between the effects of treatment and location to be determined. No data transformation was used for these analyses. Similarity matrixes were calculated using the Bray-Curtis similarity measure.

Similarity percentages analyses (SIMPER) were used to determine the relative contribution of individual species to compositional differences observed between diatom communities. Clarke and Warwick (1994) state that species which have a SIMPER ratio greater than 1.3 are likely to be useful for discriminating between groups. The ten species with the highest average ratios were selected as potential indicator species, and subsequently used in univariate analyses.

Natural logarithms were used to calculate Shannon-Wiener diversity ( $H'$ ) values, Simpsons' dominance index ( $SI$ ), Margalef's species richness ( $d$ ) values, and Pielou's evenness ( $J'$ ) values. Collectively these values are defined as the structural parameters of the diatom communities.

Two-way analysis of variance (ANOVA) were used to determine if the potential indicator species or structural parameters varied significantly between groups. Cochran's  $C$  test was used to check the assumption of homogeneity of variances before using ANOVA. Any data transformations that were necessary to fulfil this



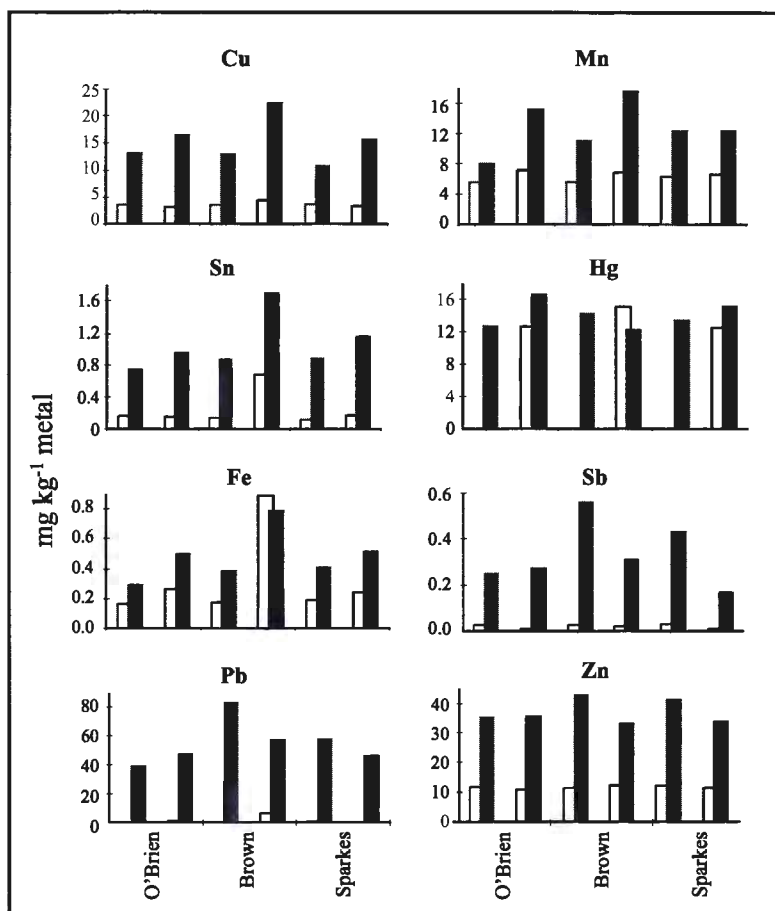
assumption are noted in the results. Where ANOVAs indicated significant differences between samples, SNK tests were used for multiple comparisons ( $\alpha = 0.05$ ). ANOVAs and SNK tests were performed using GMAV5 (Institute of Marine Ecology, University of Sydney, Australia).

## **Results**

### **Chemical contamination**

Contaminant concentrations were higher in the metal and hydrocarbon treatments than in the controls. The metal treatment had concentrations 2 to 60 times that of the pre-exposure control sediments, with the greatest increases occurring in copper, lead, zinc and tin concentrations (Fig. 11.3). Concentrations of several heavy metals showed a large increase within samples from Brown Bay during the eleven week deployment period, possibly reflecting further input from the Thala Valley waste disposal site during that time. Such an input of heavy metals would be associated with sediment input from the melt stream, and the subsequent settling out of these particles onto the experimental sediments. Small increases in the concentrations of several metals were also observed within Sparkes and O'Brien Bay. The reason for this is unclear, but may reflect a lack of adequate replication in the chemical analyses.

Metal concentrations increased in both contaminated and uncontaminated sediments, supporting the idea of further metal input into Brown Bay during the course of the experiment. Despite the use of tip fines as a contaminant, concentrations measured in the metal treatment varied slightly from those previously measured in Brown Bay sediments (Snape et al., 2001) (Table 11.1). Concentrations of most heavy metals, including zinc, silver, arsenic, nickel and chromium, were typically lower in the experimental treatment than in Brown Bay sediments. Lead was an exception, with higher mean concentrations occurring in the experimental treatment than in Brown Bay sediments.



**Figure 11.3** Metal concentrations (mg kg<sup>-1</sup>) in experimental sediments. Hollow bars indicate the control treatment; solid bars represent the metal contaminated treatment. Pre-exposure concentrations are shown in grey; post exposure concentrations are shown in black.

	Brown Bay		Metal Treatment	
	Mean	SE	Mean	SE
Copper	11.67	8.68	12.29	1.11
Zinc	52.77	15.82	39.75	3.21
Lead	28.99	29.00	60.15	18.16
Silver	0.32	0.32	below detection	
Cadmium	0.88	0.53	0.47	0.01
Nickel	3.60	1.54	0.65	0.041
Chromium	5.42	1.98	0.45	0.043
Antimony	0.60	0.33	0.42	0.13
Arsenic	17.25	3.13	7.49	0.44

Table 11.1 Metal concentrations in sediment samples from Brown Bay (from Snape et al., 2001) to those of the metal contaminated treatment ( $\text{mg kg}^{-1}$ ).

The petroleum hydrocarbon treatments had pre-deployment concentration ranges of 68 to 255  $\text{mg kg}^{-1}$  and 178 to 204  $\text{mg kg}^{-1}$  for SAB and lubrication oil respectively (Table 11.2). The lower measured value of SAB was in one of the Sparkes Bay samples, but it is thought this reflects sample heterogeneity and variability of the chemical extraction process, rather than a consistent difference in contaminant levels for the pots in this bay. Hydrocarbon concentrations used in this experiment were similar to those already present in Brown Bay, where fuel and lubrication oil are present in concentrations between 41–200  $\text{mg kg}^{-1}$  TPH (Snape et al., 2001). The concentration of petroleum hydrocarbons typically decreased in the contaminated sediments during the course of the experiment. One exception to this was the concentration of lubricating oil at O'Brien Bay, however this is thought to reflect sample heterogeneity (Table 11.2). Petroleum hydrocarbon concentrations were below detection limits ( $<0.001 \text{ mg kg}^{-1}$ ) in the control treatments.

	SAB		Lubricating Oil	
	Pre	Post	Pre	Post
O'Brien Bay	242	92	184	194
Brown Bay	255	26	204	122
Sparkes Bay	68	56	178	154

Table 11.2. Concentrations ( $\text{mg kg}^{-1}$ ) of petroleum-hydrocarbons in experimental sediments, both pre and post deployment.

### **Diatom communities - a general description**

Forty eight different taxa were found in the diatom communities, only two of these occurred at relative abundances greater than 10%. *Achnanthes brevipes* occurred at these abundances in all samples, except in contaminated treatments within Brown Bay (5 - 8%). *Stauroneis wislouchii*, occurred at these abundances only within Brown Bay and did not exceed 5% at either of the reference locations. Relative abundances between 5 and 10% were recorded for *Navicula* aff. *glaciei* and *Planorhynchium* spp. at all locations.

The composition of the diatom communities which formed on the experimental sediments was quite similar between locations, and treatments. In addition to the species described above, each community had approximately 10 species which occurred at relative abundances between 1 and 5%, typically including several species of *Navicula* and *Cocconeis*. *Stauroneis wislouchii*, *Thalassionema gelida*, a *Nitzschia* species and two varieties of *Staurosira construens* also generally occurred at these abundances. The diatom communities which developed on the experimental sediments generally contained a further 25 species whose relative abundances was below 1%.

### **The influence of sediment contamination on diatom communities**

A 2-way crossed ANOSIM showed that the treatment type significantly influenced the composition of the diatom communities, with a global *R*-value of 0.375 ( $p < 0.0001$ ). Whilst significant differences occurred between all three treatments, the control and petroleum hydrocarbon contaminated treatments showed the highest level of differentiation (Table 11.3).

Treatments Compared		R-value	Significance Level
<i>Overall</i>			
Control	Metal	<b>0.254</b>	<b>0.3%</b>
Control	Hydrocarbon	<b>0.635</b>	<b>0.0%</b>
Hydrocarbon	Metal	<b>0.242</b>	<b>0.2%</b>
<i>Sparkes Bay</i>			
Control	Metal	-0.074	71.6%
Control	Hydrocarbon	<b>0.569</b>	<b>0.2%</b>
Metal	Hydrocarbon	0.113	18.6%
<i>Brown Bay</i>			
Control	Metal	<b>0.633</b>	<b>0.2%</b>
Control	Hydrocarbon	<b>0.900</b>	<b>0.2%</b>
Metal	Hydrocarbon	<b>0.395</b>	<b>0.4%</b>
<i>O'Brien Bay</i>			
Control	Metal	0.183	11.9%
Control	Hydrocarbon	<b>0.353</b>	<b>1.0%</b>
Metal	Hydrocarbon	0.217	5.2%

**Table 11.3** ANOSIM results for comparison of control, metal contaminated and petroleum hydrocarbon contaminated treatments, both overall and within each of the three locations within the Windmill Islands. Significant results shown in **bold**.

Responses to sediment contamination by the diatom communities varied between locations. Within Brown Bay each of the three treatments resulted in significantly different community compositions (Table 11.3). In O'Brien Bay and Sparkes Bay, however, significant differences in community composition were only detected between the petroleum hydrocarbon contaminated treatments and the control treatments (Table 11.3, Fig. 11.4).

The differences observed as a result of contamination were predominantly due to changes in species abundances, rather than the presence or absence of individual species. Only a few species responded to the sediment treatments in the same manner at all locations. A 2-way ANOVA, and subsequent SNK tests (Table 11.4),

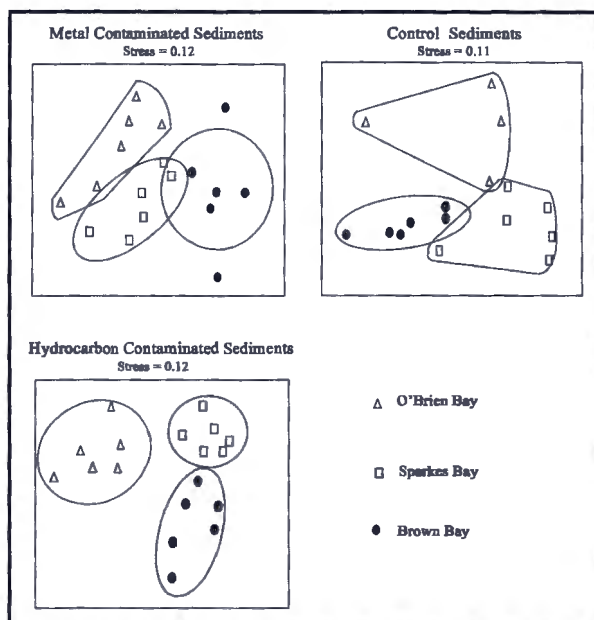


Figure 11.4 2D nMDS ordination of diatom communities showing separation into location groups within each treatment type. Reference locations are depicted by hollow symbols, whilst the contaminated location has a solid symbol.

indicated that *Navicula directa* decreased in relative abundance in the diatom communities from hydrocarbon treatments, relative to communities from the control treatments regardless of the location examined. *Navicula sp. c* also responded to contamination in a consistent fashion at all locations, increasing in abundance in response to both metal and petroleum hydrocarbon contamination relative to control treatments. The relative abundances of *Stauroneis wislouchii*, *Navicula aff. glaciei*, *Navicula sp. a*, *Staurosira construens* var. *venter* and *Planothidium* spp. also varied significantly between treatments types, however significant interactions between location and treatment type were found for these species (Table 11.4).

Despite differences in the relative abundances of the species present, no statistically significant differences in the species diversity, richness, dominance or evenness values were detected between the treatments overall (Table 11.5).

	Location		Treatment
<i>Achnanthes brevipes</i>	Overall	O>S>B	
<i>Planothidium spp. complex</i>	Overall	S>B>O	Sparkes C>M=H
	Control	S>B>O	
<i>Cocconeis fasciolata</i>	Overall	O>B	
<i>Stauroneis construens var. venter</i>	Overall	M>C=H	Overall
	Metal	B>O	Brown M>C=H
<i>Navicula sp. b</i>	Overall	B>S>O	
<i>Navicula sp. c</i>	Overall	B>S>O	Overall H>M>C
<i>Navicula directa</i>	Overall	O>B>S	Overall C>H
<i>Navicula aff. glaciei</i>	Overall	O>B>S	Overall C>M>H
	Metal	O>B>S	Brown C>M>H
	Hydrocarbon	O>B>S	Li Brown M>C>H
<i>Navicula perminuta</i>	Overall	O>B	
<i>Navicula sp. a</i>	Overall	S>B>O	Sparkes C>H
	Control	B>O>B	
	Hydrocarbon	S>B>O	
<i>Pseudostauroneis brevistriata</i>	Control	S>B	Sparkes C>H
	Metal	B>S>O	Brown M>H>C
	Hydrocarbon	O>S	
<i>Stauroneis wislouchii</i>	Overall	B>S>O	Overall H>C>M
	Control	B>S>O	Brown H>M>C
	Metal	B>S>O	
	Hydrocarbon	B>S>O	
<i>Synedropsis cf. recta</i>	Overall	S>O>B	

Table 11.4 ANOVA and SNK results for comparisons of species relative abundances between locations, between treatments and interactions thereof.

	Location	Treatment	L x T
Richness	0.70	0.09	0.06
Diversity (H')	0.79	0.43	0.37
Evenness	0.85	0.72	0.66
Dominance	0.83	0.75	0.41

Table 11.5 ANOVA results for structural parameters of diatom communities for comparisons between treatments, locations and the interactions thereof.

### The influence of location on the diatom communities

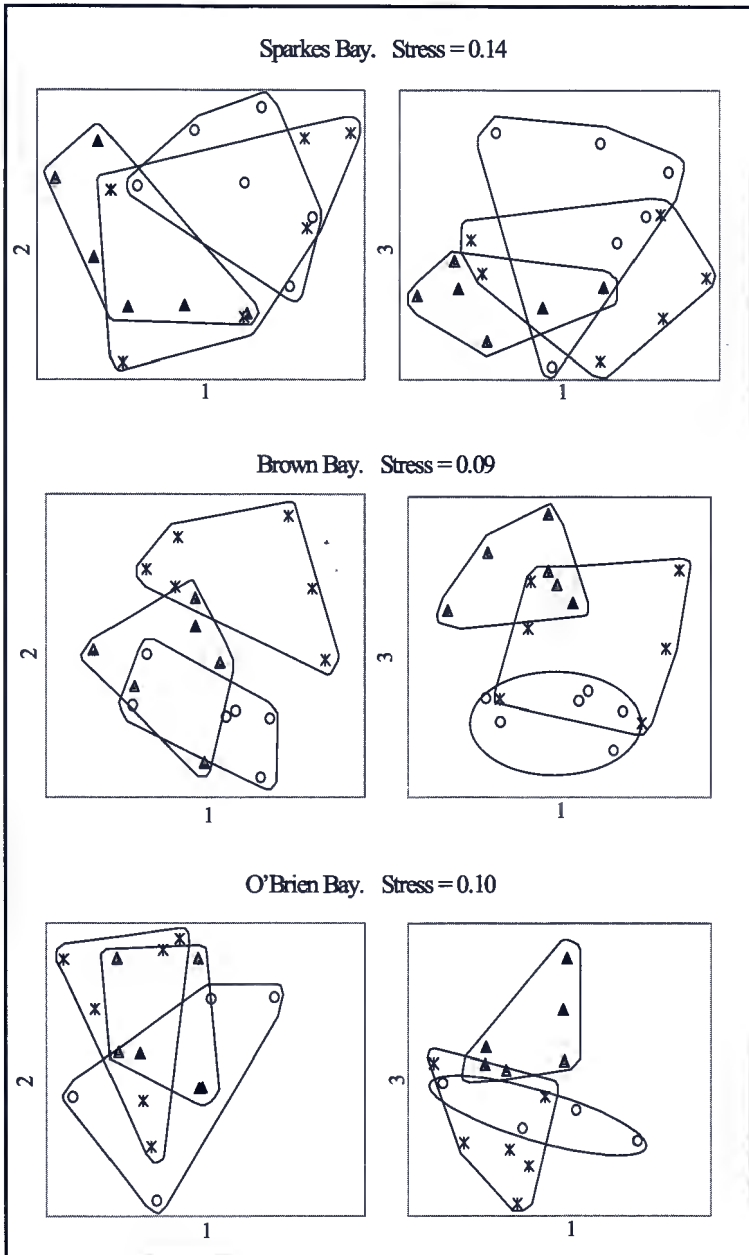
The location of deployment had the greatest influence on the composition of the diatom communities, with a global  $R$ -value of 0.734 ( $p < 0.0001$ ). All three locations had significantly different community compositions (Fig. 11.5), although structural parameters were not statistically different. O'Brien Bay and Sparkes Bay had the most similar compositions regardless of the treatments compared (Table 11.6). The greatest dissimilarity in diatom communities from metal contaminated sediments occurred between O'Brien Bay and Brown Bay. In contrast the greatest dissimilarity between diatom communities from both the control and petroleum hydrocarbon contaminated treatments occurred between Sparkes Bay and Brown Bay.

The differences in composition observed between locations were produced by differences in the relative abundances of a number of species. Consistent differences in the relative abundances of several species occurred between locations, regardless

Treatments Compared		$R$ -value	Significance Level
<i>Overall</i>			
Sparkes Bay	Brown Bay	0.631	0.0%
Sparkes Bay	O'Brien Bay	0.414	0.0%
Brown Bay	O'Brien Bay	0.553	0.0%
<i>Control</i>			
Sparkes Bay	Brown Bay	0.850	0.2%
Sparkes Bay	O'Brien Bay	0.607	0.5%
Brown Bay	O'Brien Bay	0.766	0.5%
<i>Metal Contaminated</i>			
Sparkes Bay	Brown Bay	0.563	0.2%
Sparkes Bay	O'Brien Bay	0.357	1.9%
Brown Bay	O'Brien Bay	0.757	0.2%
<i>Hydrocarbon Contaminated</i>			
Sparkes Bay	Brown Bay	0.974	0.2%
Sparkes Bay	O'Brien Bay	0.767	0.2%
Brown Bay	O'Brien Bay	0.945	0.2%

Table 11.6 ANOSIM results for comparison of samples deployed at each location, both overall and for each treatment type. All results were significant.





**Figure 11.5.** 3D nMDS ordination of diatom communities showing the separation of treatment types within each location. Control treatments are indicated by a hollow circle; metal contaminated sediments are depicted by an asterisk; hydrocarbon contaminated sediments are indicated by a solid triangle. Stress levels indicated that a 3D ordination was required; ordination axes as indicated.

of treatment type. For example, *Navicula* sp. b occurred at higher relative abundances within Brown Bay, than in either of the reference locations (Table 11.5). In contrast, *Achnanthes brevipes* and *Synedropsis* cf. *recta* occurred at significantly higher relative abundances within both the reference locations, than they did in Brown Bay. *Cocconeis fasciolata* and *Navicula perminuta* both had significantly higher abundances in O'Brien Bay than in Brown Bay (Table 11.5). Significantly higher relative abundances of *Navicula directa* occurred in O'Brien Bay than at either Sparkes Bay or Brown Bay.

The relative abundance of several other species varied between locations however these differences were not consistent across treatment types. Significant interactions between location and treatment were observed for *Navicula* sp. a, *Navicula* aff. *glaciei*, *Stauroneis wislouchii* and *Planothidium* spp. (Table 11.5). For example, *Navicula* sp. a was observed to have higher relative abundances in samples from Sparkes Bay for the hydrocarbon treatment (Table 11.5). Similarly, O'Brien Bay had significantly higher relative abundances of *Navicula* aff. *glaciei* than Sparkes Bay or Brown Bay, within the metal and hydrocarbon treatments (Table 11.5).

### Comparison of developing and remnant diatom communities

Remnant diatom communities refers to those diatoms originally present in sediment collected from O'Brien Bay, which represent the naturally occurring communities from this location. These communities were significantly different to the communities which developed on the deployed sediments during the experiment (Fig. 11.6). Structural parameters were significantly different between the remnant communities, and those that developed on the experimental sediments. The remnant communities had higher dominance values, with lower diversity and evenness values than the developing communities (Table 11.7).

A number of species were present in the experimental sediments that were not recorded in the remnant communities. These species were: *Anomoeoneis* cf. *foliis*

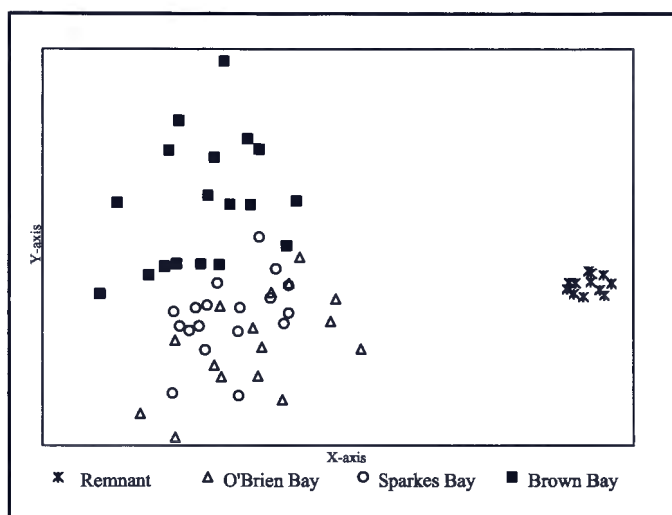


Figure 11.6 2D nMDS ordination indicating the differences in composition observed between the pre-existing natural communities from O'Brien Bay (remnant) and the diatom communities which developed on the experimental sediments. Stress = 0.13

	Remnant Communities	Developing Communities	<i>p</i> value
Diversity	2.903 $\pm$ 0.007	3.091 $\pm$ 0.021	0.00005
Dominance	0.073	0.0592 $\pm$ 0.0003	0.012
Evenness	0.789 $\pm$ 0.004	0.8457 $\pm$ 0.009	0.000001

Table 11.7 ANOVA results for structural parameters between recruiting and developing communities. Results shown are for the calculated value  $\pm$  standard error (if greater than 0.0001).

var. *hannae*, *Amphora* sp. a, *Ctenophora pulchella*, *Nitzschia dubis* var. *australis*, *Luticola muticopsis*, *Navicula perminuta* and two unidentified pennates. In contrast, *Pleurosigma* sp. a was present in the remnant communities, but not observed in the communities which developed on the experimental sediments. The developing communities had lower relative abundances of *Cocconeis costata*, *C. fasciolata*, *Stauroneis construens* var. *venter* and *Pseudostauroneis brevistriata*. The developing communities had higher relative abundances of *Navicula* sp. a, *Stauroneis*

*wislouchii*, *Navicula* aff. *glaciei*, and *Achnanthes brevipes* than the remnant communities.

### Discussion

Contamination of marine sediments, at levels similar to those produced by station activities, can result in changes to the composition of diatom communities living in and on these sediments. Both the metal and petroleum hydrocarbon contamination significantly affected the diatom communities, however the response was complex and the location of deployment influenced the observed effects. The diatom samples collected from the experimental sediments would have initially contained some of the remnant diatom community as well as the developing communities. That the developing communities were so different from the remnant community indicates that the diatoms which developed on the sediments were in sufficient number to overcome much of the influence that the diatoms remaining from the original sediments would have had on the relative abundances. Thus it can be concluded that the observed differences in community composition are a response to the experiment itself and not simply variations present within the sediments at the time of deployment. The absence of a live diatom community at the time of deployment, would explain the increased diversity and richness values observed in the developing communities. It is possible that a longer deployment period may have enabled a more natural diatom community to develop.

The design of the experimental units used in this experiment may account for some of the variation observed between the remnant diatom communities and those which developed on the experimental sediments. The experimental sediments were raised 12 cm above the natural substrate. This may have caused a bias towards species which are more easily re-suspended. Additionally, some of the diatom species included in the analysis occur in both benthic and under-ice communities. These species could colonise the experimental sediments either via resuspended sediment, or as 'rain' from the sea-ice, which may have resulted in higher abundances of these species, relative to species which only occur in sediments. The method of deploying

manipulated sediments used in this experiment was successful and would be applicable for future investigative and monitoring work within Antarctica.

This study is one of the first to examine the effects of either petroleum hydrocarbon or metal contamination of marine sediments on the microphytobenthos that inhabit the sediments. The majority of work examining the sensitivity of marine diatoms to pollution has been based on phytoplankton (eg. Hsiao, 1978). Whilst the use of periphyton for pollution monitoring has increased in recent years, this has typically been related to water quality, not sediment contamination (eg. Ivorra et al., 1999).

Contamination by petroleum hydrocarbons had a larger effect on diatom community composition than did metal contamination. This could be related to the solubility and diffusion of the two contaminant types which are likely to be different in interstitial pore water. Metal bioavailability is controlled by a large number of complex interacting factors, most importantly for the results presented here, the free ion concentrations (Eriksen et al., 2001). Many heavy metals are known to have appreciably higher solubilities under the reducing conditions that were found at a depth of approximately 1 cm in the experimental sediments. It is therefore likely that a steep gradient in the free ion concentrations would have been present below the sediment-water interface. As diatoms are essentially restricted to the surface layer of the sediments, they would potentially have been exposed to only slightly elevated metal concentrations relative to the control treatments. In contrast, the petroleum hydrocarbons would have been less affected by reducing conditions, and thus would have been more evenly distributed throughout the sediment profile.

The response of diatom communities to petroleum hydrocarbon contamination within this experiment does not appear to be directly related to concentration. Sparkes Bay had the lowest initial hydrocarbon concentrations; final concentrations of hydrocarbons were lowest in Brown Bay. Despite this, differences between control and hydrocarbon treatments were most pronounced in Brown Bay, with Sparkes Bay showing the second strongest response. It therefore seems unlikely that the

differences in the hydrocarbon concentration are responsible for the varying responses observed between locations.

The concentrations of hydrocarbons used in this experiment were selected to represent petroleum hydrocarbon concentrations present within Brown Bay yet these are still well below concentrations that have been reported elsewhere in Antarctica (eg. Lenihan et al., 1990). Concentrations of hydrocarbons as low as  $0.04 \text{ m L}^{-1}$  have previously been demonstrated to inhibit diatom growth (Siron et al., 1991), however, this is subjective and related to the sensitivity of an individual species (Ostgaard et al., 1984). Toxic effects of petroleum hydrocarbon contamination on diatom communities increase with exposure time (Hsiao, 1978). Compositional differences, with marked changes in the presence or absence of species, have previously been observed between control communities and those exposed to either light crude oil, or diesel based oil-cuttings (Plante-Cuny et al., 1993). In contrast, the presence or absence of particular species contributed little to differences in community composition in the current experiment, probably reflecting the comparatively low levels of hydrocarbon contamination employed in our study ( $400 \text{ mg kg}^{-1}$  as opposed to  $45\,000 \text{ mg kg}^{-1}$ ).

The diversity of diatom communities has previously been reported to vary as a result of exposure to petroleum hydrocarbons (Vargo et al., 1982, El-Dib et al., 2001). Metal contamination has also been shown to influence the structure of diatom communities, resulting in lower diversity and richness, but increased dominance values (Crossey and Point, 1988). Within this study, significant differences as a result of petroleum hydrocarbon contamination and metal contamination were only observed in the composition, not the structure, of diatom communities. The low concentrations of hydrocarbons used in this experiment, and the nature of the metal contamination used may explain the lack of observed structural response to contamination within the current experiment. Crossey and Point (1998) examined the effects of water column contamination on benthic diatom communities, whereas this experiment examined the influence of sediment. Contamination via the

sediments has previously been demonstrated to produce a more muted response than contamination via the water column (Peres et al., 1997). Under the experimental conditions utilised in this study, diversity, and associated measures such as dominance, are not useful for monitoring effects of either metal or petroleum hydrocarbon contamination of marine sediments at the levels currently occurring around Casey Station.

Compositional changes in benthic diatom communities resulting from metal contamination have previously been documented in lakes (Ruggiu et al., 1998) and rivers (Ivorra et al., 1999). Both of these studies found *Achnanthes* spp. to be metal tolerant, increasing in abundance with increased copper (Ruggiu et al., 1998), zinc and cadmium concentrations (Ivorra et al., 1999). Our results did not indicate any significant changes in the relative abundances of *Achnanthes* spp. as a result of either metal or petroleum hydrocarbon contamination. The relative abundances of *Achnanthes brevipes* were higher at control locations, than in Brown Bay, however this could have resulted from factors other than contamination.

Several species did respond significantly to contamination. *Navicula* sp. c appears to be pollution tolerant, as significantly higher abundances of this species were observed within both the metal contaminated and hydrocarbon contaminated treatments, relative to the control treatment. In contrast, the lower relative abundance of *Navicula directa* within the hydrocarbon treatments, relative to the controls, suggest that this species may be sensitive to hydrocarbon contamination. *Navicula* aff. *glaciei* may also be sensitive to hydrocarbon contamination, although as this response was only observed within Brown Bay it is possible there are other contributing factors involved. Further investigation of the responses of these species to varying contaminant concentrations may enable them to be used as indicator species within the region. As a genus, *Navicula* is considered to be highly tolerant of pollution (Palmer, 1969), however, the current results clearly indicate that different species of this genus can have varying responses to the same contaminants.



It has previously been suggested that small species will become dominant in communities exposed to chemical stress (Kinross et al., 1993). Increased abundances of small forms of *Navicula* spp. have been related to organic enrichment and eutrophication (Kelly and Whitton, 1995) as well as zinc and cadmium pollution (Ivorra et al., 1999). This trend was not observed within the current study. Although the relative abundances of *Navicula directa* (a large species, 70–120  $\mu\text{m}$  in length) decreased in treatments exposed to hydrocarbon treatments, so too did the relative abundances of *Navicula* aff. *glaciei* (8–45  $\mu\text{m}$  in length).

Further comparisons of the present work to other studies is hampered by a lack of published information. Most previous studies of benthic diatom responses to chemical contaminants have examined freshwater, not marine, species (eg. Ivorra et al., 1999; Ruggiu et al., 1999). The pollution tolerances of estuarine and coastal diatom species to pollution are essentially unknown; data on this topic is so scarce it prevents the development of marine diatom indices for pollution monitoring purposes (Sullivan, 1999).

The two reference locations (Sparkes Bay and O'Brien Bay) developed the most similar diatom communities, although that of Sparkes Bay was intermediate between O'Brien Bay and Brown Bay. It is possible that this reflects metal concentrations, with O'Brien Bay having only background levels, Sparkes Bay having naturally high levels of several heavy metals while Brown Bay has very high levels of a range of heavy metals.

The Brown Bay diatom communities had a composition significantly different to that of the combined diatom communities from the reference locations. This may be a reflection of the hydrocarbon contamination present within Brown Bay. This suggestion is supported by the experimental results indicating significant changes in the composition of diatom communities as a result of hydrocarbon contamination. In addition to sediment contamination, differences in water chemistry could also be influencing the diatom communities of Brown Bay. Leaching of contaminants from



the waste disposal site has increased metal concentrations in both the sediments and water column of Brown Bay (Snape et al., 2001). Although previous studies (Ivorra et al., 1999; Ruggiu et al., 1998) have demonstrated that metal contaminants within the water column can affect the composition of benthic species, no such study has been undertaken for the diatom flora of the Windmill Islands.

Significant changes in multivariate community composition resulting from metal contamination were only observed within the polluted site, Brown Bay. There are several possible explanations for this. Concentrations of many heavy metals within experimental sediments in Brown Bay increased during the experiment, presumably indicating further input from Thala Valley. It is possible that the diatoms were affected by the resultant higher levels, but that the concentrations used in the experimental treatments themselves were too low to produce a detectable effect. In other words, the diatom communities may be able to tolerate low levels of heavy metals, but once a particular threshold has been reached, diatom community composition is significantly affected.

Alternatively, the pollution history of Brown Bay could be influencing the development of diatom communities. The level of pre-existing stress in an area can strongly influence the outcome of an experiment (Berge, 1990). Communities in areas already stressed may be more susceptible to the influence of further stressors (contamination or disturbance) than communities from reference locations (Underwood, 1989). Thus, the contamination already present in Brown Bay could increase susceptibility of the diatom community to the sediment contamination imposed by this experiment. This hypothesis is supported by the large compositional differences between diatom communities from both metal and hydrocarbon contaminated treatments in Brown Bay and all other samples. Synergism between hydrocarbon and metal contamination within Brown Bay may also be contributing to the greater effects observed within this bay.

### **Conclusions**

This study has demonstrated that the composition of diatom communities can be influenced by both metal and hydrocarbon contamination at concentrations comparable with pollution levels caused by station activity. Differences between control and contaminated locations, and between control and hydrocarbon contaminated treatments were apparent after only eleven weeks, indicating diatom communities may be a useful tool for rapidly detecting impacts caused by petroleum hydrocarbon and metal contamination. The response of diatom communities to a range of different contaminant concentrations would need to be determined before the method could be used for routine monitoring. Should diatoms be used as a monitoring tool within the region, caution must be exercised to ensure that the influence of location can be distinguished from the effects of contamination.

## Chapter 12

### **Synthesis**

#### **Diatom assemblages of the Windmill Islands**

##### **Summary of diatom communities**

The diatom assemblages used in this study consisted of elements from planktonic, sea-ice and benthic communities. Benthic species typically dominate the assemblages; over the last three thousand years the proportion of benthic species present within the diatom assemblages has always exceeded 60%, reaching a maximum of 82.2% (Chapter 6). In most analyses, only benthic diatom communities were considered.

The benthic diatom communities sampled generally consisted of 30-35 species. A total of 55 benthic species were recorded from the Windmill Islands, however, several of these only occurred within a few samples. No one species dominated the benthic diatom communities at all locations. The highest relative abundance recorded for an individual species was 44.8% for *Navicula* aff. *glaciei*, in one of the samples from Odber Island, however this species typically had abundances below 15% in both Brown Bay and Shannon Bay. *Cocconeis schuetti* attained a maximum relative abundance of 40% at Sack Island, but values for this species were typically less than 10% at other locations.

Generally only 2 or 3 species were abundant at each location, with relative abundances ranging between 10 and 20% for each of these species. The most abundant species differed between locations. For example, *Staurosira construens* var. *pumila* was the most abundant benthic species at Cloyd Island, with relative

abundances ranging between 13% and 40%, however, this species did not exceed 10% in either Brown Bay or Shannon Bay. Conversely, the relative abundances of *Planothidium* spp. typically exceeded 10% at Brown Bay, but did not exceed this amount at either Cloyd Island or Shannon Island.

Structural parameters of the benthic diatom communities varied both within a site, and between sites. Evenness values ranged between 0.530 and 0.864, dominance values ranged between 0.068 and 0.315. Diversity values varied from 1.42 to 2.89 and richness values varied between 2.61 and 7.20.

The composition and structure of the benthic diatom communities varied significantly between several locations. An average dissimilarity of 41.4% was observed between different locations. The variability of the benthic diatom communities was generally related to the scale of observation; similarities between diatom communities increased when sampling distance decreased (Chapter 4). A large proportion of the variability observed between locations was related to differences in grain-size, the proportion of surface irradiance that reached the benthos, and water depth (Chapter 5). These factors also influenced the variability of diatom communities within each location; the proportion of mud and sand accounted for approximately 40% of the variation in diatom communities at two of the locations examined (Chapter 5). This estimate is higher than has previously been reported, with grain-size accounting for only 13% of the variation observed in benthic diatom communities from fjords in the Vestfold Hills (Whitehead and McMinn, 1997). Diatom communities at two locations, namely Shannon Bay and Cloyd Island were not significantly related to grain-size, water-depth or irradiance. It has yet to be determined what factors do influence the distribution of diatom communities within these locations.

### **Comparisons with other assemblages from Antarctic marine sediments**

The diatom assemblages from the Windmill Islands had higher relative abundances of benthic species, and lower relative abundances of planktonic species compared to

other Antarctic studies. For example, the planktonic species *Fragilariopsis curta* and *Fragilariopsis cylindrus* had maximum relative abundances of 45% and 11.7% respectively in sediments from the George V Coast (Leventer, 1992) and 48% and 11% from sediments in Lutz-Holm Bay (Tanimura, 1992). Maximum relative abundances of only 10% and 3%, respectively were recorded for these in surface sediments from the Windmill Islands (Chapter 2). *Achnanthes* species have been reported at low abundances (<2.5%) in sediments from Lutz-Holm Bay (Tanimura, 1992), but were absent from sediments on the George V coast (Leventer, 1992); diatom assemblages from the Windmill Islands had relatively high abundances of *Achnanthes brevipes* (1.5 to 18%) (Chapter 2). Similarly, the total abundance of *Cocconeis* species did not exceed 0.8% on the George V Coast (Leventer, 1992), or 3.1% in Lutz-Holm Bay (Tanimura, 1992), however all *Cocconeis* species identified from the Windmill Islands individually exceeded these abundances in at least one sample (Chapter 2). Furthermore, *Cocconeis schuetti* attained a maximum relative abundance of 40% in a samples from Sack Island. The higher relative abundances of benthic species in this study probably reflects the shallow depths from which samples were collected, typically 1-16 m, while samples were collected from Lutz-Holm Bay at depths up to 500 m in (Tanimura, 1992) and from 2599 m on the George V Coast (Leventer, 1992).

Many of the benthic species identified in this study were also recorded in benthic diatom assemblages from fjords in the Vestfold Hills (Whitehead and McMinn, 1997). These species include *Cocconeis costata*, *C. fasciolata*, *C. pinnata*, *Diploneis splendida*, *Staurosira construens*, *Navicula directa*, *N. glaciei*, *N. perminuta*, *Pseudogonphonema kamschaticum* and *Trachyneis aspera*. In Maxwell Bay, *Trachyneis aspera*, and *Cocconeis* spp. each constituted 11% of the total diatom biomass in the sediment, while *Odontella litigosa* and *Cylindrotheca closterium* constituted 43% and 19% respectively (Ahn et al., 1997). Neither of the latter two species was present in diatom communities from recent sediment samples in the Windmill Islands (Chapter 2), despite similar sampling depths. The relative abundances of *Cocconeis* spp were much higher in samples from the Windmill

Islands than those reported from Maxwell Bay. In contrast, diatom assemblages from Maxwell Bay had much higher relative abundances of *Trachyneis aspera* than assemblages from the Windmill Islands, where the maximum abundance recorded was 1.5%.

The distribution of several benthic species varied from previous reports for Antarctica. For example, Whitehead and McMinn found *Navicula glaciei* to be indicative of very shallow water (0-0.5 m), however, high abundances of this species (<20%) were observed at depths of 8 m at Odbert Island. In addition, *Trachyneis aspera*, a highly shade adapted species (Palmsiano et al., 1985) is generally abundant at increased water depths (<10 m) (Whitehead and McMinn, 1997), however, in the samples from the Windmill Islands, the maximum relative abundance recorded for this species was from 4 m water depth (Chapter 2).

The benthic diatom communities examined within this study are not overly similar to any benthic diatom communities previously described from Antarctica. Although similar components are present within communities from the Windmill Islands, and other Antarctic regions, the relative abundances at which these species occur are variable but distinct.

## **Human impacts on diatom communities from the Windmill Islands**

### **Introduction**

In order to assess the influence of chemical contamination on diatom communities, only diatom species associated with the benthos were incorporated into analyses. Benthic communities were selected due to their more constant relationship with point-source contaminants, relative to planktonic organisms (McCormick and Cairns, 1994). Planktonic organisms live within the water column, and are often transported by currents; in contrast, benthic organisms are relatively immobile. In terms of impact assessment, benthic organisms have a fixed relationship with contaminants, whereas the spatial and temporal relationships between planktonic communities and

contaminants are much harder to determine. Species which grow only in planktonic communities were therefore excluded, although species that occur in both planktonic and benthic communities, or both sea-ice and benthic communities, were incorporated into the analyses.

## **Differences between control and potentially impacted locations**

### *Community composition*

Recent sediment samples revealed that the community composition of Brown Bay was significantly different to the average of two control locations (Chapter 3). No significant differences were detected in the composition or structure of diatom communities from Wilkes and the average of two control locations (Chapter 3). The diatom communities of Shannon Bay, another potentially impacted location, were compositionally more similar to diatom communities from control locations than from Brown Bay (Chapter 4 and 5).

Large dissimilarities were observed in the composition of diatom communities from different control locations (Chapter 4 and 5). A high degree of dissimilarity between communities from control locations may prevent the detection of minor impacts, particularly when no 'before data' is available (Underwood, 1992). It is therefore possible that the variability between control locations within the Windmill Islands may have prevented the detection of subtle impacts within Shannon Bay and Noonans Cove.

### *Spatial variability*

Spatial variability also differed between control locations and the potentially impacted Brown and Shannon Bays (Chapter 4). Although significant variations in diatom community composition were observed to occur between sites (80-100 m apart) at control locations, no significant differences were detected between sites within these two potentially impacted locations.

Seasonal variations in community composition differed between Brown Bay and the control locations (Chapter 6), with opposing trends observed. When values for

particular species (or ordination axes) increased at control locations, values for diatom communities in Brown Bay would decrease. Conversely when values for diatom communities in control locations decreased, diatom communities in Brown Bay increased in values (Chapter 6). It seems likely that different processes may be occurring in Brown Bay, than at the other sampling locations. Possible explanations include the greater volume of freshwater input from Thala Valley, or increased mixing of the water column within Brown Bay.

### *Temporal variability*

An assessment of the temporal variability of benthic diatom communities from the Windmill Islands indicated that significant differences in community composition between Brown Bay and Sparkes Bay have existed for approximately 150 years (Chapter 6). This indicates that the composition of these communities has been differed due to natural processes, since the establishment of human settlements has only occurred within the last fifty years. In order to demonstrate that human activities within the Windmill Islands had resulted in biological effect, the changes in relative abundances of diatom communities of Brown Bay, would need to be compared to the average of a set of control locations, as described by Underwood (1989). Whilst this could potentially be addressed in future work, the resources required to collect sediment cores from other control locations were not available during this project.

### **Temporal comparisons**

Given both the spatial and temporal variation observed between diatom communities from Brown Bay and other bays within the Windmill Islands (Chapters 4 and 6), the use of these other bays as control locations is problematical. Three cores were collected from within Brown Bay itself. Chemical analyses indicated that metal concentrations within two of these cores were similar to those measured at control locations, whilst the third core had elevated concentrations of a range of metals (Chapter 7). The two uncontaminated cores were therefore used as controls.



Changes in the third core, which were putatively related to chemical concentration, could be compared to temporal changes observed within the control cores.

Multivariate and univariate analyses indicated that significant changes in community composition and the abundances of individual species occurred in Core 3 subsequent to the operation of the Thala Valley tip (Chapter 7) and the associated chemical contamination of Brown Bay. In contrast, no significant changes in community composition were detected within Cores 1 and 2 between diatom communities which existed prior to this time, and the more recent communities. Furthermore, comparisons between cores indicated that observed increases in the relative abundances *Navicula* sp. c, *Navicula directa* and *Navicula* sp. a within Core 3 exceeded the variation observed for these species in Cores 1 and 2. This demonstrates not only that a change occurred simultaneously with the contamination of Brown Bay, but also that this change exceeded the observed range of natural temporal variation within the control cores. Thus temporal comparisons of diatom communities within Brown Bay negate the null hypothesis that chemical contamination of marine sediments has not affected the composition of diatom communities within this bay.

## Correlations

The relationship between diatom community composition and concentrations of different metals and hydrocarbons were assessed using direct gradient ordination techniques (Chapters 8 and 9). Preliminary analyses indicated that a linear response model was most applicable, thus redundancy analysis was selected as the ordination method. These analyses indicated that the relative abundances of diatom species was significantly related to concentrations of metals (Chapter 8), but not total purgeable hydrocarbons (TPH) (Chapter 9). TPH concentrations are not restricted to human derived petroleum hydrocarbons. For example, unsaturated long chain hydrocarbons (C<sub>20</sub>-C<sub>30</sub>) are typical of Antarctic microalgae, and are commonly found in zooplankton micropellets (Cripps and Priddle, 1991). Although hydrocarbons derived from anthropogenic sources can be distinguished from naturally occurring

hydrocarbons, such data was not available for this study. Until the relationship between diatom community composition and anthropogenic hydrocarbons can be more directly assessed, potential impacts can not be discounted.

Variations in metal concentrations explained 48% of the variation observed in the diatom communities, once collinear variables had been deleted. Tin and zinc accounted for 34% and 36%, respectively of the variability that could be attributable to metal concentrations. Both cadmium and copper accounted for a further 10% of this variation. Tin, copper, lead and zinc were all highly correlated, and the individual influence of an individual metal could not be determined. However, including two of these metals in the analyses increased the amount of variation which was explained, suggesting that these metals do affect the diatom communities in slightly different ways, despite the observed colinearity in their distribution. Based on the toxicological information available, it seems likely that concentrations of copper are predominantly responsible for the observed effects on benthic diatom communities.

Although a significant correlation between metal concentrations and the relative abundances of diatom communities was demonstrated by these analyses, the distribution of other environmental variables was not considered. It is therefore possible that the distribution pattern of metals matches that of a different environmental variable, such as grain-size, which may be influencing the relative abundances of diatom communities. Without demonstrating that other environmental variables do not have a similar distribution to the metal concentrations, the correlation between metal contamination and the observed biological effects does not conclusively show cause and effect.

### **Causal relationships**

Two manipulative field experiments were undertaken to assess whether the contamination of marine sediments with heavy metals and petroleum hydrocarbons influenced diatom community composition. The diatom communities which

developed over a 12 month period on polluted sediments were neither compositionally nor structurally different to diatom communities which recruited to control sediments (originally derived from O'Brien Bay) over the same time period. It is possible that the long duration of this experiment may have influenced the observed results, potentially due to increased proportion of sea-ice and planktonic species within the diatom assemblages.

A short 11 week experiment was used to compare diatom communities which developed on control sediments with those which developed on metal contaminated sediments and petroleum hydrocarbon contaminated sediments. This experiment demonstrated that both forms of contaminants could affect diatom community composition at levels representative of those currently occurring within the Windmill Islands. Contamination of sediments by petroleum hydrocarbons was shown to have a stronger influence on the composition of benthic diatom communities than metal contamination under the experimental conditions imposed.

### **Application of diatom data for environmental monitoring within the Windmill Islands**

The Protocol on Environment Protection amended to the Antarctic Treaty (the "Madrid Protocol") requires that key ecological parameters and environmental components be monitored to enable early detection of adverse effects which result from anthropogenic activities. This study has demonstrated the sensitivity of benthic diatom communities to relatively low levels of metal and petroleum hydrocarbon contamination of marine sediments. This sensitivity, and the rapid response of diatom communities to environmental changes (Sullivan, 1999), would make them an ideal monitoring tool for the early detection of anthropogenic contaminants. The advantages of biological monitoring are well known, and include temporal integration of data, and reduced sampling costs

This project demonstrated a significant relationship between metal concentrations and benthic diatom communities. This relationship could potentially be applied for monitoring purposes, however further clarification of potential interactions between metal concentrations, sediment grain-size and the benthic diatom communities would first be required. If data on both grain-size and metal concentrations was available for the same sample set, then redundancy analyses could be performed to determine what proportion of the variance in diatom communities was explained by each factor. The significance of the metal-diatom community relationship observed in Chapter 8 indicates the feasibility of creating a transfer function based on this data. Should this significance still be maintained once the effects of grain-size are allowed for, then it would be possible to infer metal concentrations from diatom data. Sediment core data would enable this model to be refined to be applicable over the entire range of metal concentrations which have occurred within the Brown Bay. This could then be applied for monitoring of metal concentrations which occur within these sediments.

Throughout this project several species have been suggested as good candidates for potential indicator species. These species were suggested based on observed changes in abundance which corresponded to the presence, or concentration, of contaminants. *Navicula cancellata* appears to be pollution tolerant as increased abundances were observed: subsequent to the start of contamination in Brown Bay (Chapter 7); within both metal contaminated and petroleum hydrocarbon contaminated sediments (Chapter 11); and in correlation with increased concentrations of metals, particularly lead and copper (Chapter 8).

Not all species behaved as consistently as this. For example, relative abundances of *Navicula directa* also increased subsequent to contamination in Brown Bay (Chapter 7) and were correlated with both metal and total hydrocarbon concentrations (Chapters 8 and 9), however, this species decreased in abundance when petroleum hydrocarbon contaminants were added to the sediments (Chapter 11). Whilst these species may have potential for monitoring purposes, more detailed ecotoxicological investigations would be required.

### Conclusions

The spatial and temporal variability of benthic diatom communities within the Windmill Islands increases the number and complexity of methods required to demonstrate if chemical contaminants present within the marine environment are affecting the composition and structure of benthic diatom communities. Despite significant differences between the contaminated Brown Bay and control locations within the Windmill Islands, simple comparisons of these communities can not be conclusive of an impact due to temporal divergence of these communities. Given this, 'before and after' comparisons appear to offer a more reliable method of detecting impact.

Temporal comparisons revealed that a significant change in community composition occurred contemporaneously with metal contamination within one core from Brown Bay. This change was shown to exceed the temporal variability of diatom communities which were observed in two uncontaminated cores from this location. Associated changes in the relative abundances of several *Navicula* spp. were also shown to exceed the temporal variation which might have been expected.

Redundancy analysis established that metal concentrations explained a major proportion of the variation within diatom communities from within Brown Bay. As other environmental variables were not assessed in conjunction with this, the evidence still did not demonstrate conclusively that the metal concentrations were causing the observed pattern of diatom abundances. In order to demonstrate that this was possible, manipulative field experiments were performed. These demonstrated that the contamination of marine sediment by either metals or petroleum hydrocarbons does influence the compositions of the benthic diatom communities which develop on these sediments.

The three methods outlined above for assessing potential impacts all indicated that contamination present within the marine sediments of Brown Bay was influencing the composition of diatom communities, however, none of these studies were conclusive independently of each other. The combination of these results indicates that::

1. Compositional differences occur between diatom communities from contaminated sediments, and those of control sediments.
2. The observed differences exceed the natural spatial and temporal variability expected to occur at certain place, at a certain time
3. These compositional differences appear related to the pattern of contamination
4. Contaminants present within the marine sediments of Brown Bay occur at concentrations capable of influencing the composition of the diatom communities which inhabit these sediments.

It is therefore concluded that the contamination of marine sediments with petroleum hydrocarbon and metals may result, and has previously resulted, in a biological impact on the benthic diatom communities within Brown Bay.

### **Implications**

Benthic diatom communities make a significant contribution to primary productivity in coastal regions of Antarctica (Gilbert, 1991b). In addition to being a vital food source for other benthic organisms (Ahn et al., 1993), benthic diatoms also form a large component of microalgal biomass which exists in the water column (Tanimura, 1992; Everitt and Thomas, 1986). Changes to the composition of benthic diatom communities as a result of chemical contamination may therefore affect organisms higher up the food chain.

Concentrations of metals are typically higher within benthic diatoms than in the sediments on which these diatoms live (Ramelow et al., 1991). The degree of

bioconcentration increases with increasing metal concentrations. Linear relationships were shown between sediment concentrations, and concentrations in diatoms for zinc and lead whilst concentrations of copper and cadmium in diatoms were less variable in diatoms than that observed in the sediments (Absil et al. and Scheppingen, 1996). The increased concentrations of metals present in diatoms may affect species which utilise benthic diatom communities as a food source, such as the common, suspension feeding, bivalve *Laternula elliptica* (Ahn, 1996). Duquesne and Riddle (2002) have demonstrated that this species has significantly higher tissue concentrations of arsenic copper, lead and zinc in animals collected from Brown Bay, than in animals collected from control locations in the Windmill Islands.

Previous studies have also demonstrated relationships between the contamination of marine sediments around Casey Station, and the distribution and abundance of soft-sediment infauna. Polluted locations within the Windmill Islands have increased abundances of the gammarid amphipods *Orchomella franklini*, *Heterophoxus videns*, and *Methalimedon* spp. relative to control locations (Stark, 2000; Lenihan et al., 1995). The distribution of soft-sediment faunal assemblages correlates with the distribution of metals, despite large disparity in grain-size between samples (Stark et al., submitted a). In addition, a causal link has been established between chemical contamination of marine sediments, and the abundance of soft-sediment infauna (Stark, 2001).

Anthropogenic contamination of marine sediments appears to be confined to several small embayments immediately adjacent to Casey Station. Two cores collected from the outer regions of Brown Bay showed no evidence of metal contamination (Chapter 7) indicating that the distribution of contaminants from Thala Valley is restricted. The contaminated areas are minute compared to the size of Antarctica, however the Windmill Islands represent an area of seasonally ice-free terrain and thus are ecologically significant. These areas represent important breeding sites for many birds and mammals. For example, the Windmill Islands is home to breeding colonies of Wilson's storm petrel, the Antarctic petrel, and Adelie penguins. In addition, the

Windmill Islands are the only known place on the Antarctic continent where southern elephant seals breed (Murray and Luders, 1980). Furthermore, several areas within the Windmill Islands are known seal 'pupping' sites. Thus, despite their restricted areal extent, ice-free regions are pivotal within Antarctic ecosystems.

Less than 0.01% of Antarctica consists of such coastal areas (Snape et al., 2001) yet the majority of all permanently manned research stations are located within these areas. All research stations so far examined exhibit a halo of heavy metal and petroleum hydrocarbon contamination (Kennicutt and McDonald, 1996). Thus anthropogenic contaminants, such as those assessed in this study, are concentrated in these areas of seasonally ice-free terrain. Even though this study has demonstrated significant anthropogenic impacts within only a small area, the ramifications of these findings are much greater than the areal extent might imply.



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## Appendix 1

### Taxonomy and Plates



## Bacillariophyceae

### *Achnanthes* Bory

#### *Achnanthes brevipes* Agardh

Plate 1, Figs. 1-4.

**Synonyms:** *Achnanthes intermedia* Kützing 1833 (Snoeijs, 1993)

*Achnanthes brevipes* var. *intermedia* (Kützing) Cleve

**Description:** Valves linear lanceolate, sometimes with a slight bend apparent. Girdle view rectangular, but with distinct “v” bend in middle. Raphe present on one valve, straight. Striae consist of a single row of areolae. Dimensions of the Windmill Island specimens (17-70  $\mu\text{m}$  long, 7-12  $\mu\text{m}$  wide) fall within the range given in John (1983) (15-25  $\mu\text{m}$  long, 5-15  $\mu\text{m}$  wide). The Windmill Island specimens show a greater range in the number of striae (7-10 striae in 10  $\mu\text{m}$ ) than that given in John (1983) (7 striae in 10  $\mu\text{m}$ ) while Dexing et al (1985) reported 7-10 striae in 10  $\mu\text{m}$ .

**Occurrence:** *Achnanthes brevipes* was present in all samples, with relative abundances between 1.5-18%.

**Distribution:** Typically benthic (Cremer et al, accepted) but also found in phytoplankton (Andreoli et al., 1995; Hakansson and Jones, 1994). This species occurs in both freshwater and marine environments. *Achnanthes brevipes* has a cosmopolitan distribution and has been recorded in sediments from Antarctica (Fumanti et al., 1994; Roberts and McMinn, 1999), Australia (John, 1983) and the Baltic Sea (Snoeijs, 1993). Lowe (1974) described this species as alkaliphilous and mesohalobus.

#### *Achnanthes* sp. a

Plate 1, Figs. 5-7.

**Description:** Heterovalvular frustules. Valves are elliptic to broad lanceolate. Valve dimensions: 7-30  $\mu\text{m}$  long, 3-11  $\mu\text{m}$  wide with coarse biserial striae (10 in 10  $\mu\text{m}$ ). The raphe is straight, with no curvature of the terminal fissures apparent under LM. Striae are interrupted around the central region on one side of the RLV. This feature is also seen in *Achnanthes lanceolata*.

**Occurrence:** This species was found at all sites, but not in all samples. *Achnanthes* sp. a was present in 73 of the 88 samples collected. Relative abundances typically ranged between 0 and 6%. The maximum relative abundance recorded for this species was 40% at Sack Island. This sample was collected shortly after ice broke out of the area, and probably represents a bloom of this species at the time of collection, rather than a year-round dominance of the benthic community, however further sampling would be required to verify this.

**Distribution:** *Achnanthes* sp. a was noticeably absent from samples with a water depth less than 4 meters.



## *Amphora* (Ehrenberg) Kützting

### *Amphora libyca* Ehrenberg

Plate 2, Fig. 1

Synonyms: *Amphora ovalis* var. *affinis* Kützting

*Amphora affinis* Kützting

*Amphora ovalis* var. *libyca* (Ehrenberg) Cleve (Patrick and Reimer, 1975).

**Description:** Valves lunatic with rounded to subacute apices. Convex margin smoothly arched. Ventral margin slightly concave. Dimensions of the Windmill Island specimens (18–40  $\mu\text{m}$  long, 5–9 wide  $\mu\text{m}$ , 13–15 striae in 10  $\mu\text{m}$ ) were frequently shorter and narrower than the range given in Patrick and Reimer (1975) (28–80  $\mu\text{m}$  long, 7–12  $\mu\text{m}$  wide with 11–15 striae in 10  $\mu\text{m}$ ). Dimensions more similar to those seen in the Windmill Island specimens were recorded by Johns (1983) (20–28  $\mu\text{m}$  long, 5–9  $\mu\text{m}$  wide with 12–15 striae in 10  $\mu\text{m}$ ).

**Occurrence:** *Amphora ovalis* var. *affinis* was present at all locations, occurring in 60 of the 88 samples. A maximum relative abundance of 5.7% was recorded for this species.

**Distribution:** Patrick and Reimer (1975) considered that this species typically occurred in standing or slow flowing waters. *Amphora ovalis* var. *affinis* has a cosmopolitan distribution and has previously been recorded in diatom floras from Western Australia (Johns, 1983), Alaska (Hein, 1990), the Laptev Sea (Cremer, 1998), America and Mexico (Patrick and Reimer, 1975). Antarctic reports of this species include the Vestfold Hills (Wassell, 1993; Whitehead and McMinn 1997) and the Antarctic Peninsula (Wassell and Håkansson, 1992). This periphytic species is indifferent to salt concentrations, but exhibits a preference for waters with a pH greater than 7 (Lowe, 1974).

### *Amphora ovalis* var. *ovalis* (Kützting) Kützting.

Plate 2, Fig. 2.

Synonyms: *Navicula amphora* Ehrenberg

*Amphora gracilis* Ehrenberg

*Amphora ovalis* var. *gracilis* (Ehrenberg) Van Heurck

*Amphora ovalis* f. *gracilis* (Ehrenberg) Hustedt (Patrick and Reimer, 1975)

**Description:** Valves lunatic with rounded to subacute apices. Convex margin smoothly arched. Ventral margin slightly concave. Dimensions and morphology of the Windmill Island specimens (35–65  $\mu\text{m}$  in length; 9–14  $\mu\text{m}$  in width; 11–12 striae in 10  $\mu\text{m}$ ) fall within the range described in Patrick and Reimer (1975) (35–85 in length, 9–17 in width, with 10–12 striae in 10  $\mu\text{m}$ ). This species is broader and has coarser striae than *Amphora ovalis* var. *affinis*.

**Occurrence:** Rare. This species was present in 70 samples, occurring at all locations. The maximum relative abundance of 1% occurred at several sites, including Brown Bay, Sparkes Bay and O'Brien Bay.

**Distribution:** Characteristic of still or slow-flowing waters, this species is regarded as an alkaliphil (Patrick and Reimer, 1975) with an optimum pH range between 7 and 8.5 (Lowe, 1974). This periphytic species is oligosaprobic but halobically indifferent (Lowe, 1974). *Amphora ovalis* has a cosmopolitan distribution. This species has been

1996), Alaska (Hein, 1990), and the Russian Arctic (Cremer, 1998). Although typically a benthic marine species, *Cocconeis costata* has also been recorded in lakes (Roberts and McMinn, 1999; Hein, 1990) and in marine phytoplankton (Ligowski, 1986).

**Comments:** No attempt was made to distinguish between the different varieties of this species.

***Cocconeis fasciolata* (Ehrenberg) Brown**

Plate 4, Figs 3-5

**Synonyms** *Raphoneis fasciolata* Ehrenberg

*Cocconeis imperatrix* Schmidt

**Description:** Valves elliptical with no pronounced ends. The sternum valve (SV) is flat to slightly convex, and has a central linear or tapering sternum. The raphe sternum valve (RSV) is flat to slightly concave with an obvious hylaine margin area. Raphe is straight externally, but may appear slightly sinuous on internal view. Central and terminal raphe ends slightly expanded. Biseriate striae; parallel in centre, radiate towards apices. Areolae arranged in a quincunx, areolae shape is more variable than in *C. costata* with circular, oval and triangular areolae reported (Romero, 1996). Sternum and interstriae readily apparent. Both areolae and striae are more widely spaced in *C. fasciolata* than in *C. costata* or *C. pinnata*. The morphology of the Windmill Island specimens is essentially the same as that described in Romero (1996). The dimensions given (27.7-59  $\mu\text{m}$  long, 16-40  $\mu\text{m}$  wide, 3-4 striae in 10  $\mu\text{m}$  on the RSV with 2.5-3 striae in 10  $\mu\text{m}$  on the SV) represent a smaller size range than the dimensions observed within our samples (12-90  $\mu\text{m}$  long, 8-35  $\mu\text{m}$  wide, 3-4.5 striae in 10  $\mu\text{m}$  on the RSV with 3 striae in  $\mu\text{m}$  on the SV).

**Occurrence:** *Cocconeis fasciolata* was present in all but 7 of the 88 samples examined, occurring at all locations. The maximum relative abundance of this species was 6.7% however a relative abundance of 1% was more typical.

**Distribution:** Typically a marine species, *Cocconeis fasciolata* has a circumpolar distribution (Cremer et al., In Press) and has been recorded in both plankton (Gilbert 1991) and benthos (Romero, 1996). Krebs (1983) recorded this species as being associated with sea-ice, however Krebs et al. (1987) stated that the presence of *Cocconeis fasciolata* in sea-ice was attributable to the high abundance of this species in near-shore benthic environments. *Cocconeis fasciolata* has also been recorded in Antarctic lakes (Roberts and McMinn, 1999).

***Cocconeis pinnata* Gregory**

Plate 3, Figs. 2-3.

**Synonyms:** *Rhaphoneis archeri* O'Meara

*Cocconeis denticulata* Leudiger-Fortmal (Hustedt, 1985)

**Description:** Frustules elliptical lanceolate to rounded hexagonal. Sternum broadly lanceolate to linear, occasionally tapering; always reached margin. Broad striae are widely spaced; biseriate apart from at ends of individual striae (both near sternum and margins) where striae are triseriate. The small areolae are always circular. Morphology of our specimens is very similar to that described by Romero and Rivera (1996). The dimensions of the Windmill Island specimens (8-32  $\mu\text{m}$  long, 5-15  $\mu\text{m}$  wide, 4-5 striae in 10  $\mu\text{m}$ ) are occasionally longer than the range given in Romero

and Rivera (1996) (8-28  $\mu\text{m}$  long, 7-17  $\mu\text{m}$  wide, 4-5 striae in 10  $\mu\text{m}$ ). This species can be distinguished from the other *Cocconeis* species described here by its broad sternum area.

**Occurrence:** *Cocconeis pinnata* was recorded in 50 of the 88 samples. It was absent from all samples collected near Odber Island, but was present at all other sites sampled. This species was only present at low frequencies, and never attained a relative abundance greater than 1%.

**Distribution:** *Cocconeis pinnata* has previously been recorded from several sites around Antarctica, including Adelie Land (Frenguelli, 1960), Deception Islands (Zhu, 1989) and the Vestfold Hills (Roberts and McMinn, 1999). This species has also been recorded from Cape Horn (Petit in Riaux-Gobin, 1994). *Cocconeis pinnata* has been described as a freshwater species (Roberts and McMinn, 1999) but has also been recorded in marine waters and sediments (Romero and Rivera, 1996).

### *Cocconeis schuettii* Van Heurck

Plate 3, Figs. 6-8.

**Description:** Frustules elliptical to elongate elliptical with no pronounced ends. Valve surfaces strongly curved. Raphe straight terminating well short of valve margin. Striae fine, parallel towards the centre of the valve, radiate at margins. Dimensions of the Windmill Island specimens are 50-85  $\mu\text{m}$  long, 30-50  $\mu\text{m}$  wide with 15-18 striae in 10  $\mu\text{m}$ . This species can be readily distinguished from other *Cocconeis* species found in the Windmill Islands, due to the finer arrangement of striae.

**Occurrence:** This species was found in 29 of the 88 samples. *Cocconeis schuettii* was found at low relative abundances (<1%) in Sparkes Bay, O'Brien Bay, Odber Island, O'Connor Island and Little Herring Island. This species was common in Brown Bay and Noonan Bay, with a maximum relative abundance of 15% recorded in the latter.

**Distribution:** This marine species has a circumantarctic distribution (Cremer et al., In Press). *Cocconeis schuettii* has previously been identified in benthic communities from King George Island (Klözner, 1998) and in a sediment core from the Windmill Islands (Cremer et al., In Press). Although typically benthic, *Cocconeis schuettii* has also been found in sea-ice (Krebs et al., 1987) and in the water column (Krebs, 1983).

### *Cymbella* Agardh

#### *Cymbella* sp. a

Plate 3, Fig. 7-8.

**Description:** Strongly dorsiventral valves with a smoothly arched dorsal margin, and straight ventral margin. Valve measurements: 72-125  $\mu\text{m}$  in length; 11-15  $\mu\text{m}$  in width. Axial area is narrow, dorsally expanded in the middle of the valve. Raphe is located on the ventral side of valve; relatively straight; central nodule distinct, deflected slightly towards the dorsal margin; distal raphe ends are deflected ventrally. Dorsal striae parallel to radiate; slightly curved; central striae slightly shortened; 8-10 in 10  $\mu\text{m}$ . Ventral striae radiate; small interruption near centre; 8-10 in 10  $\mu\text{m}$ .

**Occurrence:** This species was extremely rare. It was present in 12 samples, collected from Brown Bay, O'Brien Bay and Sparkes Bay. Only single specimens were observed in an individual samples.

### ***Diploneis* (Ehrenberg) Cleve**

***Diploneis splendida*** (Gregory) Cleve

Plate 5, Figs 1-2.

**Synonyms:** *Navicula splendida* Gregory

*Navicula didyma* Gregory

*Navicula enotom* Donkin

*Navicula gemmatula* Cleve

**Description:** Valves elliptical to linear elliptical, with strong median constriction. Central nodule thickened, "H" shaped. Longitudinal canals present along outside of central nodule, canals approximately equal in width. Longitudinal costae undulate, 2-3 each side of median line.. Dimensions of the Windmill Island specimens (60-150 µm long, 25-40 µm at the widest point of the valve, 6-7 costae in 10 µm) fall within the range given in Hustedt (1958) (55-220 µm long, 20-50µm wide at the widest point, with 5-8 costae in 10 µm).

**Occurrence:** Found in 21 of the 88 samples with a maximum abundance of 9.7% in Newcomb Bay. This species was also present in samples from Odbert Island, Brown Bay, Sparkes Bay, and O'Brien Bay.

**Distribution:** *Diploneis splendida* is widely distributed from the Mediterranean to north arctic Oceans (Hustedt, 1958), and has previously been reported from China, Hawaii, and the Spitsbergen Islands (Dexing et al., 1985). *Diploneis splendida* has also been found in low abundances (<2%) in Antarctic lakes (Roberts and McMinn, 1999).

**Comments:** Hustedt (1958) stated that *Diploneis splendida* var. *puella* is synonymous with *Navicula puella* Schmidt, however, Patrick (1968) states that *Navicula puella* is synonymous with *Diploneis puella* var. *puella* - a much smaller, elliptical species without any median constriction of the valve.

***Diploneis* sp. e.**

Plate 6, Figs. 1-2.

**Description:** Valves broad-elliptical with broadly rounded ends and convex margins; not constricted. Valve dimensions: 40-80 µm long, 8-12 µm wide. Raphe straight with simple ends. Central nodule moderately large, round to quadratic. Longitudinal canals fairly wide, narrowing from middle towards apical ends; inner margins convex on both sides of the central nodules; outside canal margins enclose an area ~ 1/2 valve width. Transapical ribs 12-16 in 10 µm; radial at apices, parallel in central region.

**Occurrence:** Extremely rare. Single specimens of this species were observed in samples from O'Brien Bay, Sparkes Bay and Cloyd Island.

**Comments:** Dimensions stated are based on the measurement of 8 individuals.

## *Entomoneis* Ehrenberg

### *Entomoneis* sp. a

Plate 6, Fig. 3.

**Description:** Frustules strongly constricted at the centre in girdle view. Valve dimensions: 35-70  $\mu\text{m}$  in length, 8-15  $\mu\text{m}$  in breadth. Junction line distinct; appearing as a line of thickened areola under light microscopy; arched at terminal apices, sinuous in centre. Wings externally bordered by a narrow hyaline band; 20-22 wing striae in 10  $\mu\text{m}$ . Valve striae further apart at the centre (20-22 striae in 10  $\mu\text{m}$ ) becoming more dense and curved at apices (28-30+ striae in 10  $\mu\text{m}$ ).

Several species of *Entomoneis* have previously been reported from Antarctic regions, including:

- o *Entomoneis kjellmanii* (Cleve) Poulin and Cardinal in Roberts and McMinn, (1999), Everitt and Thomas (1986) and Tucker and Burton (1988); and,
- o *Entomoneis paludosa* (W. Smith) Reimer (syn *Amphiprora paludosa* W. Smith) in Andreoli et al. (1995) and Krebs et al. (1987);

Several *Amphiprora* species were also reported in the Antarctic prior to the name change to *Entomoneis*. These include:

- o *Amphiprora oestrupii* Van Heurck - recorded in Antarctica by Cremer et al. (In Press) and Tanimura (1992);
- o *Amphiprora kufferanthii* Manguin - reported by Manguin (1960) and Riaux-Gobin et al. (2000); and,
- o *Amphiprora kjellmanii* var. *subtilissima* Van Heurck- recorded by Van Heurck (1909)

In terms of valve shape, the Windmill Island specimens most resemble *Entomoneis paludosa*, however the junction line of the Windmill Island specimens lacks the bulge described in Patrick and Reimer (1975) and have coarser wing striae than is described for *Entomoneis paludosa* in Poulin and Cardinal (1983). Furthermore, the valve striae of the Windmill Island specimens are spaced further apart in the centre of the valve than at the ends, a feature not seen in *Entomoneis paludosa*. Of the varieties of *Entomoneis kjellmanii* described, the dimensions of the Windmill Island specimens are similar only with those of *Entomoneis kjellmanii* var. *subtilis* (37-63  $\mu\text{m}$  long, 7-9  $\mu\text{m}$  wide, with 14 wing striae and 23-24 valve striae in 10  $\mu\text{m}$ ) (Poulin and Cardinal, 1983), however the Windmill Island specimens are more strongly constricted in girdle view, and have finer striae, particularly on the wing.

**Occurrence:** This species was present in 27 of the 88 samples, attaining a maximum abundance of 4.1% in O'Brien Bay.

**Distribution:** *Entomoneis kjellmanii* is often associated with ice floras (Scott et al, 1994). This species has previously been recorded in Terra Nova Bay (Andreoli et al, 1995), Lützow-Holm Bay (Tanimura, 1992) as well as in both the lacustrine (Roberts and McMinn, 1999) and inshore marine environment of the Vestfold Hills (Tucker and Burton, 1988).

**Comments:** Dimensions given above result from the measurement of 50 individuals.

***Entomoneis* sp. b.**

Plate 3, Fig. 4-5.

**Description:** Frustules strongly constricted at the centre in girdle view. Valve dimensions: 150-200  $\mu\text{m}$  in length, 25-31  $\mu\text{m}$  in breadth (single valve). Junction line distinct; appearing as a line of thickened areola under light microscopy; sinous. Wings externally bordered by a narrow hyaline band which has a single row of areola (12-14 in 10  $\mu\text{m}$ ). Wing striae 11-15 in 10  $\mu\text{m}$ . Valve striae 11-15.

**Occurrence:** Extremely rare. This species was present in 7 of the 88 samples, attaining a maximum relative abundance of 0.5% in Brown Bay.

**Comments:** Dimensions of this species were based on the measurement of 10 individual specimens.

***Fallacia* Stickle and Mann**

***Fallacia marnieri*** (Manguin) Witkowski, Lange-Bertalot and Metzeltin.

Plate 3, Figs 6-7.

**Synonyms:** *Navicula diploneiformis* Hustedt

**Description:** Valves elliptical with rounded apices. Raphe straight, slightly expanded central nodules. Transapical striae punctate, parallel at the centre of the valve, radiate at ends. The Windmill Island specimens (10-25  $\mu\text{m}$  long, 6-10  $\mu\text{m}$  wide with 7-10 striae in 10  $\mu\text{m}$ ) slightly exceed the range of length measurements, but are within other measurements described in Witkowski et al (2000) (11-24  $\mu\text{m}$  long, 6-11  $\mu\text{m}$  wide, with 7-12 striae in 10  $\mu\text{m}$ ).

**Occurrence:** Single specimens of this species were observed in samples from Cloyd Island, Herring Island, Sack Island, and Odbert Island. In addition, this species had a relative abundance of 1 % at Werlein Island.

**Distribution:** This marine species was originally described from Antarctic but is also found in norther polar regions, and is quite common within the Baltic Sea (Witkowski et al, 2000).

**Comments:** The dimensions given for this taxa are based on measurements of 5 individuals

***Gyrosigma* Hassall**

***Gyrosigma* sp. a**

Plate 9, Figs. 1-2.

**Description:** Dimensions of the Windmill Island specimens are 145-170  $\mu\text{m}$  long, and 20-25  $\mu\text{m}$  wide with 15-20 striae in 10  $\mu\text{m}$ . Valve is sigmoid lanceolate. Raphe central, straight in central region but slightly curved at proximities. Central nodule distinct and circular.

**Occurrence:** This species was only observed within Brown Bay, where it was present in 15 of the 20 samples collected. A maximum relative abundance of 1% was recorded for this species.



## ***Licmophora* Agardh**

### ***Licmophora antarctica* Peragello**

Plate 10, Figs. 1-2.

**Description:** Valves clavate with bluntly rounded apices. Valves are gently attenuated from the summit to the base. Valve dimensions: 60-130  $\mu\text{m}$  in length, 10-17  $\mu\text{m}$  in width (at the widest point of valve). Pseudoraphe narrow. Striae coarse, distinctly areolate, 8-12 in 10  $\mu\text{m}$ .

**Occurrence:** This species was present in 43 of the 88 samples, with a maximum relative abundance of 1.68% in Newcomb Bay, near Wilkes. Odbert Island had the second highest relative abundance, with 1.51% recorded for this site.

### ***Licmophora* sp. b**

Plate 10, Fig. 3.

**Description:** Valves clavate, gently attenuated from summit to base.. Valve dimensions: 35-70  $\mu\text{m}$  in length, 6-9  $\mu\text{m}$  in width. Pseudoraphe narrow, frequently indistinct. Striae finely areolate, 15-18 in 10  $\mu\text{m}$ .

**Occurrence:** Rare. This species was only recorded in Brown Bay and Sparkes Bay, where relative abundances never exceeded 0.35%.

**Comments:** Dimensions of this species are based on the measurement on 10 individuals

### ***Licmophora belgicae* Peragello**

Plate 10, Figs 4-5.

**Description:** Valves clavate to hastate, with a slightly undulate margin. Attenuation of the valve margin is most pronounced in the inferior third. Valve dimensions: 100-150  $\mu\text{m}$  long, 14-15  $\mu\text{m}$  wide at the broadest part of the valve. Pseudoraphe is narrow. Striae are areolate, 10-11 in 10  $\mu\text{m}$ .

**Occurrence:** Rare. This species only occurred as a single specimen within 7 different samples. It was present in Brown Bay samples in both collecting season. *Licmophora* sp. a. was also present in one sample from O'Brien Bay.

**Comments:** Dimensions of this species are based on the measurement on 10 individuals.

## ***Luticola* Mann**

### ***Luticola muticopsis* (Van Heurck) Mann**

Plate 11, Figs. 4-5.

**Synonyms:** *Navicula muticopsis* Van Heurck

**Description:** Frustules biraphid, symmetrical to the apical and transapical axes, apices protracted, puncta distinct, central area expanded with a distinct stigma present. Raphe straight, with proximal ends slightly recurved in the same direction, distal ends curved. Morphology of the Windmill Island specimens matches the description of *Navicula muticopsis* (syn. *Luticola muticopsis*) given in Seaburg et al (1979). Dimensions of the Windmill Island specimens (10-18  $\mu\text{m}$  long, 8-9  $\mu\text{m}$  wide with 18-20 striae in 10  $\mu\text{m}$ ) are within the range given for this species, including its varieties, in Seaburg et al (1979) (10-50  $\mu\text{m}$  long, 5-12  $\mu\text{m}$  wide with 12-16 striae in 10  $\mu\text{m}$ ) except that the Windmill Island specimens have finer striae..

**Occurrence:** Extremely rare. *Luticola muticopsis* was present in two samples from Brown Bay, one sample from Odber Island, and one samples from Newcomb Bay near Wilkes. The maximum relative abundance of this species was 0.5%.

**Distribution:** *Luticola muticopsis* is typically a freshwater (Wasell and Håkansson, 1992) species, however Roberts and McMinn (1999) recorded a salinity tolerance range of 3-39‰ for *Navicula mutica*/*Navicula muticopsis*. This complex has previously been reported from Livingston Island, King George Island, (Håkansson and Jones, 1994), the Vestfold Hills (Roberts and McMinn, 1999) and the Syowa Coast (Watanuki, 1979). *Navicula muticopsis* is common in glacial meltstreams and lakes of Southern Victoria Land (Seaburg et al., 1979). This benthic diatom is reported to have a cosmopolitan distribution (Cremer et al., In Press).

**Comments:** Differentiation between species and interspecific varieties of the *Luticola mutica/muticopsis* complex is difficult, as it is based on subtle variations in the raphe, valve outline, and the form and placement of the stigma (Wasell and Håkansson, 1992). The stigma of *Luticola mutica* is elongate whilst that of *Luticola muticopsis* is areolate (Wasell and Håkansson; 1992). It was this feature that enabled us to identify the Windmill Island specimens as *Luticola muticopsis*, however further identification within the different varieties was not undertaken. All forms observed were therefore assigned to *Luticola muticopsis*.

Dimensions given above were based on measurements of only 5 individuals, due to the rarity of this species.

### ***Navicula* Bory**

***Navicula directa* (Smith) Ralfs**

Plate 11, Figs. 1-3.

**Synonyms:** *Pinnularia directa* Smith

**Description:** Frustules biraphid, symmetrical to apical and transapical axes, elongate broad to narrow lanceolate in outline, rounded ends. Raphe straight; axial area narrow; central area small, circular. The morphology of the Windmill Island specimens is essentially identical to the description given in Medlin and Priddle (1990). Whilst the Windmill Island specimens (7-120 µm long) fall within dimensions given by Medlin and Priddle (1990) (52-137 µm long, 7-11 µm wide, 9-10 striae in 10µm), the Windmill Island specimens are wider (10-15 µm wide), with greater variability in striae density (7-11 in 10 µm).

**Occurrence:** *Navicula directa* occurred in 60 of the 88 samples, with a maximum relative abundance of 8.8% in one of the Brown Bay samples.

**Distribution:** *Navicula directa* has a bi-polar distribution (Cremer, 1998). Typically a marine species, *Navicula directa* is usually associated with benthos or sea-ice but has also been reported in phytoplankton (Andreoli et al., 1995). This species has also been reported in Antarctic lakes of varying salinity (Roberts and McMinn, 1999).



*Navicula* aff. *glaciei* Van Heurck

Plate 12, Figs. 7-8.

**Synonyms:** *Navicula gelida* var. *parvula* Heiden and Kolbe (Krebs, 1983)

**Description:** Frustules biraphid, symmetrical to apical and transapical axes, narrow lanceolate in outline, rounded ends. Striation not resolved to punctate. Raphe straight. Distinct central area with shortened or absent striae. The morphology of the Windmill Island specimens is very similar to that given in Poulin and Cardinal (1982b), however the central area of the Windmill Island specimens frequently extends to the valve margin (size of central area not described in Poulin and Cardinal). Dimensions of the Windmill Island specimens (8-45  $\mu\text{m}$  in length, 2.5-6  $\mu\text{m}$  in breadth, with 12-16 striae in 10  $\mu\text{m}$ ) are narrower, more variable in length, but usually shorter, than the range given in Poulin and Cardinal (1982b) (29-42  $\mu\text{m}$  long, 7-13  $\mu\text{m}$  wide with 14-15 striae in 10  $\mu\text{m}$ ). Whitaker and Richardson (1980) described a smaller size range than Poulin and Cardinal (1982b) of this species (15-28  $\mu\text{m}$  long, 4.8-7.2  $\mu\text{m}$  wide) however the Windmill Island specimens are occasionally smaller than this. Whilst the combined size range of these authors (15-42  $\mu\text{m}$  long, 4.8-13  $\mu\text{m}$  wide, with 14-15 striae) is similar in length to the Windmill Island specimens, the latter are still often narrower.

**Occurrence:** This species was present in all samples. Relative abundances ranged from 0.8% in one sample from Brown Bay to 52.5% in a Sparkes' Bay sample.

**Distribution:** *Navicula glaciei* has been reported in sea-ice assemblages from Signy Island (Whitaker and Richardson, 1980), Arthur Harbour (Krebs, 1983), east Antarctica (Scott et al., 1994, McMinn et al., in press), the Scotia Sea, Antarctica and Hudson Bay, Canada (Poulin and Cardinal, 1982b). This species has also been found in benthic communities from Signy Island (Gilbert, 1991) and Davis Station, east Antarctica (as *Navicula gelida* var. *parvula* in Everitt and Thomas, 1986). *Navicula glaciei* has previously been found in sediments from the Windmill Islands (Cremer et al., In Press) and the Vestfold Hills (Whitehead and McMinn, 1997). This species has also been documented in phytoplankton from Terra Nova Bay (Andreoli et al., 1995). Although typically regarded as a marine species, *Navicula glaciei* also occurs in some Antarctic lakes from the Vestfold Hills (Roberts and McMinn, 1999; Wasell, 1993) and on Horseshoe Island (Wasell and Håkansson, 1992).

*Navicula perminuta* Grunow in Van Heurck

Plate 11, Figs. 6-7.

**Synonyms:** ?*Navicula diserta* Hustedt

?*Navicula hanseni* Møller (Snoeijs, 1993)

**Description:** Frustules biraphid, symmetrical to apical and transapical axes, narrow lanceolate in outline, rounded ends. Striae elongate, aligned with length of frustule. Raphe straight. Dimensions of the Windmill Island specimens (5-20  $\mu\text{m}$  long, 2-4  $\mu\text{m}$  wide) are more variable than the range described in Snoeijs (1993) (7.5-18  $\mu\text{m}$  long, 2.5-4  $\mu\text{m}$  wide). The Windmill Island specimens have 14-20 striae in 10  $\mu\text{m}$ , a measurement which isn't given in Snoeijs (1993).

**Occurrence:** *Navicula perminuta* was present at all locations, occurring in 83 of the 85 samples collected. A maximum relative abundance of 33% occurred in Sparkes Bay. With the exception of this one sample, relative abundances were below 15%.

**Distribution:** *Navicula perminuta* is a benthic species, usually found in fresh to brackish water (Cremer et al., In Press). This species has previously been reported from Sweden (Snoeijs, 1993), and Antarctic lakes situated on Horseshoe Island (Wasell and Håkansson, 1992) and in the Vestfold Hills (Roberts and McMinn, 1999).

***Navicula* sp. a**

Plate 1, Figs 8-10.

**Description:** Frustules symmetrical; narrow lanceolate with rounded ends, possibly slightly produced. Dimensions: 25-55  $\mu\text{m}$  in length, 6-11  $\mu\text{m}$  in breadth. Raphe straight, axial area narrow, central area small. Striae parallel throughout; 10-14 striae in 10  $\mu\text{m}$ ; punctae not resolvable under LM.

**Occurrence:** This taxa was absent in three samples from Noonan Cove, but occurred in all of the remaining 85 samples. A maximum relative abundance of 13% was recorded in a sample from Odbert Island.

***Navicula* sp. b**

Plate 12, Figs 1-3.

**Description:** Frustules biraphid, elliptic to linear lanceolate with well rounded ends. Frustule dimensions: 38-55  $\mu\text{m}$  long, 6-10  $\mu\text{m}$  wide. Raphe straight, axial area narrow; central area small, irregular. Striae radiate at centre of valve, parallel at valve ends; 6-8 striae in 10  $\mu\text{m}$ . The striae of this taxa are more sparsely arranged in the central region; the length of the middle striae is variable, with some specimens exhibiting two shortened striae, some with one shortened striae, and some specimens with no shortening of the striae.

**Occurrence:** This species occurred in 49 of the 88 samples and was present at all locations except O'Brien Bay and Newcomb Bay near Wilkes. A maximum relative abundance of 3.5% was recorded in Brown Bay.

**Comments:** This species often appears on an angle, giving it a dorsi-ventral appearance.

***Navicula* sp. c**

Plate 12, Figs. 4-6.

**Description:** Frustules biraphid, narrowly elliptic to linear lanceolate with rounded ends. Frustule dimensions: 40-70  $\mu\text{m}$  in length, 7-12  $\mu\text{m}$  in breadth. Raphe straight, apical endings hooked to one side; axial area narrow; central area small, round to rectangular. 7-10 striae in 10  $\mu\text{m}$ . Striae sub-radiate at centre of valve, parallel at valve ends.

**Occurrence:** This taxa was present in all samples apart from 4 shallow water (>2m) samples from Noonan Cove. A maximum relative abundance of 10% was recorded in a samples from Cloyd Island

### ***Nitzschia* Hassall**

#### ***Nitzschia dubia* var. *australis* Pergallo**

Plate 13, Figs 1-3.

**Description:** Valves, depending on position, bilobate; constricted in the centre; narrowing to protracted apices. Valve dimensions 85-105 µm long, 13-15 µm wide at widest point of valve. Raphe raised on a keel, central nodule distinct. Keel areola rectangular, 10 in 10 µm. Striae could not be resolved under LM.

**Occurrence:** This species was present in all samples collected from Brown Bay and Newcomb Bay near Wilkes, achieving a maximum relative abundance of 3.3% in the latter. This species also occurred sporadically in samples from O'Brien Bay, Sparkes Bay but never at abundances greater than 0.5%. A single specimen was collected from Noonan Bay.

#### ***Nitzschia* sp. a**

Plate 14, Figs. 3-4.

**Description:** Valves slightly arched with slight median constriction of margins, keel margin concave; apices generally sub-capitate. Valve dimensions: 50-100 µm long by 2-5 µm wide at broadest point of valve. Keel areola 8-13 in 10 µm. Striae too fine to be resolved under LM.

**Occurrence:** *Nitzschia* sp. a. was present in 44 of the 88 samples collected. A maximum relative abundance of 10% was attained in Brown Bay. Several samples in this bay had similar abundances, however outside of Brown Bay, the highest abundance recorded was 3.4% in Newcomb Bay near Wilkes.

#### ***Nitzschia* sp. b**

Plate 14, Figs. 1-2.

**Description:** The external dimensions of the Windmill Island specimens are 70-95 µm long, 11-16 µm. Fibulae were 9-13 in 10 µm while the striation density could not be clearly resolved under LM. Frustules contracted in girdle view.

**Occurrence:** This species was present in 33 of the 88 samples, including samples from O'Connor Island, Herring Island, Brown Bay, and Sparkes Bay. A maximum relative abundance of 1.8% was recorded near Odbert Island.

### ***Parlibellus* Cox**

#### ***Parlibellus cruciuloides* (Brockmann) Witkowski, Lange-Bertalot and Metzeltin**

Plate 17, Figs. 1-2.

**Description:** Valves lanceolate with rostrate apices. Raphe straight, apical ends hooked. Axial area narrow; central area small, elliptical to broadly lanceolate. The Windmill Island specimens (34-77 µm long, 10-25 µm wide, 14-16 striae in 10 µm) are wider, and more variable in length than those recorded by Witkowski et al. (2000) (45-75 µm long, 10-12 µm wide, with 14-16 striae in 10 µm).

**Occurrence** Extremely rare. This species was present in a total of 7 samples, occurring in O'Brien Bay, Brown Bay and at Odbert Island. The maximum relative

abundance of 0.25% was recorded in samples from both Brown Bay and Odbert Island.

**Distribution:** *Parlibellus cruciculoides* is widespread in the North Sea and Baltic sea. This species is found in brackish and marine waters (Witkowski et al., 2000).

### ***Pinnularia* Ehrenberg**

***Pinnularia quadratarea*** (A.Schmidt) Cleve.

Plate 14, Figs. 5-6.

**Synonyms:** *Navicula quadratarea* Schmidt (Snoeijs, 1994)

*Navicula pinnularia* Cleve

*Pinnularia quadratarea* var. *genuina* Cleve-Euler

**Description:** Valves linear with rounded apices. Raphe straight; axial area narrow.; large rectangular fascia extends to valve margins. Striae parallel, individual areolae not resolvable under LM. The morphology of the Windmill Island specimens matches the description given in Poulin and Cardinal (1982a). The dimensions of the Windmill Island specimens (40-55 µm long, 8-10 µm wide, with 9-10 striae in 10 µm) are much smaller than the range given in Poulin and Cardinal (1982a) (72-100 µm long, 12-19 µm wide with 8-10 striae in 10 µm), however they fall within the range given in Snoeijs (1994) (36-55 µm long, 8-10 µm wide).

**Occurrence:** This species was present in 49 of the 88 samples, occurring in samples from Brown Bay, O'Brien Bay, Newcomb Bay near Wilkes, Herring Island and Sack Island. A maximum relative abundance of 1.5% was recorded in both O'Brien Bay and Brown Bay.

**Distribution:** This marine species is found either in benthic or sea-ice communities (Cremer et al, accepted). *Pinnularia quadratarea* has previously been found in the North, arctic and Mediterranean Seas, as well as from Australia, Canada and Greenland (Poulin and Cardinal, 1982a). Antarctic records of this species include Terra Nova Bay (Andreoli et al., 1995), Lützow-Holm Bay (Tanimura, 1992), the Windmill Islands (Cremer et al., In Press), the Vestfold Hills (Wasell, 1993), and Horseshoe Island (Wasell and Håkansson, 1992).

**Comments:** Snoeijs (1994) states that *Pinnularia quadratarea* is synonymous with *Navicula quadratarea*, whilst Poulin and Cardinal (1982a) state that *Pinnularia quadratarea* var. *quadratarea* is synonymous with *Navicula quadratarea*. Therefore, this study has regarded these three species names as synonymous with each other.

***Pinnularia quadratarea* var. *constricta*** (Østrup) Heiden

Plate 14, Figs. 7-8.

**Synonyms:** *Navicula pinnularia* var. *subconstricta* Østrup

*Navicula pinnularia* var. *constricta* Østrup

**Description:** Valves linear with median constriction; apices rounded. Raphe straight; axial area narrow.; rectangular fascia generally extends to valve margins. Striae slightly radiate, becoming more radiate with distance from median constriction. Individual areolae not resolvable under LM. The Windmill Island specimens (44-75 µm long, 14-16 µm wide, with 8-10 striae in 10 µm) occasionally have finer striae than the description given in Poulin and Cardinal, (1982a) (40-83 µm long, 14-17 µm wide with 8-9 striae in 10 µm).

**Occurrence:** *Pinnularia quadratarea* var. *constricta* was present in 30 of the 88 samples collected. This species was present at Herring Island, Odber Island, Sack Island, Sparkes Bay Brown Bay, O'Brien Bay and Newcomb Bay near Wilkes. A maximum relative abundance of 1.5% was recorded in Sparkes Bay.

**Distribution:** This species has previously been reported from the Kara and Laptev Seas, Canada and East Greenland (Poulin and Cardinal, 1982). Usachev (1949) considered *Pinnularia quadratarea* var. *constricta* a typical benthic sea-ice diatom. This species has previously been reported in both lakes (Roberts and McMinn, 1999) and marine sediments from the Vestfold Hills (Whitehead and McMinn, 1997) and Lützow-Holm Bay (Tanimura, 1992).

### ***Planothidium* Round and Buktiyarova**

**Notes:** Light microscopy didn't allow resolution of individual species within the genus *Planothidium*; subsequently these taxa were enumerated as a group. This genus was both widespread and abundant, occurring in all samples with relative abundances between 3.5 and 24.5%. Dimensions of the Windmill Island specimens were 8-25 µm long, 4-7 µm wide with 10-16 striae in 10 µm. Based on SEM photos it appears likely that individuals of this genus found in the Windmill Islands consisted predominantly of the following species.

#### ***Planothidium delicatulum* (Kützing) Round and Buktiyarova**

Plate 15, Figs. 2-4.

**Synonyms:** *Achnanthes delicatula* (Kützing) Grunow ssp. *delicatula* Lange-Bertalot.

**Description:** The morphology of the Windmill Islands is similar to that given in Witkowski et al. (2000), namely elliptical-lanceolate valves with slightly produced wedge-shaped obtusely rounded apices.

**Distribution:** *Planothidium delicatulum* has a cosmopolitan distribution, (Oppenheim, 1994) and has been recorded in China, Greenland, Sweden and Mongolia (Dexing et al., 1985). *Planothidium delicatulum* has previously been identified in sediments from the Antarctic (Oppenheim, 1994; Schmidt et al., 1990). This species has been reported in both lacustrine (Wasell and Håkansson, 1992) and marine (Cremer, 1998) environments. This species is sometimes abundant in areas associated with waste-water outflow (Witkowski et al., 2000).

#### ***Planothidium robustum* (Hustedt) Lange-Bertalot**

Plate 15, Fig. 1.

**Synonyms:** *Achnanthes delicatula* var. *australis*

**Description:** Valves elliptic-lanceolate with rostrate produced apices. Dimensions given in Witkowski et al (2000) are 10-26 µm long, 5-10 µm wide with 11-16 striae in 10 µm.

**Distribution:** This widespread species occurs in both marine and brackish waters (Witkowski et al., 2000).

#### ***Planothidium septentrionalis* (Oestrup) Lange-Bertalot**

Plate 15, Fig. 5

**Synonyms:** *Achnanthes delicatula* var. *septentrionalis*

**Description** Witkowski et al describe this species as “broadly lanceolate, broadly elliptic to rhombic-lanceolate” with “broadly rounded apices”. Striae density varies between 10-14 and 11-14 on the rapheless valve (RLV) and the raphe valve (RV), respectively. Unlike *Planothidium robusta*, there is no curvature of the raphe ends, and the raphe valve has a large central area. The striae consist of multiple rows of areolae, which increase in width towards the rim of the frustule. The shortened central striae consist of 1-3 rows of areolae whilst the outermost striae have 3-4 rows of areolae.

**Distribution:** This cosmopolitan species is found in marine and brackish waters (Witkowski et al., 2000).

### ***Pleurosigma* W. Smith**

#### ***Pleurosigma elongatum* W. Smith**

Plate 16, Figs. 1-2

**Description:** Morphology of the Windmill Island specimens matches the description given by Patrick and Reimer (1966). Dimensions of the Windmill Island specimens (200-285 µm long, 27-35 µm wide, with 18-19 transverse striae in 10 µm and 17-18 oblique striae in 10 µm) are occasionally broader than the range given in Patrick and Reimer (1966) (200-380 µm long, 20-30 µm wide with 18-20 transverse striae and 16-19 oblique striae).

**Occurrence:** *Pleurosigma elongatum* was only found in samples collected in Brown Bay, where it occurred in 12 of the 16 samples, achieving a maximum relative abundance of 1%.

#### ***Pleurosigma* aff. *obscurum* W. Smith emend. Sterrenburg**

Plate 15, Figs 3-4.

**Synonyms:** *Gyrosigma alboris* Carter and Bailey-Watts  
*Gyrosigma obscurum* (W. Smith) Griffith and Henfrey  
*Pleurosigma portoricense* Hagelstein?  
*Gyrosigma rapsonii* Chohnoky?  
*Gyrosigma dubium* Meister?  
*Pleurosigma subsalsum* Wislouch and Kolbe?  
*Gyrosigma subsalsum* (Wislouch and Kolbe) Cardinal, Poulin and  
Berard-Therriault?  
*Pleurosigma depauperata* Manguin?  
*Gyrosigma elegans* Ricard?

**Description:** Valves slightly sigmoidal linear lanceolate, with almost parallel sides. Raphe curved throughout; axial area broad. The morphology of the Windmill Island specimens under light microscopy is consistent with that described by Sterrenburg (1993) for *Pleurosigma obscurum*. Dimensions of the Windmill Island specimens (190-250 µm long; 15-25 µm wide) exceed the range given by Sterrenburg (1993) (90-180 µm long, 12-16 µm wide). Sterrenburg (1993) gives the size range of transverse striae as 27-30 in 10 µm whilst Cardinal et al. (1986) state 25-27 transverse striae in 10 µm. The Windmill Island specimens covered the combined range, having 25-30 striae in 10 µm. Oblique striae were not apparent in the Windmill Island specimens under light microscopy, which is consistent with

Sterrenburg's (1993) description of *Pleurosigma obscurum*. Further examination under SEM would be required to confirm whether oblique striae are present and, if so, whether there is a switch to a 2-system striation at the apices, for a positive identification of this species.

**Occurrence:** This species was present in 34 of the 88 samples, attaining a maximum abundance of 3.3% in Brown Bay.

**Distribution:** Cremer et al., (accepted) list *Pleurosigma obscurum* (= *Gyrosigma subsalsum*) as a marine diatom which occurs in both planktonic and benthic communities around Antarctica, however Sterrenburg (1993) states that *Pleurosigma obscurum* can only be verified as living in inland waters. Wasell and Håkansson (1992) tentatively identified a marine species as "*Pleurosigma subsalsum* or *Gyrosigma subsalsum*". Sterrenburg states that this species could not be distinguished from *Pleurosigma obscurum* on the basis of previous descriptions but notes that under low magnification, under a standardized light field, the marine species of Wasell and Håkansson appeared deep blue, whilst *Pleurosigma obscurum* was colourless.

*Pleurosigma obscurum* has previously been reported (as *Gyrosigma subsalsum*) in Antarctic regions, including Horseshoe Island (Wasell and Håkansson, 1992), the Vestfold Hills (Roberts and McMinn, 1999), the Windmill Islands (Cremer et al., In Press), and King George Island (Klöser, 1998).

#### *Pleurosigma* sp. a

Plate 15, Figs. 5-6.

**Description:** Valve sigmoidal. Valve dimensions: 200-350 µm long, 25-25 µm wide. Raphe sigmoidal, eccentric, but does not follow valve margin at the apices. Striae fine; 25-30 transapical striae in 10 µm; 22-25 oblique striae in 10 µm.

**Occurrence:** Extremely rare. This species was present in a total of 13 samples, which were collected from Brown Bay, Noonan Bay, O'Brien Bay and Newcomb Bay near Wilkes. Only one or two specimens were present in each sample, with a maximum relative abundance of 0.5% recorded Newcomb Bay.

### *Pseudogomphonema* Medlin

#### *Pseudogomphonema kamtschaticum* (Grunow) Medlin

Plate 17, Fig. 3.

**Synonyms:** *Gomphonema kamtschaticum* Grunow

*Gomphonema kamtschaticum* var. *californicum* Grunow ex Heurck

*Gomphonema kamtschaticum* var. *islandicum* Østgaard (Medlin and Round, 1986).

**Description:** Valves linear lanceolate to slightly clavate with rounded apices. Striae radiate throughout. Raphe straight, axial area linear, central area circular to elliptical. Dimensions of the Windmill Island specimens (20-65 µm long, 5-18 µm wide) fall within the range given in Medlin and Round (1986) (18-70µm long, 4-11 µm wide). The Windmill Island specimens frequently have fewer striae (13-17 in 10 µm) than the given for the Medlin and Round (1986) (16-23 striae in 10 µm) however these authors noted that specimens from Bouvet Island had finer striae (10-11 striae in 10 µm). The morphology of the Windmill Island specimens is within the

range described in Medlin and Round (1986), including the Bouvet Island specimens. The linear axial area and circular central area of the Windmill Island specimens were always present, but varied in width between individuals.

**Occurrence** *Pseudogomphonema kamtschaticum* and *Pseudogomphonema* sp. a were not distinguished from each other during the diatom counts in this study. *Pseudogomphonema* spp. occurred at all locations, but not in all replicates from the one location. This taxon was present in sixty five of the 88 samples. The maximum relative abundance recorded for this species was 2.5%

**Distribution:** *Pseudogomphonema kamtschaticum* is typically epiphytic (Medlin and Round, 1986) but has also been associated with sea-ice communities (Cremer, 1998). This marine species has a circumpolar distribution in the arctic (Cremer, 1998). In the Antarctic, *Pseudogomphonema kamtschaticum* has previously been reported from Bouvet Island, (Medlin and Round, 1986), the Windmill Islands (Cremer et al., In Press) and the Vestfold Hills (Whitehead and McMinn, 1997).

**Comments:** Medlin and Round (1986) noted that the coarser striae and wider axial area of the Bouvet Island specimens might warrant classifying these specimens as a separate variety. The density of striae observed in the Windmill Island specimens are intermediate between the Bouvet Islands specimens and those of *Pseudogomphonema kamtschatica sensu stricto*. As noted above, the width of the axial area was variable in the Windmill Island specimens, suggesting a transition between the Bouvet Island specimens and *Pseudogomphonema kamtschatica sensu stricto*.

### ***Stauroneis* Ehrenberg**

***Stauroneis wislouchii* Poretzky and Anisimowa**

Plate 17, Figs. 8-9.

**Synonyms:** *Stauroneis wislouchii forma parva* Poretzky and Anisimowa  
*Stauroneis salina* var. *wislouchii* Cleve-Euler (Hustedt, 1985).

**Description:** Valves linear to elliptical lanceolate with protracted or bluntly rounded ends. Raphe straight, axial area narrow. Central area a narrow fascia extending to the valve margins. The morphology of the Windmill Islands specimens is similar to that described by Hustedt (1985). The Windmill Island specimens (15-32  $\mu\text{m}$  in length, 5-8 $\mu\text{m}$  in breadth with 14-20 striae in 10  $\mu\text{m}$ ) have coarser striae and are occasionally shorter than the dimensions given for *Stauroneis wislouchii* in Hustedt (1985) (23-36  $\mu\text{m}$  long, 5-8  $\mu\text{m}$  wide with 22-28 striae in 10  $\mu\text{m}$ ). A further difference between the Windmill Island specimens, and *Stauroneis wislouchii*, is that Hustedt (1985) describes the striae as slightly radial, whereas the Windmill Island specimens have slightly radial to radial striae.

**Occurrence:** *Stauroneis wislouchii* occurred at all locations, being present in 79 of the 88 samples. This species was absent from 4 samples from Brown Bay, 1 sample from Cloyd Island, and 4 samples from Noonan Cove but occurred in other sample from these locations.

**Distribution:** *Stauroneis wislouchii* has previously been reported from Russia, Eastern Europe, and Central Asia where it is found in saline lakes (Hustedt, 1985).



## ***Trachyneis* Cleve**

***Trachyneis aspera* Ehrenberg**

Plate 18, Figs. 7-8

**Synonyms** *Stauroptera aspera* Ehrenberg,  
*Navicula aspera* Van Heurck  
*Navicula pseudo-aspera*  
*Stauroneis robusta* Petit.

**Description** Valve elongate rhombic. Raphe straight, ends bent to one side. Axial area narrow, but broadens towards center of valve. Striae coarsely punctate; alignment varies with specimen, ranging from parallel to radiate. Central area large and bow-shaped, does not extend to valve margins. Morphology, length and striae of the Windmill Island specimens (135-225  $\mu\text{m}$  long, 6-10 striae in 10  $\mu\text{m}$ ) fall within the range given in Hustedt (1985) (60-300  $\mu\text{m}$  long, 24-50  $\mu\text{m}$  wide, 6-18 striae in 10  $\mu\text{m}$ ) but the Windmill Island specimens are occasionally thinner (20-45  $\mu\text{m}$  wide). Thin specimens of *Trachyneis aspera* (20  $\mu\text{m}$  wide) have previously been reported (Roberts and McMinn, 1999).

**Occurrence** *Trachyneis aspera* occurred in 38 of the 88 samples, with a maximum abundance of 5%. This species occurred at all sites where multiple samples were collected: O'Brien Bay, Sparkes Bay, Brown Bay, Noonan Cove, Newcomb Bay, Odbert Island, and Cloyd Island.

**Distribution:** This benthic marine species (Cremer et al., In Press) has a cosmopolitan distribution and has previously been reported from Australia, New Zealand, Japan, Greenland, the Galapagos Islands and the North Sea (Hustedt, 1985). *Trachyneis aspera* has previously been recorded in Antarctic marine sediments from McMurdo Sound (Palmisano et al., 1985) and Davis Station (Everitt and Thomas, 1986) as well as in Antarctic lakes (Roberts and McMinn, 1999).

## *Fragilariophyceae*

### ***Catacombas* Williams and Round**

***Catacombas camtschatica*** (Grunow) Williams and Round.

Plate 20, Fig. 3.

**Synonyms:** *Synedra kamtschatica* Grunow in Grunow and Cleve

*Fragilaria camtschatica* (Grunow) Poulin, Berard-Therriault &  
Cardinal

**Description:** Valves linear, tapered at ends. Valves areolate. A single rimportula occurs at each pole. Sternum distinct, central. Dimensions of our specimens (120-220  $\mu\text{m}$  long, 4-7  $\mu\text{m}$  wide, 9-14 striae in 10  $\mu\text{m}$ ) are narrower than the range given in Williams and Round (1986) (120-220  $\mu\text{m}$  long, 7-8  $\mu\text{m}$  wide).

**Occurrence:** Rare. *Catacombas camtschatica* was present in 25 samples, with a maximum abundance of 0.75%.

**Distribution:** This epiphytic species has previously been reported from several locations in Antarctica including Adelie Land (Manguin, 1960) and Arthur Harbour (Krebs, 1983).

**Comments:** Whilst several varieties have previously been identified (e.g. *Synedra camtschatica* var. *minor* Grunow, and as var. *antarctica* Manguin) most authors believe that these are not separate taxa, but merely minor variations in size and shape (Williams and Round, 1986).

Dimensions of the Windmill Island specimens are based on the measurement of 40 individuals.

### ***Ctenophora* (Grunow) Williams and Round**

***Ctenophora pulchella*** (Ralfs ex Kützing) Williams and Round.

Plate 3, Figs. 4-6.

**Synonyms:** *Synedra pulchella* Ralfs ex Kützing

*S. pulchella* var. *smithii* (Ralfs) Grunow,

*S. pulchella* var. *abnormis* Macchiati

*Synedra acicularis* W. Smith non *Synedra acicularis* Kützing

*Synedra smithii* Ralfs in Pritchard

**Description:** Valves linear to lanceolate with rounded to weakly capitate poles. Striae punctate. Sternum broad and conspicuous, extending the entire length of the valve. Morphology and dimensions of the Windmill Island specimens (45-90  $\mu\text{m}$  long, 5-7  $\mu\text{m}$  wide, with 12-14 striae in 10  $\mu\text{m}$ ) fall within the range given in Williams and Round (1986) (30-150  $\mu\text{m}$  long, 5-8  $\mu\text{m}$  wide, with up to 15 striae in 10  $\mu\text{m}$ ).

**Occurrence:** *Ctenophora pulchella* was present in 72 of the 88 samples. A maximum relative abundance of 11% was recorded in of the Odbert Island samples.

**Distribution:** This benthic species has a cosmopolitan distribution (Williams and Round 1986). *Ctenophora pulchella* is typically found in brackish water or freshwater with a high mineral content (Patrick and Reimer, 1966).

### ***Fragilariopsis* Hustedt**

***Fragilariopsis curta*** (Van Heurck) Hustedt

Plate 7, Figs. 1-3.

**Synonyms:** *Fragilaria curta* Van Heurck

*Nitzschia curta* (Van Heurck) Hasle

*Fragilariopsis linearis* var. *curta* (Van Heurck) Frenguelli, Frenguelli  
and Orlando

**Description:** Valves linear. Striae well defined, relatively broad. The morphology of the Windmill Island specimens is essentially identical to the description given in Hasle and Syvertsen (1996). The Windmill Island specimens were occasionally longer, but otherwise their dimensions (10-50  $\mu\text{m}$  long, 4-6  $\mu\text{m}$  wide, 9-12 striae in 10  $\mu\text{m}$ ) were within the range given in Hasle and Syvertsen (1996) (10-42  $\mu\text{m}$  long, 3.5-6 wide with 9-12 striae in 10  $\mu\text{m}$ )

**Occurrence:** *Fragilariopsis curta* was present in all samples. Relative abundances ranged from 0.2% to 10%.

**Distribution:** This species is restricted to Antarctic waters (Fenner et al., 1976). *Fragilariopsis curta* is usually associated with plankton (McMinn et al., 2000) and pack ice (Scott, 1990; Gilbert, 1991). Despite this, *Fragilariopsis curta* has been found in growing in sediments from Signy Island (Gilbert, 1991). This species has also been reported in sediments from the George V Coast (Leventer, 1992), Lützow-Holm Bay (Tanimura, 1992), and Prydz Bay (Taylor et al., 1997). Whilst typically a marine species, *Fragilariopsis curta* has also been reported from Antarctic lakes in the Vestfold Hills (Roberts and McMinn, 1999), and on Horseshoe Island (Wasell and Håkansson, 1992).

***Fragilariopsis cylindrus*** (Grunow) Krieger

Plate 7, Figs. 4-5.

**Synonyms:** *Fragilaria cylindrus* Grunow

*Nitzschia cylindrus* (Grunow) Hasle

**Description:** Valves linear. The morphology and dimensions of the Windmill Island specimens (8-25  $\mu\text{m}$  long, 2-4  $\mu\text{m}$  wide, with 13-15 striae in 10  $\mu\text{m}$ ) fit within the range given in Hasle and Syvertsen (1996) (3-48  $\mu\text{m}$  long, 2-4 wide with 13-17 striae in 10  $\mu\text{m}$ ).

**Occurrence:** *Fragilariopsis cylindrus* occurred in only 36 of the 88 samples, attaining a maximum abundance of 3% in O'Brien Bay.

**Distribution:** This species is usually associated with sea-ice communities (Medlin and Priddle, 1990) but can also be an important component of phytoplankton (McMinn et al., 2000). *Fragilariopsis cylindrus* has also been recorded as part of the benthic community of Signy Islands (Gilbert, 1991). This marine species is found at high latitudes in both hemispheres (Hasle and Syvertsen, 1996). *Fragilaria cylindrus* has a wide distribution within the Antarctic marine environment, including the Ongul Islands (Tanimura et al., 1990), the George V Coast (Leventer, 1992), the Windmill

Islands (Cremer et al., In Press), Arthur Harbour (Krebs, 1983), the South Pacific sector of the Antarctic Ocean (Fenner et al., 1976), Prydz Bay, (Talyor et al, 1997) and Lützow-Holm Bay (Tanimura, 1992). This species has also been found in Antarctic lakes (Wasell and Håkansson, 1992).

***Fragilariopsis kerguelensis* (O'Meara) Hustedt**

Plate 7, Figs. 6-8.

**Synonyms:** *Fragilariopsis antarctica* (Castracane) Hustedt

*Nitzschia kerguelensis* (O'Meara) Hasle

**Description:** Valves rhombic, heavily silicified. Morphology and dimensions of the Windmill Island specimens (20-40 µm long, 7-9 µm wide, with 5-6 striae in 10 µm) fit within the range given in Hasle and Syvertsen (1996) (10-76 µm long, 5-11 wide with 4-7 striae in 10 µm)

**Occurrence:** Rare. *Fragilariopsis kerguelensis* was found in only 10 samples, of which 8 were from Brown Bay and Noonan Cove. Relative abundances were low (<1%).

**Distribution:** *Fragilariopsis kerguelensis* is typically planktonic (Hasle and Syvertsen, 1996), however Krebs et al. (1987) recorded this species in sea ice. *Fragilariopsis kerguelensis* is a marine species. This species is common in Antarctic waters (Fenner et al., 1976) but has also been reported as far north as Tasmania (McMinn et al., in press). Antarctic records of *Fragilariopsis kerguelensis* include Arthur Harbour (Krebs, 1983; Krebs et al., 1987), Prydz Bay (Taylor et al., 1997), Lützow-Holm Bay (Tanimura, 1992) and the George V Coast (Leventer, 1992).

**Comments:** The dimensions given for this species are based on the measurement of 20 individual specimens.

***Fragilariopsis obliquecostata* (Van Heurck) Hasle**

Plate 7, Figs. 9-10.

**Synonyms:** *Nitzschia obliquecostata* (Van Heurck) Hasle

*Fragilaria obliquecostata* Van Heurck

**Description:** Valves linear to fusiform lanceolate. The mid-section of the valve is characteristically swollen. Dimensions of the Windmill Island specimens (55-90 µm long, 7-10 µm wide with 8-9 striae in 10 µm) slightly exceed the range given Fenner et al. (1976) (62-87 µm long, 7-9 µm wide with 6.5-9 striae in 10 µm), however, Tanimura (1992) recorded individuals of this species with widths of 10 µm.

**Occurrence:** This species was present in 44 of the 88 samples, attaining a maximum relative abundance of 3.2% in Brown Bay.

**Distribution:** *Fragilariopsis obliquecostata* is a planktonic marine species, often restricted to the Antarctic coastline and ice-front (Frenguelli and Orlando, 1958). Fenner et al. (1976) also reported solitary specimens in open Antarctic and Subantarctic waters. *Fragilariopsis obliquecostata* has previously been reported in a sediment core from the Windmill Islands (Cremer et al., In Press). This species has also been found in sediments from Prydz Bay (Taylor et al., 1997), Lützow-Holm Bay (Tanimura, 1992), and the George V Coast (Leventer, 1992).

***Fragilariopsis rhombica* (O'Meara) Hustedt**

Plate 8, Figs. 1-2.

**Synonyms:** *Nitzschia rhombica* Hustedt

*Nitzschia angulata* Hasle (Hasle and Syvertsen),

*Fragilariopsis angulata* sensu Roberts and McMinn, 1999

**Description:** Valves rhombic to rounded hexagonal. Striae and areolae relatively fine. Striae parallel in mid section of valve, to almost semicircular at valve ends. Morphology and dimensions of the Windmill Island specimens (20-40 µm long, 8-12 µm wide, with 9-11 striae in 10 µm) falls within the range given in Hasle and Syvertsen (1996) (8-53 µm long, 7-13 wide with 8-16 striae in 10 µm).

**Occurrence:** *Fragilariopsis rhombica* was present at most locations, occurring in 46 of the 88 samples. A maximum relative abundance of 2.8% was recorded in Sparkes Bay.

**Distribution:** This marine species usually occurs in the plankton (Krebs, 1983). *Fragilariopsis rhombica* has a circumpolar distribution within Antarctic and subantarctic waters (Hasle, 1969), and has been found as far north as 49° S latitude (Hustedt, 1958). *Fragilariopsis rhombica* was been reported in marine sediments from Lützow-Holm Bay (Tanimura, 1992), Prydz Bay (Taylor et al., 1997) and the George V Coast (Leventer, 1992). This species has also been found in Antarctic lakes in the Vestfold Hills (Roberts and McMinn, 1999) and on Horseshoe Island (Wasell and Håkansson, 1992).

***Fragilariopsis ritscheri* Hustedt**

Plate 8, Figs. 3-4.

**Synonyms:** *Nitzschia ritscheri* (Hustedt) Hasle

**Description:** Valves linear to narrowly elliptic. Striae biseriate, fine. Striae parallel in midsections of valve, but curved at ends. Morphology of the Windmill Island specimens is given in Hasle and Syvertsen (1996). Dimensions of the Windmill Island specimens (40-70 µm long, 8-9 µm wide, with 10-11 striae in 10 µm) are within the range described by Hasle and Syvertsen (1996) (22-70 µm long, 8-9 µm wide with 6-11 striae in 10 µm).

**Occurrence:** *Fragilariopsis ritscheri* was present in 15 of the 88 samples. A maximum abundance of 1.0% was recorded in Sparkes Bay.

**Distribution:** This species is found in planktonic communities around Antarctica (Krebs, 1983) and in ocean waters as far north as 49° S latitude (Hustedt, 1958). *Fragilariopsis ritscheri* has been reported in a sediment core from the Windmill Islands (Cremer et al., In Press). This species has also been recorded in sediments from Lützow-Holm Bay (Tanimura, 1992), the George V Coast (Leventer, 1992) and Signy Island (Gilbert, 1991).

***Fragilariopsis sublinearis* (Van Heurck) Heiden**

Plate 8, Fig. 5.

**Synonyms:** *Nitzschia sublineata* (Van Heurck) Hasle

*Fragilaria sublinearis* Van Heurck

**Description:** Valves linear to fusiform lanceolate. Striae angled. Morphology of the Windmill Island specimens is given in Tanimura (1992). The Windmill Island specimens (45-80 µm long, 5-7 µm wide, with 8-10 striae in 10 µm) are occasionally

narrower with finer striae than the range given in Tanimura (1992) (42-83  $\mu\text{m}$  long, 6-7  $\mu\text{m}$  wide with 8-9 striae in 10  $\mu\text{m}$ ).

**Occurrence:** *Fragilariopsis sublinearis* was present in 35 of the 88 samples. A maximum abundance of 2.8% was recorded in Sparkes Bay.

**Distribution:** This planktonic marine species is restricted to the cold southern waters (Cremer et al., In Press). *Fragilariopsis sublinearis* has previously been reported in sediments from the Windmill Islands (Cremer et al., In Press), Prydz Bay (Taylor et al., 1997), Signy Island (Gilbert, 1991) and the George V Coast (Leventer, 1992).

### ***Pseudostaurosira* Williams and Round**

***Pseudostaurosira* sp. a**

Plate 17, Figs. 5-7.

**Description:** Valves narrowly elliptical. Striae uniseriate. Sternum wide along length of valve, tapering slightly at ends. Dimensions of the Windmill Island specimens are 5-20  $\mu\text{m}$  long, 1.5-4  $\mu\text{m}$  wide, 13-16 striae in 10  $\mu\text{m}$ . This taxa is similar to the described as *Pseudostaurosira brevistriata* (Williams and Round, 1987) except for the valve shape which is not cruciform.

**Occurrence:** This taxa occurred in all samples, with a minimum relative abundance on 1% in a Cloyd Island sample. A maximum relative abundance of 74.3% was recorded near Little Herring Island.

### ***Staurosira* Ehrenberg**

***Staurosira* aff. *construens* var. *pumila* Grunow.**

Plate 18, Figs. 2-3.

**Description:** Frustules rectangular in girdle view. Valves narrowly elliptical to elliptical. Sternum narrow at ends, broader in middle. Striae uniseriate. The morphology of the Windmill Island specimens is similar to that of *Fragilaria construens* var. *pumila* (syn. *Staurosira construens* var. *pumila*) described by Patrick and Reimer (1966), however the dimensions differ. The Windmill Island specimens (10-24  $\mu\text{m}$  long, 5-7  $\mu\text{m}$  wide, 12-16 striae in 10  $\mu\text{m}$ ) are broader, have coarser striations and are occasionally longer than the description given in Patrick and Reimer (1966) (10-20  $\mu\text{m}$  long, 3-5  $\mu\text{m}$  wide with 17-18 striae in 10  $\mu\text{m}$ ).

**Occurrence:** This species was present in all samples except for two Noonan Bay samples which were collected below 10 meters of water. Cloyd Island had exceptionally high abundances of this species, with all samples collected having a minimum relative abundance of 13%, and a maximum abundance of 40%.

**Distribution:** *Staurosira construens* var. *pumila* is found in both planktonic and benthic communities and has previously been reported from America (Patrick and Reimer, 1966).

***Staurosira construens* var. *venter* (Ehrenberg) Kingston**

Plate 18, Fig. 1.

**Synonyms:** *Fragilaria construens* var. *venter* (Ehrenberg) Grunow  
*Fragilaria venter* Ehrenberg

**Description:** Valves circular to ovoid elliptical. Striae uniseriate, sternum narrow. Morphology of the Windmill Island specimens is within the range described in Patrick and Reimer (1966). Dimensions given in Patrick and Reimer (1966) (5-9  $\mu\text{m}$  long, 3-6  $\mu\text{m}$  wide, with 14-16 striae in 10  $\mu\text{m}$ ) are larger with coarser striae than the Windmill Island specimens (3-8  $\mu\text{m}$  long, 2-5  $\mu\text{m}$  wide with 16-20 striae in 10  $\mu\text{m}$ ). Wasell and Håkansson (1992) identified specimens of similar dimensions (2-12.5  $\mu\text{m}$  long, 2.5-4.5  $\mu\text{m}$  wide with 14-18 striae in 10  $\mu\text{m}$ ) as *Fragilara construens* var. *venter*.

**Occurrence:** *Staurosira construens* var. *venter* was present in all samples, attaining a maximum relative abundance of 43% at Herring Island.

**Distribution:** This species has a cosmopolitan distribution and has previously been reported in Antarctic lakes from Horseshoe Island (Wasell and Håkansson, 1992). This species is typically most abundant in waters of low nutrient content (Patrick and Reimer, 1966) and had a lake-water salinity optimum of 36 ‰ (Roberts and McMinn, 1999). This periphytic or tychoplanktonic species is halobically indifferent, meso-saprobic and characteristic of standing waters (Lowe, 1974).

**Comments:** The classification of *Staurosira* is problematic (Wasell and Håkansson, 1992). Williams and Round (1987) reviewed the genus, creating several new genera, however Krammer and Lange-Bertalot (1991) used a different classification system, confusing matters (Wasell and Håkansson, 1992). Williams and Round (1987) resurrected *Staurosira* Ehrenberg, the type species of which is *Staurosira construens* (= *Staurosira construens*).

### ***Synedropsis* Hasle, Medlin et Syvertsen**

*Synedropsis* cf. *recta* Hasle, Medlin et Syvertsen.

Plate 18, Figs. 4-6.

**Synonyms:** *Fragilaria* (?) sp. a Tanimura in Tanimura et al. (Hasle et al., 1994)

**Description** Valves elongate, linear lanceolate with pronounced apices. Sternum broad. Striae parallel; uniseriate with circular areolae. This taxon has the same morphology as *Synedropsis recta*, described in Hasle et al. (1994). The dimensions of the Windmill Island specimens (20-60  $\mu\text{m}$  long, 3.5-5  $\mu\text{m}$  wide, 15-24 striae in 10  $\mu\text{m}$  with 5-7 apical slits) are longer, with denser striae than those described in Hasle et al. (1994) (18-40  $\mu\text{m}$  long, 3.5-5  $\mu\text{m}$  wide, 11-14 striae in 10  $\mu\text{m}$  with 5-7 apical slits).

**Occurrence:** *Synedropsis* cf. *recta* was present in all samples, with a minimum relative abundance of 1%. The maximum relative abundance of 17.6% was recorded in O'Brien Bay.

**Distribution:** *Synedropsis recta* is widely distributed around Antarctica, predominantly within sea-ice communities, although Tanimura et al. recorded this species as planktonic (Hasle et al., 1994).

### ***Thalassionema***

*Thalassionema gelida* Pergallo

Plate 20, Figs. 14-15.

**Description:** Valves elongate, linear, isopolar. Ends of valves slightly tapering and rounded. Valve face flat with large axial area, areolae reduced and confined to the margins. The Windmill Island specimens (40-200  $\mu\text{m}$  long, 2.5-3  $\mu\text{m}$  wide, 10 -20



striae in 10µm with 3-5 apical slits) have fewer striae in 10 µm and are sometimes longer than those described in Hasle et al. (1994) (38-137 µm long, 2.5-3 µm wide, 35-40 striae in 10 µm with 3-5 apical slits).

**Occurrence:** *Thalassionema gelida* was present at all locations, occurring in 77 of the 88 samples collected. This species was absent from Noonan Cove samples that had an overlying water column depth of less than 8 meters. *Thalassionema gelida* attained a maximum abundance of 2.9% in Brown Bay.

### ***Thalassiothrix* Cleve and Grunow**

***Thalassiothrix antarctica* Schimper ex Karsten**

Plate 21, Fig. 5.

**Description:** Morphology and dimensions of the Windmill Island specimens (500-760 µm long, 2-5 µm wide, 13-15 areolae in 10 µm, 2 marginal spines in 10 µm) fall within the range given in Hasle and Syvertsen (1996) (420-5680 long, 1.5-6 µm wide, 12-17 areolae in 10 µm, 1-2 marginal spines in 10µm).

**Occurrence:** Extremely rare. *Thalassiothrix antarctica* was present in only 7 samples, with a maximum abundance 0.25%.

**Distribution:** This species occurs within cold southern waters (Hasle and Syvertsen, 1996). *Thalassiothrix antarctica* has previously been reported in sediments from the George V Coast (Leventer, 1992) and the Windmill Islands (Cremer et al., In Press).

**Comments:** This species typically occurred as fragments. Only specimens where either a head pole, or foot pole remained, were included in the species counts, to reduce the likelihood of counting fragments from the one individual as separate specimens. Only two entire specimens were recorded, resulting in a restricted size range.



## *Coscinodiscophyceae*

### *Actinocyclus* Ehrenberg

*Actinocyclus actinochilus* (Ehrenberg) Simonsen

Plate 19, Figs. 1-2.

**Synonyms:** *Coscinodiscus actinochilus* Ehrenberg

*Charcotia actinochila* (Ehrenberg) Hustedt (Hasle and Syvertsen, 1996).

**Description:** Valves circular. Areolae rows radially arranged; straight to gently undulating; irregular in length with less than half reaching the centre. Dimensions and morphology of the Windmill Island specimens (20-66  $\mu\text{m}$  diameter) fall within the range given in Hasle and Syvertsen (1996) (20-112  $\mu\text{m}$  diameter).

**Occurrence:** Rare. *Actinocyclus actinochilus* was present in 20 of the 88 samples, with a maximum abundance of 0.33%.

**Distribution:** This species is widely distributed within the southern cold water region (Hasle and Syvertsen (1996). Typically planktonic, *Actinocyclus actinochilus* has been found in plankton from Terra Nova Bay (Andreoli et al., 1995) but has also been recorded in sea-ice from Arthur Harbour (Krebs et al., 1987). In addition, this species has been reported in sediments from Prydz Bay (Taylor et al., 1997), the George V Coast (Leventer, 1992) as well as sediment cores from the Windmill Islands (Cremer et al., accepted) and Lützow-Holm Bay (Tanimura, 1992). Although commonly regarded as marine, *Actinocyclus actinochilus* has also been reported from Antarctic lakes on Horseshoe Island (Wasell and Håkansson, 1992) and in the Vestfold Hills (Roberts and McMinn, 1999).

**Comments:** Dimensions of this species are based on a count of 20 individuals.

### *Arachnoidiscus* H.Deane ex Pritchard

*Arachnoidiscus* sp. a

Plate 19, Figs. 3-4.

**Description:** Frustules discoidal. Valve face differentiated into wedge shaped sectors by radial ribs which interrupt the concentric rings. Valve dimensions: 300-550  $\mu\text{m}$  in diameter.

**Occurrence:** Extremely rare. Single specimens of this species were found in samples from Odbert Island, Cloyd Island, O'Connor Island, Herring Island, Little Herring Island, and Sack Island.

**Comments:** Dimensions are based on the measurement of 7 individuals.

### *Asteromphalus* Ehrenberg

*Asteromphalus hookeri* Ehrenberg

Plate 19, Fig. 5.

**Description:** Morphology of the Windmill Island specimens matches the description given in Hernandez-Becerril (1991). Dimensions of the Windmill Island

specimens (32-60  $\mu\text{m}$  in diameter, 5-8 areolae in 10  $\mu\text{m}$ , with 6-7 hyaline rays) are occasionally smaller than the description given by Hernandez-Becerril (1991) (43-78 in diameter, 7-8 areolae in 10  $\mu\text{m}$ , with 6-7 hyaline rays) but are within the range described in Hasle and Syvertsen (1996) (25-60  $\mu\text{m}$  in diameter, 5-9? areolae in 10  $\mu\text{m}$ , with 6-9 hyaline rays).

**Occurrence:** Extremely rare. This species had a maximum relative abundance of 0.25 %, and was recorded in 10 of the 88 samples collected.

**Distribution:** Hasle and Syvertsen describe *Asteromphalus hookeri* as distributed within the southern cold water region, but note that Hendey (1969) recorded this planktonic marine species as common in northern temperate waters. Fenner et al. (1976) found this species was present in all samples collected between 69 °S and 53 °S. *Asteromphalus hookeri* has previously been recorded in Terra-Nova Bay (Andreoli et al., 1995) and the Windmill Islands (Cremer et al., In Press).

**Comments:** Due to the rarity of this species, dimensions are based on measurements of only 10 individuals.

#### *Asteromphalus* sp. a

Plate 19, Figs. 6-7.

**Description:** Valve roughly circular; 50-60  $\mu\text{m}$  in diameter; central area 25-30  $\mu\text{m}$  in diameter. 8 hyaline rays; straight; broad (3-4  $\mu\text{m}$  wide); blunt to square ends; ray extensions rectangular or bell shaped. The extension of the narrow hyaline ray is wide, and semicircular at the base, constricted at the centre of the extension, then flared out into a bulbous shape before the ray exits the central area.. Separating lines relatively straight with small branches in middle. Areolated sectors wide (6-8 aerolae between 2 hyaline rays); concave towards central area. Areolae 8-11 in 10  $\mu\text{m}$ .

Several species of *Asteromphalus* have previously been reported from the Antarctic, namely *A. hookeri* (Andreoli et al., 1995; Fenner et al., 1976; Krebs et al., 1987), *A. hyalinus* (Tanimura, 1992; Wasell, 1993), *A. heptactis* (Andreoli et al., 1995; Fenner et al., 1976) and *A. parvulus* (Krebs et al., 1987; Tanimura, 1992). Whilst *A. hyalinus* and *A. parvulus* have a similar number of sector areolae in 10  $\mu\text{m}$  (8-12 and 8-10 respectively), both these species are smaller than the Windmill Island specimens (15-32  $\mu\text{m}$  and 22-48  $\mu\text{m}$  in diameter respectively), with fewer hyaline rays (3-5 and 6) (Hasle and Syvertsen, 1996). Furthermore, both these species have areolae sector margins that are convex towards the central area, whereas the Windmill Island specimens have concave margins. The Windmill Island specimens differ from *A. heptactis* (42-175  $\mu\text{m}$  in diameter, central area 0.25-0.33 x diameter, 7 hyaline rays, 5-7 areolae in 10  $\mu\text{m}$ ) (Hasle and Syvertsen, 1996) in the number of hyaline rays, the coarseness of the areolae and the proportion of the valve that is occupied by the central area. The Windmill Island specimens are most similar to *A. hookeri* (Hasle and Syvertsen, 1996) (25-60  $\mu\text{m}$  in diameter, central area 0.33-0.5 x diameter, 6-9 hyaline rays, with 5-9? areolae in 10  $\mu\text{m}$ ). The areolae sector margins of *A. hookeri* are curved towards the central area, as seen in the Windmill Island specimens. Differences between the Windmill Island specimens and *A. hookeri* are that the separating lines of *A. hookeri* are straight whilst the Windmill Island specimens are consistently crossed by small branches, further more *A. hookeri* has finer areolation than the Windmill Island specimens. Additionally *A. hookeri* lacks

the median constriction and subsequent protuberance of the narrow hyaline ray that was present in the Windmill Island specimens.

**Occurrence:** Rare. Single specimens were observed at several locations including O'Brien Brown Bay, Sparkes Bay and Newcomb Bay near Wilkes. A maximum relative abundance of 1% was observed at Sack Island.

**Comments:** Dimensions of this species are based on measurement of 10 individuals.

*Asteromphalus* sp. b

Plate 19, Figs. 8-9.

**Description:** Valves circular; 50-108  $\mu\text{m}$  in diameter. Central area  $\sim 1/2$  the valve width. Hyaline rays straight or slightly curved; 12-16. Separating lines branched. Areolae fine; 12-15 in 10  $\mu\text{m}$ . Areolae sectors concave towards centre.

**Occurrence:** Extremely rare. This species occurred in only 6 samples, attaining a maximum relative abundance of 0.5% in Brown Bay.

**Comments:** Dimensions are based on the measurements of 7 individuals.

*Biddulphia* Gray

*Biddulphia areolata* Greville

Plate 20, Figs. 1-2.

**Synonyms:** *Biddulphia anthropomorpha* Van Heurck (Krebs, 1983).

**Description:** Bipolar valves with horns. 2, occasionally 3, labiate processes in centre of valve. The Windmill Island specimens ranged between 46 and 75  $\mu\text{m}$  in diameter.

**Occurrence:** Extremely rare. *Biddulphia areolata* was present in five samples, representing 3 locations; Brown Bay, Noonan Cove and Newcomb Bay near Wilkes. A maximum relative abundance of 0.5% was attained in Noonan Cove.

**Distribution:** *Biddulphia areolata* has previously been reported from Arthur Harbour, Antarctica where it occurred in 5 sea-ice samples with a mean abundance of 0.1% (Krebs et al, 1987).

**Comments:** Dimensions given for this species are based the measurement of 10 individuals.

*Dactyliosolen* Castracane

*Dactyliosolen antarcticus* Castracane

Plate 20, Figs. 4-6.

**Description:** Valves crescent shaped with thickened nodes along the outer rim. Morphology of this species is given in Hasle and Syvertsen (1996). The Windmill Island specimens are occasionally smaller in diameter (10-50  $\mu\text{m}$  diameter, 4-8 band ribs in 10 $\mu\text{m}$ ) than the range given in Hasle and Syvertsen (1996) (13-90  $\mu\text{m}$  diameter, 4-15 band ribs in 10  $\mu\text{m}$ ).

**Occurrence:** Rare. This species was present in samples from following locations: Herring Island (Nth), Odber Island, Cloyd Island, Sparkes Bay, O'Brien Bay and Brown Bay. *Dactyliosolen antarcticus* was present in only 18 of the 88 samples, with low relative abundances (<1%).

**Distribution:** This planktonic species probably has a cosmopolitan distribution, but is especially important within the southern cold water region (Hasle and Syvertsen, 1996). *Dactylisolen antarcticus* has been reported from both Antarctic and subantarctic waters (Fenner et al., 1976). This species has previously been found in the Windmill Islands (Cremer et al., In Press).

**Comments:** Dimensions of this species were based on a count of 20 individuals.

### ***Eucampia* Ehrenberg**

***Eucampia antarctica* (Castracane) Manguin**

Plate 20, Figs. 7-9.

**Synonyms:** *Eucampia balaustium* Castracane

**Description** The morphology of the Windmill Island specimens matches that described by Hasle and Syvertsen (1996). Dimensions of the Windmill Island specimens (20-95 µm in diameter, 4-10 areolae in 10 µm) are occasionally larger than the range given in Hasle and Syvertsen (1996) (18-82 µm in diameter, 3-10 areolae in 10 µm).

**Occurrence:** *Eucampia antarctica* was present in 70 of the 88 samples. Whilst this species was present at most locations, it was not found at Little Herring Island, or the northern site at Herring Island. Relative abundances were typically below 7%, however a maximum abundance of 30% was recorded within Sparkes Bay, possibly indicating a localised bloom.

**Distribution:** This planktonic marine species is widely distributed within the southern cold water region (Hasle and Syvertsen, 1996). *Eucampia antarctica* was previously been found in Terra Nova Bay (Andreoli, 1995), in Arthur Harbour (Krebs, 1983) as well as in sediments from Prydz Bay (Taylor et al., 1997) and the George V coast (Leventer, 1992). This species has also been reported in Antarctic lakes (Wasell and Håkansson, 1992; Roberts and McMinn, 1999).

### ***Melosira* Agardh**

***Melosira* sp. a**

Plate 20, Figs. 12-13.

**Description:** Frustules in girdle view, cylindrical, united in distinct pairs to form filaments. Valve face flat with small areolae. The size of the Windmill Island specimens ranged from 35-85 µm in diameter.

**Occurrence:** Rare. This species had a maximum relative abundance of 0.75% which was recorded in one samples from Brown Bay. This was the only sample in which the relative abundance exceeded 0.5%. *Melosira* spp. were present in 23 of the 88 samples occurring in all bays except Sparkes. This taxa was also present in several samples collected near islands, including Werlein and O'Connor Islands.

**Distribution:** Species of *Melosira* are found in oligotrophic to eutrophic, fresh, brackish and marine waters.

### ***Paralia* Heiberg**

***Paralia sulcata*** (Ehrenberg) Cleve

Plate 20, Figs. 10-11.

**Synonyms:** *Melosira sulcata* (Ehrenberg) Kützing

*Gallionella sulcata* Ehrenberg (Cremer, 1998)

**Description:** Frustule disk-shaped. Valve face circular with large hyaline central area and coarse costate radial markings or dots. Morphology and dimensions of the Windmill Island specimens (20-85 µm in diameter) are within the range given in Hasle and Sverston (1996) (8-130 µm in diameter).

**Occurrence:** This species was present in 20 of the 88 samples, occurring in Brown Bay, O'Brien Bay, Newcomb Bay near Wilkes, Noonans Bay and at O'Connor Island. Relative abundances were low, with a maximum of 0.75% recorded in Brown Bay.

**Distribution:** *Paralia sulcata* is typically a benthic form, but has also been recorded in plankton (Hasle and Syvertsen, 1996). This marine species has a cosmopolitan distribution (Cremer, 1998). *Paralia sulcata* has previously been found in Antarctic waters, including King George Island (Klöser, 1998), and the George V Coast (Leventer, 1992).

### ***Porosira* Jørgensen**

***Porosira glacialis*** (Grunow) Jørgensen

Plate 21, Fig. 3.

**Synonyms:** *Podosira glacialis* (Grunow) Cleve

*Lauderia glacialis* (Grunow) Gran.

**Description:** Morphology and dimensions of the Windmill Island specimens (40-55 µm in diameter) are within the range described in Medlin and Prislle (1990) (36-64 µm in diameter).

**Occurrence:** Rare. *Porosira glacialis* was present in only 15 samples. Sites where this species occurred included Brown Bay, Noonan Cove, Herring Island and Little Herring Island. This species attained a maximum relative abundance of 1% in O'Brien Bay.

**Distribution:** Within the northern hemisphere this species is found in cold to temperate waters, but is restricted to the cold water region within the southern hemisphere (Hasle and Syvertsen, 1996). This species has previously been reported from phytoplankton in Arthur Harbour (Krebs, 1983), as well as sediments from Prydz Bay (Taylor et al., 1997) and the George V coast (Leventer, 1992). *Porosira glacialis* has also been found in lakes from the Vestfold Hills (Roberts and McMinn, 1999).

**Comments:** Due to the rarity of this species, dimensions given above are based on the measurement of 25 individuals.

***Porosira pseudodenticulata*** (Hustedt) Jousé

Plate 21, Fig. 4.

**Description:** Dimensions and morphology of the Windmill Island specimens (25-40  $\mu\text{m}$  in diameter) fall within the range given in Hasle and Syvertsen (1996) (25-50  $\mu\text{m}$  in diameter).

**Occurrence:** Rare. *Porosira pseudodenticulata* was present in only 12 samples. This species attained a maximum relative abundance of 0.3% in Sparkes Bay.

**Distribution:** This planktonic marine species is restricted to the southern cold water region (Hasle and Syvertsen, 1996). *Porosira pseudodenticulata* has previously been reported from phytoplankton in Terra Nova Bay (Andreoli et al., 1995), from sea-ice communities in Arthur Harbour (Krebs et al., 1987) and from a lake on Horseshoe Island (Wasell and Håkansson, 1992).

**Comments:** Dimensions of this species were based on measurements from 10 individuals.

***Porosira* sp. a**

Plate 21, Figs. 1-2.

**Description:** The Windmill Island specimens range between 8 and 20  $\mu\text{m}$  in diameter. Under LM the valves have an appearance of “frosted glass” and no areolae or processes can be distinguished. Under SEM two marginal rings of processes are visible, with the processes in the inner ring spaced much further apart than those of the outer ring. Areolation fine, 25-30 in 10  $\mu\text{m}$ .

**Occurrence:** This species was present in low abundances (<0.5%) in 51 of the 88 samples. Locations where this species was found included Herring Island, Odber Island, Brown Bay, Newcomb Bay near Wilkes, Sparkes Bay, Shannon Bay and O'Brien Bay.

***Thalassiosira* Cleve**

***Thalassiosira antarctica*** Comber

Plate 21, Fig 8.

**Synonyms:** *Thalassiosira antarctica* var. *borealis* Fryxell, Doucette and Hubbard  
*Thalassiosira fallax* Meunier

**Description:** Frustules in girdle view, drum-shaped. Valve face circular, flat or undulate with visible marginal spines and processes, fine areolae. Morphology and dimensions of the Windmill Island specimens (25-50  $\mu\text{m}$  in diameter) fall within the range given in Hasle and Syvertsen (1996) (14-50  $\mu\text{m}$  in diameter).

**Occurrence:** *Thalassiosira antarctica* was present in a total of 16 samples, from O'Brien Bay, Sparkes Bay, Brown Bay, Cloyd Island and Noonan Cove. Relative abundances were all below 0.75%.

**Distribution:** *Thalassiosira antarctica* has a circumpolar distribution in both the northern and southern hemisphere, this species has also been reported from northern temperate waters (Hasle and Syvertsen, 1996). *Thalassiosira antarctica* has been found in sea-ice communities (Krebs et al., 1987) and in Antarctic lakes (Wasell and Håkansson, 1992; Roberts and McMinn, 1999). This species is often restricted to near coastal or ice-edge waters (Hasle and Heindal, 1968).

**Comments** Fryxall et al. (1981) differentiated between the southern *Thalassiosira antarctica* var. *antarctica* and the northern *Thalassiosira antarctica* var. *borealis*, however the morphological differences are not apparent under light microscopy (Hasle and Syvertsen, 1996).

*Thalassiosira gracilis* var. *expecta* (Van Landingham) Fryxell and Hasle  
Plate 21, Figs. 6-7.

**Synonyms:** *Thalassiosira expecta* Van Landingham

*Thalassiosira coronata* Gaarder

*Thalassiosira delicatula* Hustedt

non *Thalassiosira delicatula* Ostenfeld in Borgert

**Description:** Valves circular; flat or undulate. Marginal spines and processes visible. Areolae fine. Morphology and dimensions of the Windmill Island specimens (10-20 µm in diameter) is within the range given in Hasle and Syvertsen (1996) (5-25 µm in diameter).

**Occurrence:** *Thalassiosira gracilis* was present in 35 of the 88 samples. A maximum relative abundance of 1.2% was recorded in Noonan Cove.

**Distribution:** This species has frequently been reported from the Antarctic and sub-Antarctic regions (Fenner et al, 1976). *Thalassiosira gracilis* has been reported from melt pools (Priddle and Belcher, 1981), a marine lagoon (Roberts and McMinn, 1999) and continental margin sediments (Leventer, 1992). The distribution of *Thalassiosira gracilis* extends from coastal waters northwards past the Antarctic convergence (Fenner et al., 1976). This species has even been reported in sub-tropical waters (Fryxell and Hasle, 1979).

**Comments:** *Thalassiosira gracilis* var. *expecta* can be distinguished from *Thalassiosira gracilis* var. *gracilis* by the smaller areolae on the central part of valve face of the latter (Hasle and Syvertsen, 1996).

### ***Trigonium* Cleve**

*Trigonium arcticum* (Brightwell) Cleve

Plate 21, Fig. 9.

**Description** Triangular valves with loculate areolae. Areolae are coarse and radially arranged within the central region of the valve, grading to finer areolation at pseudocellate elevations. The Windmill Island specimens varied between 80-200 µm in size.

**Occurrence:** *Trigonium arcticum* was present in low abundances (<1%) in 23 of the 88 samples.

**Distribution:** *Trigonium arcticum* is typically a benthic marine species (Everitt and Thomas, 1986). This species has previously been reported in Antarctic marine sediments near Davis station (Everitt and Thomas, 1986) and from the Vestfold Hills (Whitehead and McMinn, 1997; Tucker and Burton, 1988).

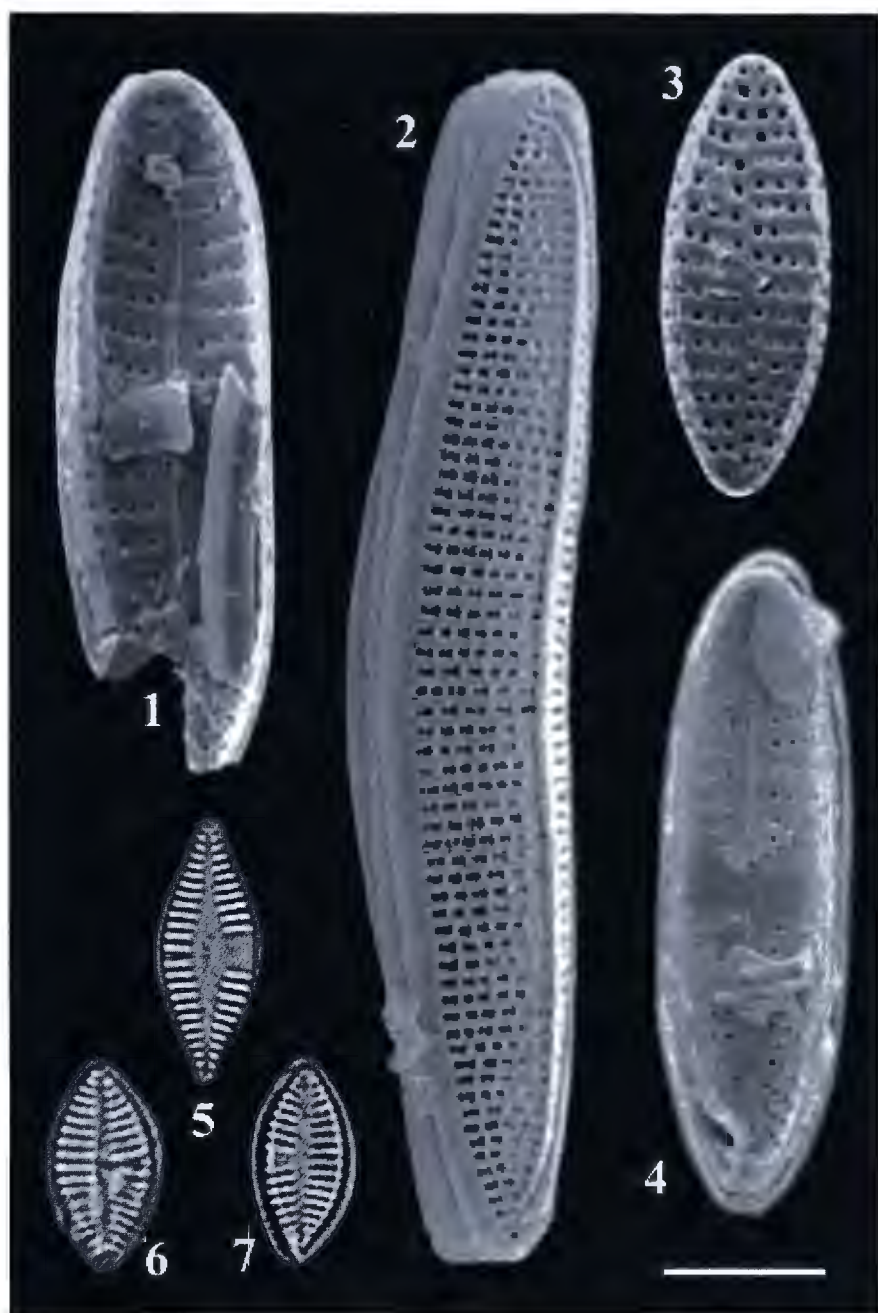
**Comments:** The dimensions given for this species are based on the measurement of 20 individual specimens.

**Plate 1**

Figs. 1 - 4: *Achnanthes brevipes* Agardh  
SEM views of *Achnanthes brevipes*  
Scale = 10  $\mu\text{m}$

Figs. 5 - 7: *Achnanthes* sp. a  
Scale = 20  $\mu\text{m}$





## Plate 2

Fig. 1: *Amphora libyca* Kützing  
SEM view

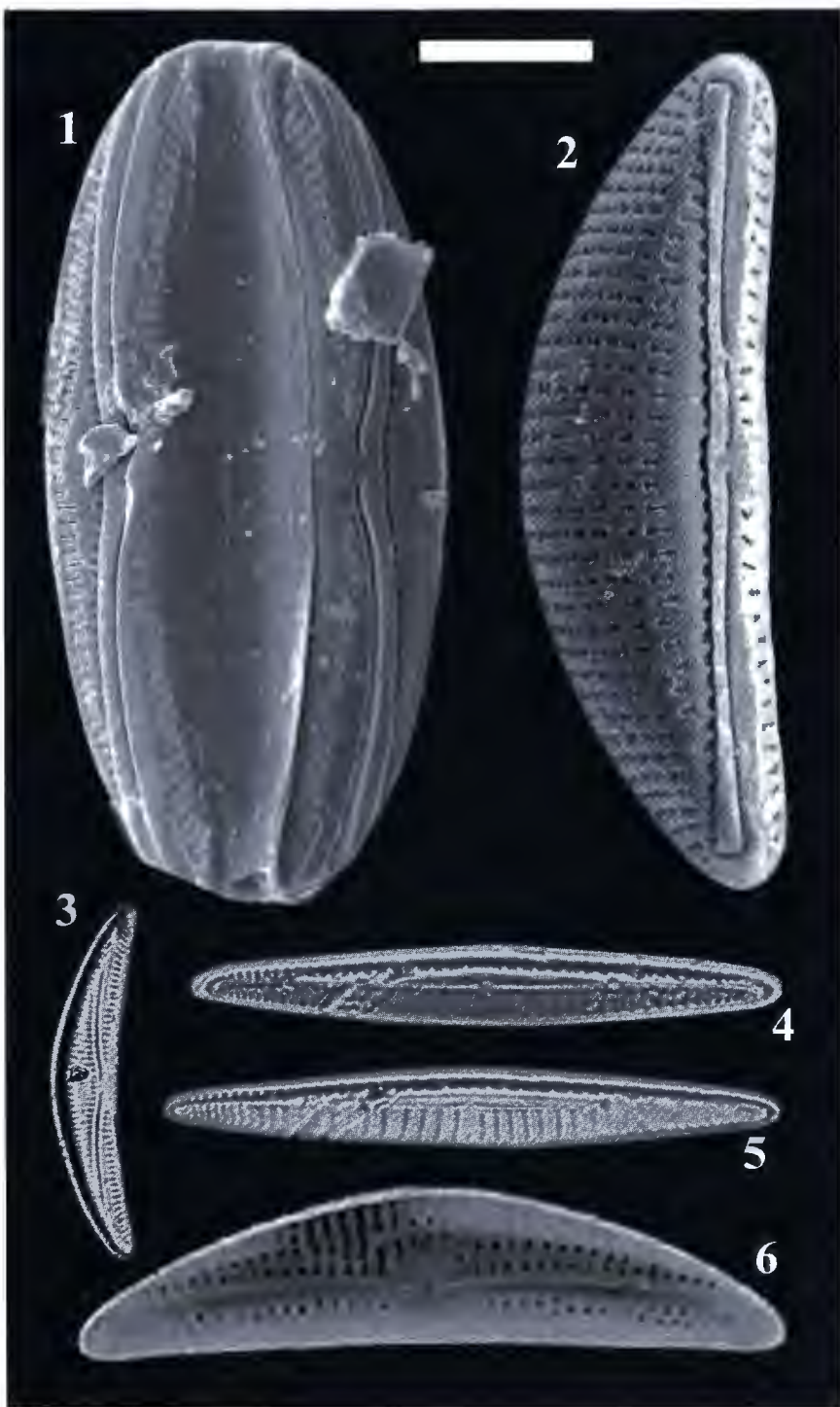
Fig. 2: *Amphora ovalis* var. *ovalis* (Kützing) Kützing  
SEM view

Fig. 3: *Amphora pediculus* (Kützing) Van Heurck

Figs. 4 - 5: *Amphora* sp. a

Fig. 6: *Amphora* sp. c  
SEM view

Scale bar = 10µm



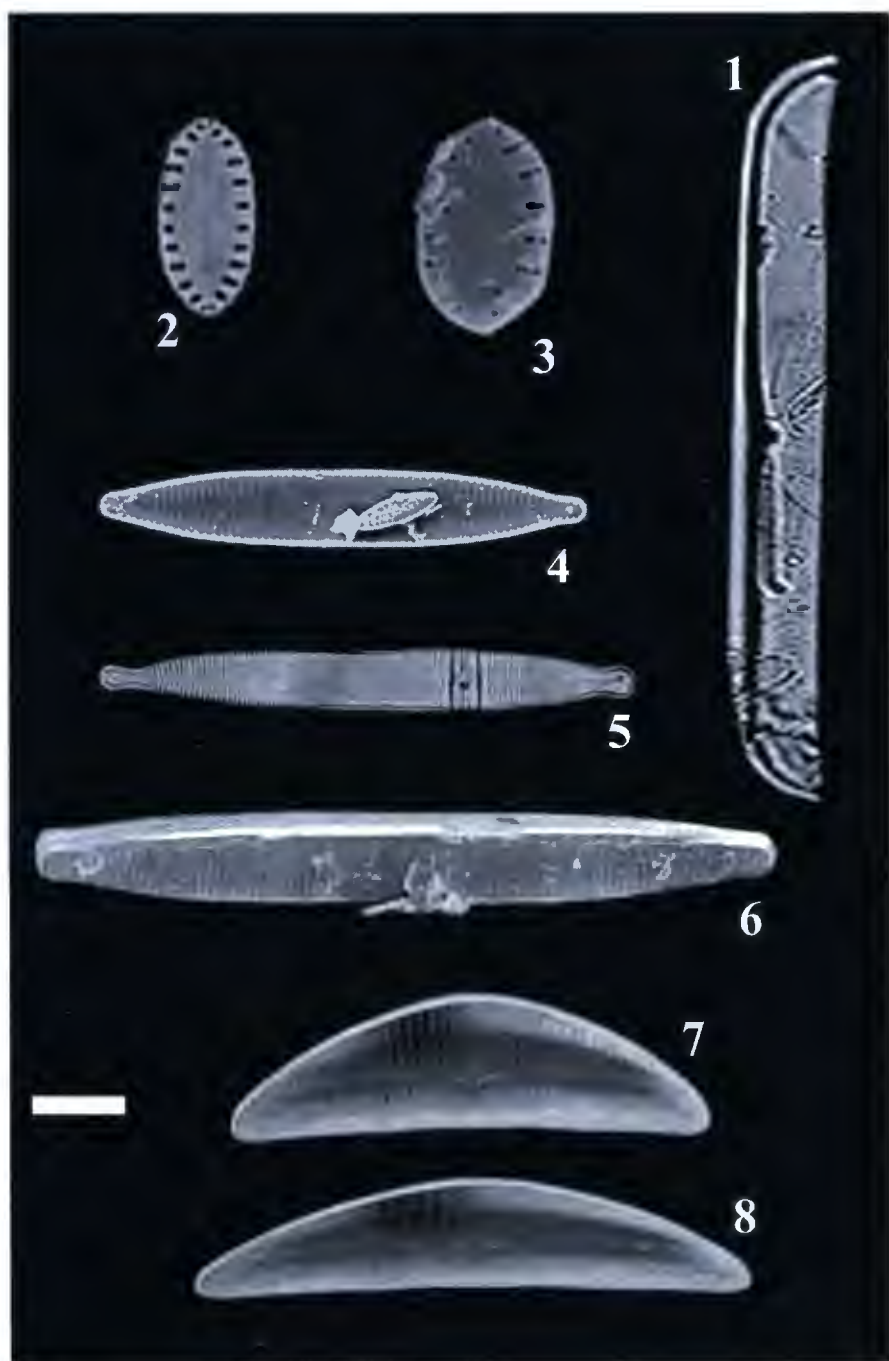
### Plate 3

Fig. 1: *Auricula compacta* (Hustedt) Medlin  
Scale bar = 15  $\mu$ m

Figs. 2 - 3: *Cocconeis pinnata* Gregory  
Fig. 2: LM view of the SV  
Fig. 3: SEM view of the SV  
Scale bar = 10  $\mu$ m

Figs. 4 - 6: *Ctenophora pulchella*  
Fig. 4: SEM view  
Fig. 5: LM view  
Fig. 6: SEM view  
Scale bar = 20  $\mu$ m

Figs. 7 - 8 *Cymbella* sp. a  
Scale bar = 15  $\mu$ m



#### **Plate 4**

Figs. 1 - 2      *Cocconeis costata* Gregory

Fig. 1: LM view

Fig. 2: SEM view

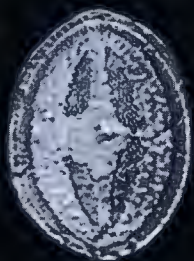
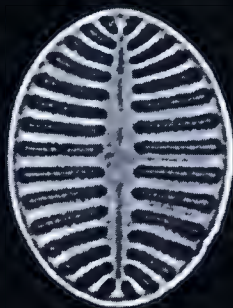
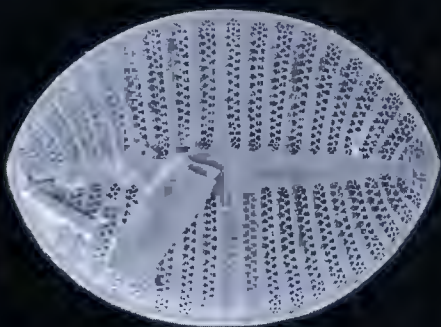
Figs. 3 - 5      *Cocconeis fasciolata* (Ehrenberg) Brown

Fig. 3: SEM view

Figs. 4 - 5: LM views

Figs. 6 - 8:      *Cocconeis schuettii* Van Heurck

Scale = 10  $\mu\text{m}$



**Plate 5**

Figs. 1 - 2:     *Diploneis splendida* (Gregory) Cleve

Scale bar = 10  $\mu\text{m}$ .





2

## Plate 6

Figs. 1 - 2: *Diploneis* sp. c

Fig. 3: *Entomoneis* sp. a

Figs. 4 - 5: *Entomoneis* sp. b  
SEM view

Figs. 6 - 7: *Fallacia marnieri* (Manguin) Lange-Bertalot

Scale bar = 10  $\mu\text{m}$ .



1



2



3



6



7



4



5



**Plate 7**

Figs. 1 - 3: *Fragilariopsis curta* (Van Heurck) Hustedt

Figs. 4 - 5: *Fragilariopsis cylindrus* (Grunow) Kreiger

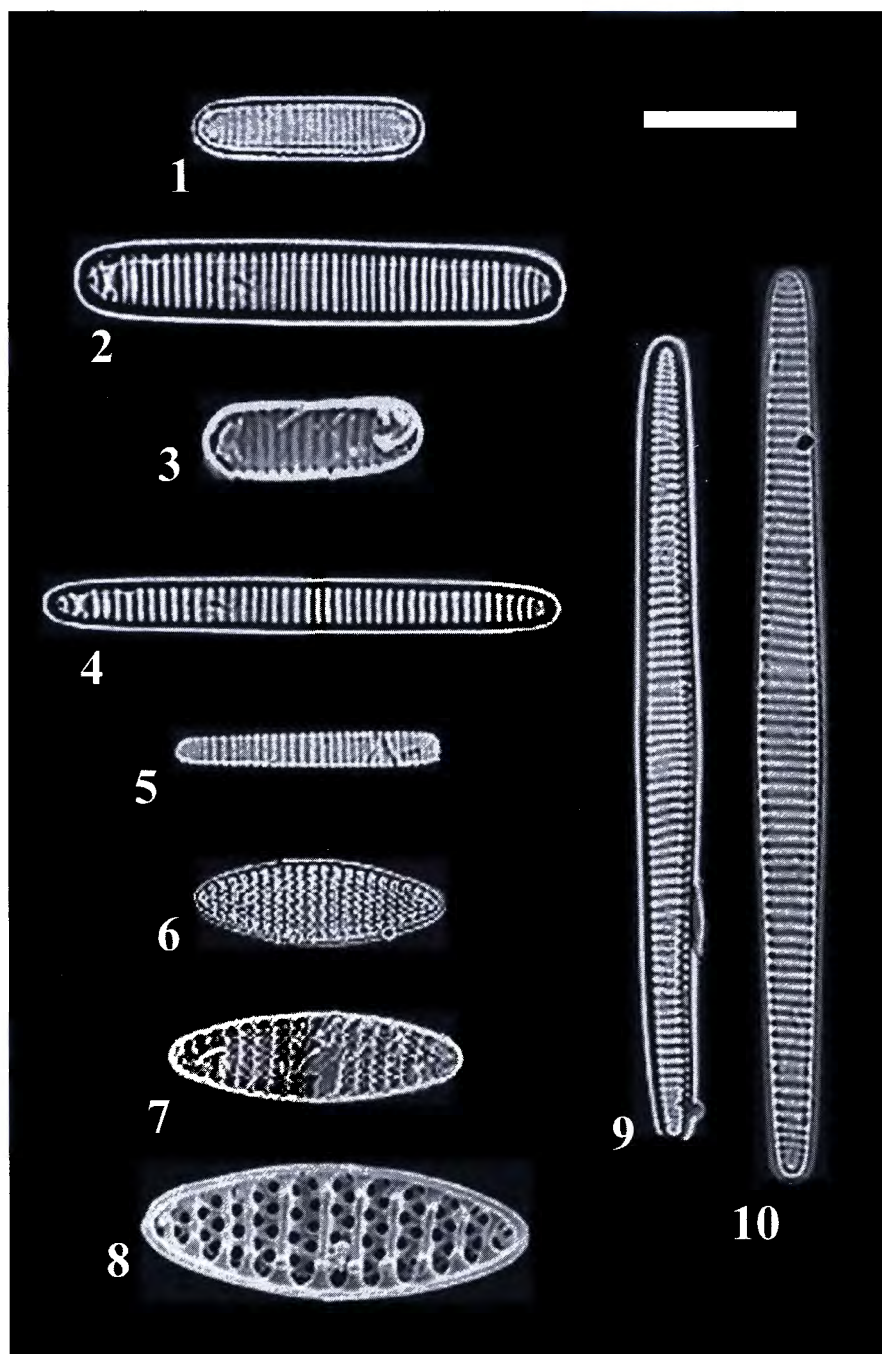
Figs. 6 - 8: *Fragilariopsis kergulensis* (O'Meara) Hustedt

Fig. 6: LM view

Figs. 7-8: SEM view

Figs. 9 - 10: *Fragilariopsis obliquecostata* (Van Heurck) Hasle

Scale bar = 10  $\mu\text{m}$ .



**Plate 8**

Figs. 1 - 2: *Fragilariopsis rhombica* (O'Meara) Hustedt

Fig. 1: LM view

Fig. 2: SEM view

Fig. 3 - 4: *Fragilariopsis ritscheri* Hustedt

Fig. 3: SEM view

Fig. 4: LM view

Fig. 5: *Fragilariopsis sublinearis* (Van Heurck) Heiden

LM view

Scale bar = 10  $\mu\text{m}$ .



**Plate 9**

Figs. 1 - 2:     ***Gyrosigma*** sp. a

Scale bar = 10  $\mu\text{m}$ .



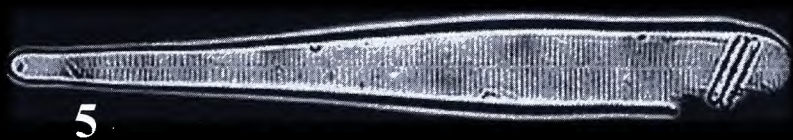
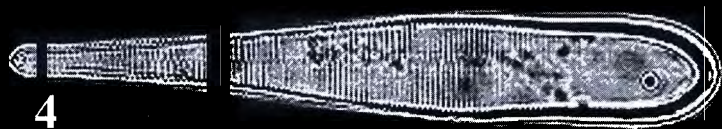
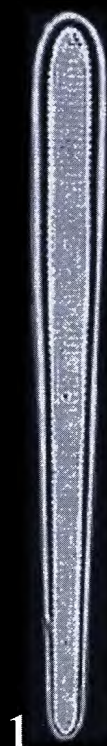


**Plate 10**

Figs. 1 - 2      *Licmophora antarctica*  
Scale bar = 10  $\mu\text{m}$

Fig. 3          *Licmophora* sp. b  
SEM view  
Scale bar = 5  $\mu\text{m}$

Figs. 4 - 5      *Licmophora belgicae*  
Scale bar = 10  $\mu\text{m}$



**Plate 11**

Figs. 1 - 3: *Navicula directa* (W. Smith) Ralfs

Fig. 1: SEM view

Figs. 2 - 3: LM views

Figs. 4 - 5: *Luticola muticopsis* (Van Heurck) Mann

Figs. 6 - 7: *Navicula perminuta* Grunow

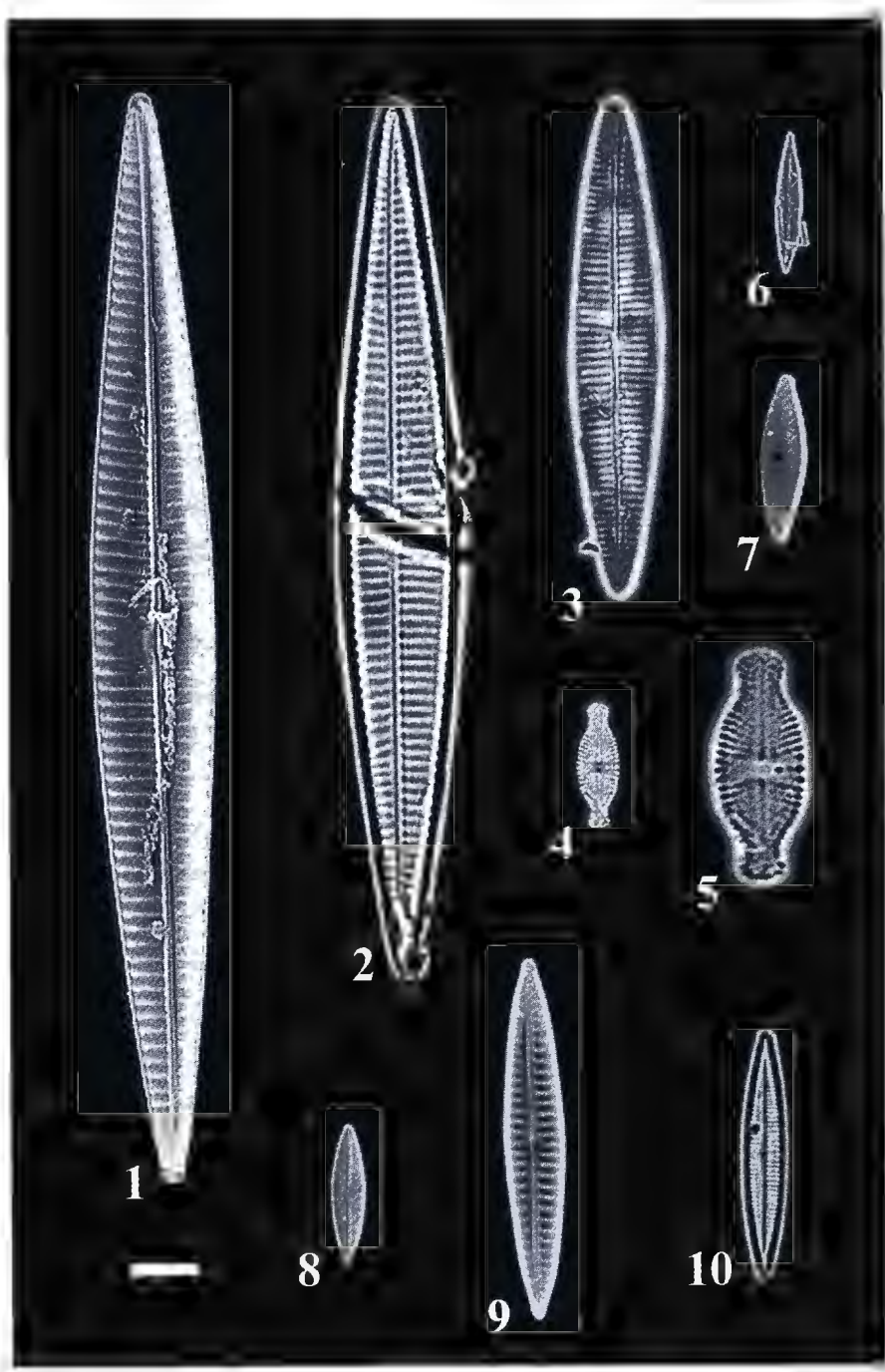
Figs. 8 - 10: *Navicula* sp. a (Van Heurck) Patrick

Fig. 8: LM view

Fig. 9: SEM view

Fig. 10: LM view

Scale bar = 10  $\mu\text{m}$ .



## Plate 12

Figs. 1-3: *Navicula* sp. b  
Figs. 1-2: LM views  
Fig. 3: SEM view

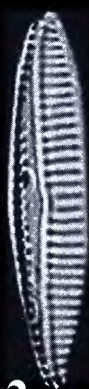
Figs. 4-6: *Navicula* sp. c

Figs. 7-8: *Navicula* aff. *glaciei* Van Heurck  
SEM views

Scale bar = 10  $\mu$ m.



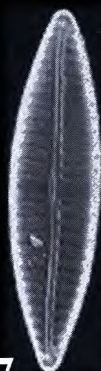
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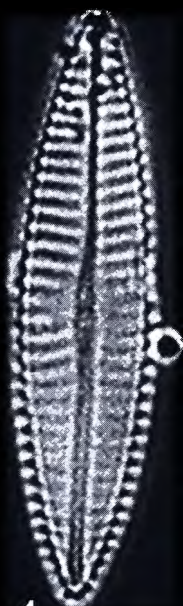
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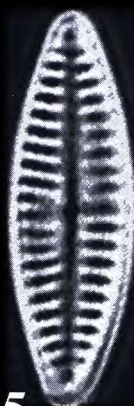
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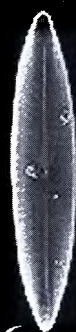
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specimens (32-60  $\mu\text{m}$  in diameter, 5-8 areolae in 10  $\mu\text{m}$ , with 6-7 hyaline rays) are occasionally smaller than the description given by Hernandez-Becerril (1991) (43-78 in diameter, 7-8 areolae in 10  $\mu\text{m}$ , with 6-7 hyaline rays) but are within the range described in Hasle and Syvertsen (1996) (25-60  $\mu\text{m}$  in diameter, 5-9? areolae in 10  $\mu\text{m}$ , with 6-9 hyaline rays).

**Occurrence:** Extremely rare. This species had a maximum relative abundance of 0.25 %, and was recorded in 10 of the 88 samples collected.

**Distribution:** Hasle and Syvertsen describe *Asteromphalus hookeri* as distributed within the southern cold water region, but note that Hendey (1969) recorded this planktonic marine species as common in northern temperate waters. Fenner et al. (1976) found this species was present in all samples collected between 69 °S and 53 °S. *Asteromphalus hookeri* has previously been recorded in Terra-Nova Bay (Andreoli et al., 1995) and the Windmill Islands (Cremer et al., In Press).

**Comments:** Due to the rarity of this species, dimensions are based on measurements of only 10 individuals.

#### *Asteromphalus* sp. a

Plate 19, Figs. 6-7.

**Description:** Valve roughly circular; 50-60  $\mu\text{m}$  in diameter; central area 25-30  $\mu\text{m}$  in diameter. 8 hyaline rays; straight; broad (3-4  $\mu\text{m}$  wide); blunt to square ends; ray extensions rectangular or bell shaped. The extension of the narrow hyaline ray is wide, and semicircular at the base, constricted at the centre of the extension, then flared out into a bulbous shape before the ray exits the central area.. Separating lines relatively straight with small branches in middle. Areolated sectors wide (6-8 aerolae between 2 hyaline rays); concave towards central area. Areolae 8-11 in 10  $\mu\text{m}$ .

Several species of *Asteromphalus* have previously been reported from the Antarctic, namely *A. hookeri* (Andreoli et al., 1995; Fenner et al., 1976; Krebs et al., 1987), *A. hyalinus* (Tanimura, 1992; Wasell, 1993), *A. heptactis* (Andreoli et al., 1995; Fenner et al., 1976) and *A. parvulus* (Krebs et al., 1987; Tanimura, 1992). Whilst *A. hyalinus* and *A. parvulus* have a similar number of sector areolae in 10  $\mu\text{m}$  (8-12 and 8-10 respectively), both these species are smaller than the Windmill Island specimens (15-32  $\mu\text{m}$  and 22-48  $\mu\text{m}$  in diameter respectively), with fewer hyaline rays (3-5 and 6) (Hasle and Syvertsen, 1996). Furthermore, both these species have areolae sector margins that are convex towards the central area, whereas the Windmill Island specimens have concave margins. The Windmill Island specimens differ from *A. heptactis* (42-175  $\mu\text{m}$  in diameter, central area 0.25-0.33 x diameter, 7 hyaline rays, 5-7 areolae in 10  $\mu\text{m}$ ) (Hasle and Syvertsen, 1996) in the number of hyaline rays, the coarseness of the areolae and the proportion of the valve that is occupied by the central area. The Windmill Island specimens are most similar to *A. hookeri* (Hasle and Syvertsen, 1996) (25-60  $\mu\text{m}$  in diameter, central area 0.33-0.5 x diameter, 6-9 hyaline rays, with 5-9? areolae in 10  $\mu\text{m}$ ). The areolae sector margins of *A. hookeri* are curved towards the central area, as seen in the Windmill Island specimens. Differences between the Windmill Island specimens and *A. hookeri* are that the separating lines of *A. hookeri* are straight whilst the Windmill Island specimens are consistently crossed by small branches, further more *A. hookeri* has finer areolation than the Windmill Island specimens. Additionally *A. hookeri* lacks



the median constriction and subsequent protuberance of the narrow hyaline ray that was present in the Windmill Island specimens.

**Occurrence:** Rare. Single specimens were observed at several locations including O'Brien Brown Bay, Sparkes Bay and Newcomb Bay near Wilkes. A maximum relative abundance of 1% was observed at Sack Island.

**Comments:** Dimensions of this species are based on measurement of 10 individuals.

*Asteromphalus* sp. b

Plate 19, Figs. 8-9.

**Description:** Valves circular; 50-108  $\mu\text{m}$  in diameter. Central area  $\sim 1/2$  the valve width. Hyaline rays straight or slightly curved; 12-16. Separating lines branched. Areolae fine; 12-15 in 10  $\mu\text{m}$ . Areolae sectors concave towards centre.

**Occurrence:** Extremely rare. This species occurred in only 6 samples, attaining a maximum relative abundance of 0.5% in Brown Bay.

**Comments:** Dimensions are based on the measurements of 7 individuals.

*Biddulphia* Gray

*Biddulphia areolata* Greville

Plate 20, Figs. 1-2.

**Synonyms:** *Biddulphia anthropomorpha* Van Heurck (Krebs, 1983).

**Description:** Bipolar valves with horns. 2, occasionally 3, labiate processes in centre of valve. The Windmill Island specimens ranged between 46 and 75  $\mu\text{m}$  in diameter.

**Occurrence:** Extremely rare. *Biddulphia areolata* was present in five samples, representing 3 locations; Brown Bay, Noonan Cove and Newcomb Bay near Wilkes. A maximum relative abundance of 0.5% was attained in Noonan Cove.

**Distribution:** *Biddulphia areolata* has previously been reported from Arthur Harbour, Antarctica where it occurred in 5 sea-ice samples with a mean abundance of 0.1% (Krebs et al, 1987).

**Comments:** Dimensions given for this species are based the measurement of 10 individuals.

*Dactyliosolen* Castracane

*Dactyliosolen antarcticus* Castracane

Plate 20, Figs. 4-6.

**Description:** Valves crescent shaped with thickened nodes along the outer rim. Morphology of this species is given in Hasle and Syvertsen (1996). The Windmill Island specimens are occasionally smaller in diameter (10-50  $\mu\text{m}$  diameter, 4-8 band ribs in 10 $\mu\text{m}$ ) than the range given in Hasle and Syvertsen (1996) (13-90  $\mu\text{m}$  diameter, 4-15 band ribs in 10  $\mu\text{m}$ ).

**Occurrence:** Rare. This species was present in samples from following locations: Herring Island (Nth), Odber Island, Cloyd Island, Sparkes Bay, O'Brien Bay and Brown Bay. *Dactyliosolen antarcticus* was present in only 18 of the 88 samples, with low relative abundances (<1%).

**Distribution:** This planktonic species probably has a cosmopolitan distribution, but is especially important within the southern cold water region (Hasle and Syvertsen, 1996). *Dactylisolen antarcticus* has been reported from both Antarctic and subantarctic waters (Fenner et al., 1976). This species has previously been found in the Windmill Islands (Cremer et al., In Press).

**Comments:** Dimensions of this species were based on a count of 20 individuals.

### ***Eucampia* Ehrenberg**

***Eucampia antarctica* (Castracane) Manguin**

Plate 20, Figs. 7-9.

**Synonyms:** *Eucampia balaustium* Castracane

**Description** The morphology of the Windmill Island specimens matches that described by Hasle and Syvertsen (1996). Dimensions of the Windmill Island specimens (20-95 µm in diameter, 4-10 areolae in 10 µm) are occasionally larger than the range given in Hasle and Syvertsen (1996) (18-82 µm in diameter, 3-10 areolae in 10 µm).

**Occurrence:** *Eucampia antarctica* was present in 70 of the 88 samples. Whilst this species was present at most locations, it was not found at Little Herring Island, or the northern site at Herring Island. Relative abundances were typically below 7%, however a maximum abundance of 30% was recorded within Sparkes Bay, possibly indicating a localised bloom.

**Distribution:** This planktonic marine species is widely distributed within the southern cold water region (Hasle and Syvertsen, 1996). *Eucampia antarctica* was previously been found in Terra Nova Bay (Andreoli, 1995), in Arthur Harbour (Krebs, 1983) as well as in sediments from Prydz Bay (Taylor et al., 1997) and the George V coast (Leventer, 1992). This species has also been reported in Antarctic lakes (Wasell and Håkansson, 1992; Roberts and McMinn, 1999).

### ***Melosira* Agardh**

***Melosira* sp. a**

Plate 20, Figs. 12-13.

**Description:** Frustules in girdle view, cylindrical, united in distinct pairs to form filaments. Valve face flat with small areolae. The size of the Windmill Island specimens ranged from 35-85 µm in diameter.

**Occurrence:** Rare. This species had a maximum relative abundance of 0.75% which was recorded in one samples from Brown Bay. This was the only sample in which the relative abundance exceeded 0.5%. *Melosira* spp. were present in 23 of the 88 samples occurring in all bays except Sparkes. This taxa was also present in several samples collected near islands, including Werlein and O'Connor Islands.

**Distribution:** Species of *Melosira* are found in oligotrophic to eutrophic, fresh, brackish and marine waters.

### ***Paralia* Heiberg**

***Paralia sulcata*** (Ehrenberg) Cleve

Plate 20, Figs. 10-11.

**Synonyms:** *Melosira sulcata* (Ehrenberg) Kützing

*Gallionella sulcata* Ehrenberg (Cremer, 1998)

**Description:** Frustule disk-shaped. Valve face circular with large hyaline central area and coarse costate radial markings or dots. Morphology and dimensions of the Windmill Island specimens (20-85  $\mu\text{m}$  in diameter) are within the range given in Hasle and Sverston (1996) (8-130  $\mu\text{m}$  in diameter).

**Occurrence:** This species was present in 20 of the 88 samples, occurring in Brown Bay, O'Brien Bay, Newcomb Bay near Wilkes, Noonans Bay and at O'Connor Island. Relative abundances were low, with a maximum of 0.75% recorded in Brown Bay.

**Distribution:** *Paralia sulcata* is typically a benthic form, but has also been recorded in plankton (Hasle and Syvertsen, 1996). This marine species has a cosmopolitan distribution (Cremer, 1998). *Paralia sulcata* has previously been found in Antarctic waters, including King George Island (Klöser, 1998), and the George V Coast (Leventer, 1992).

### ***Porosira* Jørgensen**

***Porosira glacialis*** (Grunow) Jørgensen

Plate 21, Fig. 3.

**Synonyms:** *Podosira glacialis* (Grunow) Cleve

*Lauderia glacialis* (Grunow) Gran.

**Description:** Morphology and dimensions of the Windmill Island specimens (40-55  $\mu\text{m}$  in diameter) are within the range described in Medlin and Prislle (1990) (36-64  $\mu\text{m}$  in diameter).

**Occurrence:** Rare. *Porosira glacialis* was present in only 15 samples. Sites where this species occurred included Brown Bay, Noonan Cove, Herring Island and Little Herring Island. This species attained a maximum relative abundance of 1% in O'Brien Bay.

**Distribution:** Within the northern hemisphere this species is found in cold to temperate waters, but is restricted to the cold water region within the southern hemisphere (Hasle and Syvertsen, 1996). This species has previously been reported from phytoplankton in Arthur Harbour (Krebs, 1983), as well as sediments from Prydz Bay (Taylor et al., 1997) and the George V coast (Leventer, 1992). *Porosira glacialis* has also been found in lakes from the Vestfold Hills (Roberts and McMinn, 1999).

**Comments:** Due to the rarity of this species, dimensions given above are based on the measurement of 25 individuals.

***Porosira pseudodenticulata*** (Hustedt) Jousé

Plate 21, Fig. 4.

**Description:** Dimensions and morphology of the Windmill Island specimens (25-40  $\mu\text{m}$  in diameter) fall within the range given in Hasle and Syvertsen (1996) (25-50  $\mu\text{m}$  in diameter).

**Occurrence:** Rare. *Porosira pseudodenticulata* was present in only 12 samples. This species attained a maximum relative abundance of 0.3% in Sparkes Bay.

**Distribution:** This planktonic marine species is restricted to the southern cold water region (Hasle and Syvertsen, 1996). *Porosira pseudodenticulata* has previously been reported from phytoplankton in Terra Nova Bay (Andreoli et al., 1995), from sea-ice communities in Arthur Harbour (Krebs et al., 1987) and from a lake on Horseshoe Island (Wasell and Håkansson, 1992).

**Comments:** Dimensions of this species were based on measurements from 10 individuals.

***Porosira* sp. a**

Plate 21, Figs. 1-2.

**Description:** The Windmill Island specimens range between 8 and 20  $\mu\text{m}$  in diameter. Under LM the valves have an appearance of “frosted glass” and no areolae or processes can be distinguished. Under SEM two marginal rings of processes are visible, with the processes in the inner ring spaced much further apart than those of the outer ring. Areolation fine, 25-30 in 10  $\mu\text{m}$ .

**Occurrence:** This species was present in low abundances (<0.5%) in 51 of the 88 samples. Locations where this species was found included Herring Island, Odvert Island, Brown Bay, Newcomb Bay near Wilkes, Sparkes Bay, Shannon Bay and O'Brien Bay.

***Thalassiosira* Cleve**

***Thalassiosira antarctica*** Comber

Plate 21, Fig 8.

**Synonyms:** *Thalassiosira antarctica* var. *borealis* Fryxell, Doucette and Hubbard  
*Thalassiosira fallax* Meunier

**Description:** Frustules in girdle view, drum-shaped. Valve face circular, flat or undulate with visible marginal spines and processes, fine areolae. Morphology and dimensions of the Windmill Island specimens (25-50  $\mu\text{m}$  in diameter) fall within the range given in Hasle and Syvertsen (1996) (14-50  $\mu\text{m}$  in diameter).

**Occurrence:** *Thalassiosira antarctica* was present in a total of 16 samples, from O'Brien Bay, Sparkes Bay, Brown Bay, Cloyd Island and Noonan Cove. Relative abundances were all below 0.75%.

**Distribution:** *Thalassiosira antarctica* has a circumpolar distribution in both the northern and southern hemisphere, this species has also been reported from northern temperate waters (Hasle and Syvertsen, 1996). *Thalassiosira antarctica* has been found in sea-ice communities (Krebs et al., 1987) and in Antarctic lakes (Wasell and Håkansson, 1992; Roberts and McMinn, 1999). This species is often restricted to near coastal or ice-edge waters (Hasle and Heindal, 1968).

**Comments** Fryxall et al. (1981) differentiated between the southern *Thalassiosira antarctica* var. *antarctica* and the northern *Thalassiosira antarctica* var. *borealis*, however the morphological differences are not apparent under light microscopy (Hasle and Syvertsen, 1996).

*Thalassiosira gracilis* var. *expecta* (Van Landingham) Fryxell and Hasle  
Plate 21, Figs. 6-7.

**Synonyms:** *Thalassiosira expecta* Van Landingham

*Thalassiosira coronata* Gaarder

*Thalassiosira delicatula* Hustedt

non *Thalassiosira delicatula* Ostenfeld in Borgert

**Description:** Valves circular; flat or undulate. Marginal spines and processes visible. Areolae fine. Morphology and dimensions of the Windmill Island specimens (10-20 µm in diameter) is within the range given in Hasle and Syvertsen (1996) (5-25 µm in diameter).

**Occurrence:** *Thalassiosira gracilis* was present in 35 of the 88 samples. A maximum relative abundance of 1.2% was recorded in Noonan Cove.

**Distribution:** This species has frequently been reported from the Antarctic and sub-Antarctic regions (Fenner et al, 1976). *Thalassiosira gracilis* has been reported from melt pools (Priddle and Belcher, 1981), a marine lagoon (Roberts and McMinn, 1999) and continental margin sediments (Leventer, 1992). The distribution of *Thalassiosira gracilis* extends from coastal waters northwards past the Antarctic convergence (Fenner et al., 1976). This species has even been reported in sub-tropical waters (Fryxell and Hasle, 1979).

**Comments:** *Thalassiosira gracilis* var. *expecta* can be distinguished from *Thalassiosira gracilis* var. *gracilis* by the smaller areolae on the central part of valve face of the latter (Hasle and Syvertsen, 1996).

### ***Trigonium* Cleve**

*Trigonium arcticum* (Brightwell) Cleve

Plate 21, Fig. 9.

**Description** Triangular valves with loculate areolae. Areolae are coarse and radially arranged within the central region of the valve, grading to finer areolation at pseudocellate elevations. The Windmill Island specimens varied between 80-200 µm in size.

**Occurrence:** *Trigonium arcticum* was present in low abundances (<1%) in 23 of the 88 samples.

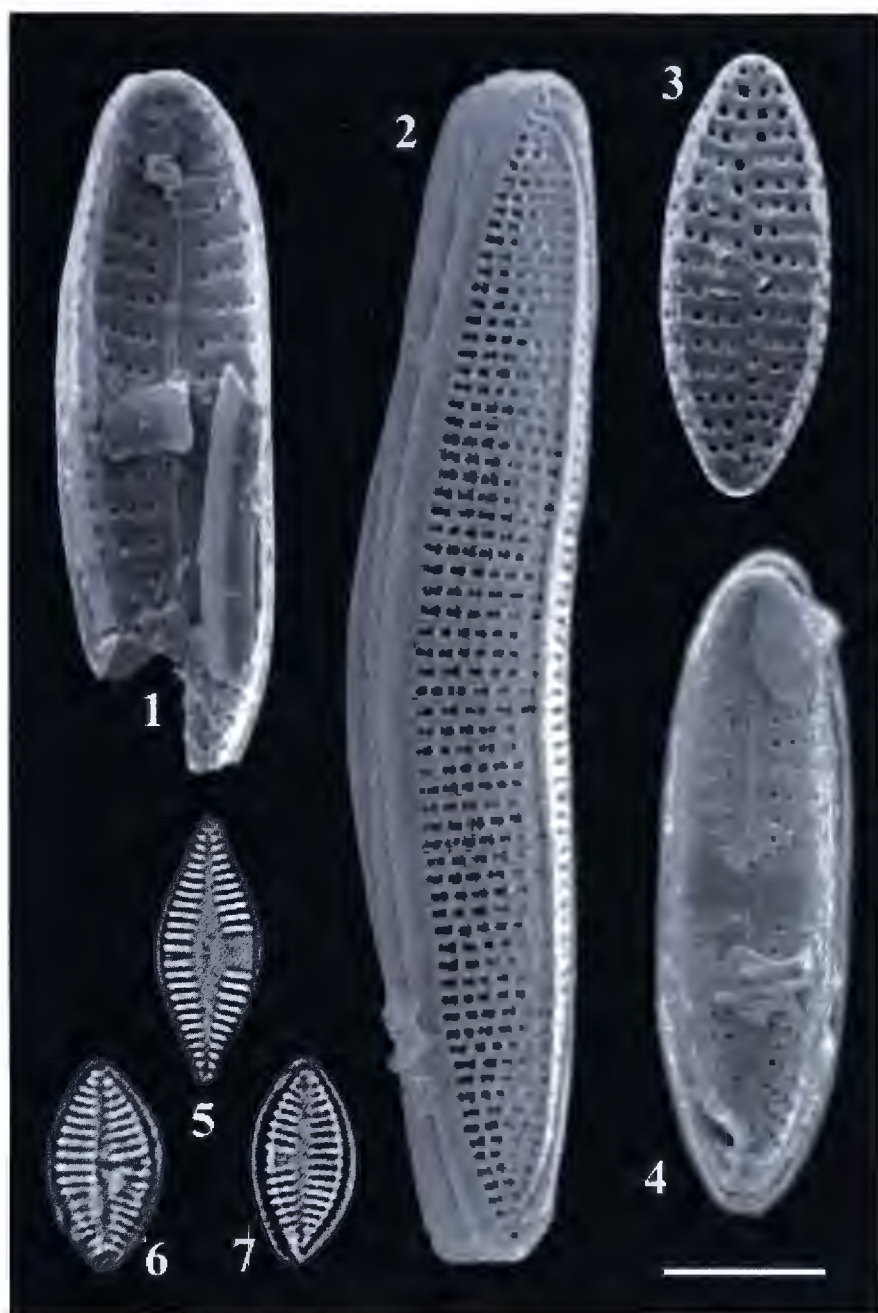
**Distribution:** *Trigonium arcticum* is typically a benthic marine species (Everitt and Thomas, 1986). This species has previously been reported in Antarctic marine sediments near Davis station (Everitt and Thomas, 1986) and from the Vestfold Hills (Whitehead and McMinn, 1997; Tucker and Burton, 1988).

**Comments:** The dimensions given for this species are based on the measurement of 20 individual specimens.

**Plate 1**

Figs. 1 - 4: *Achnanthes brevipes* Agardh  
SEM views of *Achnanthes brevipes*  
Scale = 10  $\mu\text{m}$

Figs. 5 - 7: *Achnanthes* sp. a  
Scale = 20  $\mu\text{m}$



## Plate 2

Fig. 1: *Amphora libyca* Kützing  
SEM view

Fig. 2: *Amphora ovalis* var. *ovalis* (Kützing) Kützing  
SEM view

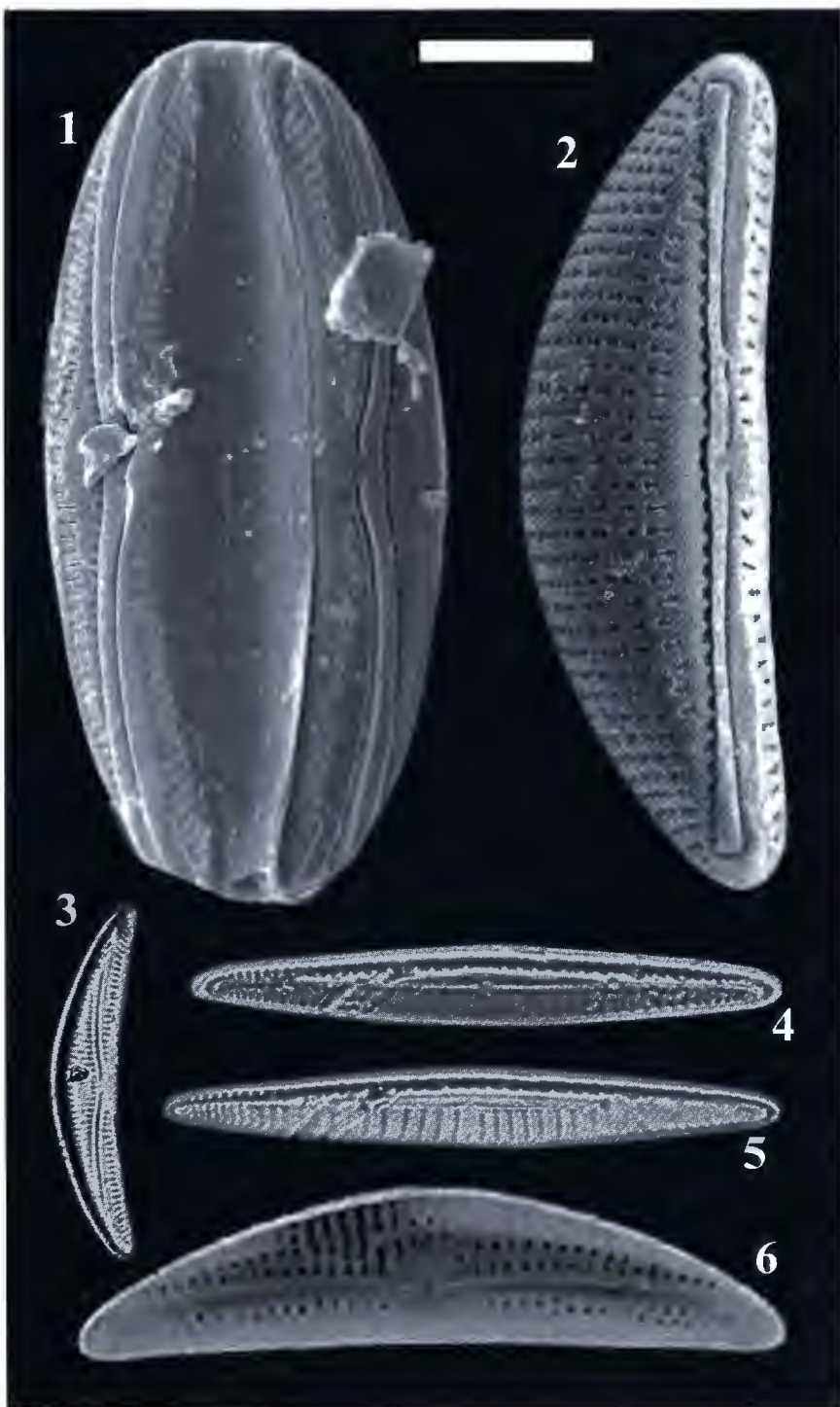
Fig. 3: *Amphora pediculus* (Kützing) Van Heurck

Figs. 4 - 5: *Amphora* sp. a

Fig. 6: *Amphora* sp. c  
SEM view

Scale bar = 10µm





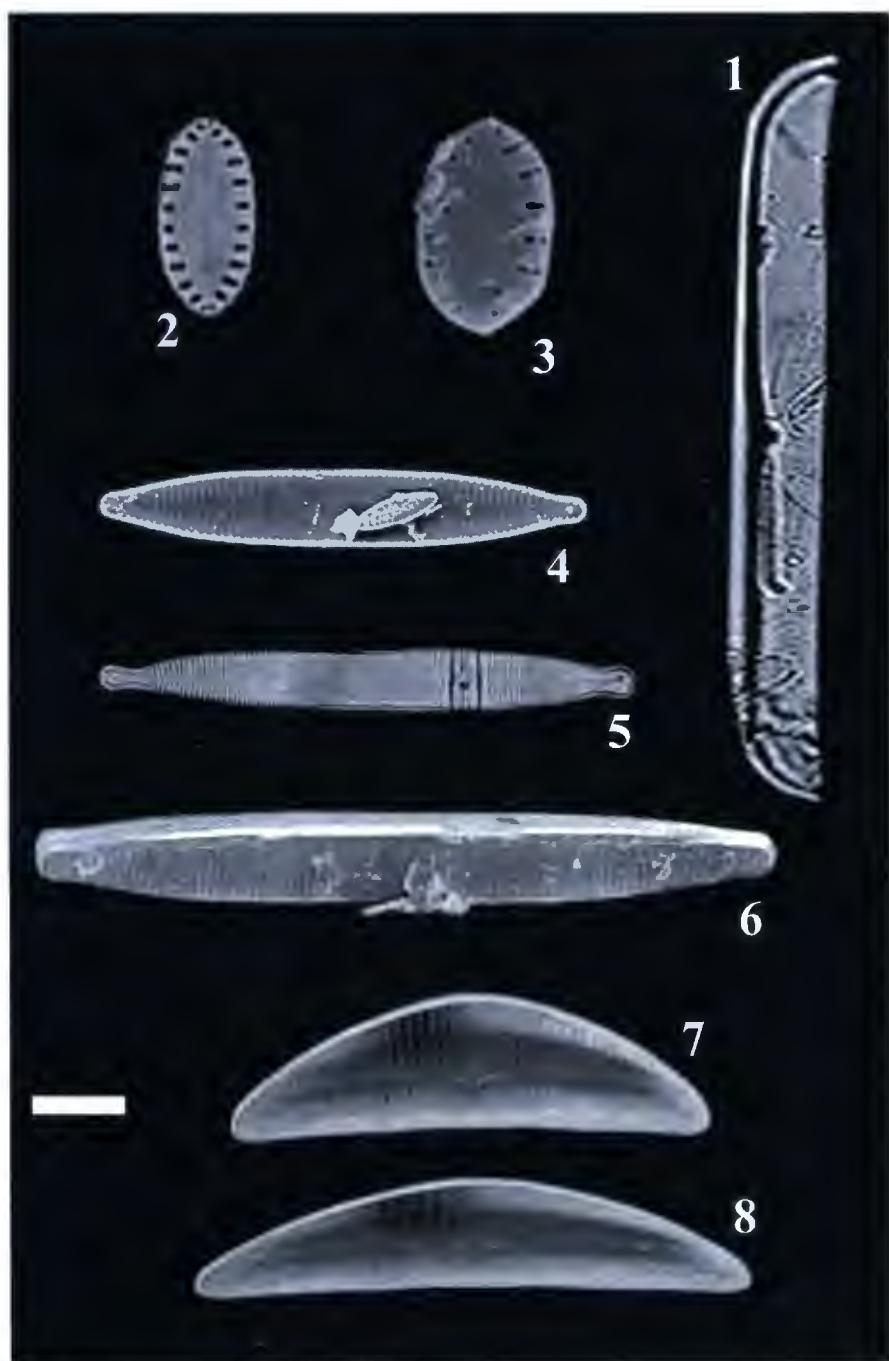
### Plate 3

Fig. 1: *Auricula compacta* (Hustedt) Medlin  
Scale bar = 15  $\mu\text{m}$

Figs. 2 - 3: *Cocconeis pinnata* Gregory  
Fig. 2: LM view of the SV  
Fig. 3: SEM view of the SV  
Scale bar = 10  $\mu\text{m}$

Figs. 4 - 6: *Ctenophora pulchella*  
Fig. 4: SEM view  
Fig. 5: LM view  
Fig. 6: SEM view  
Scale bar = 20  $\mu\text{m}$

Figs. 7 - 8 *Cymbella* sp. a  
Scale bar = 15  $\mu\text{m}$



#### **Plate 4**

Figs. 1 - 2      *Cocconeis costata* Gregory

Fig. 1: LM view

Fig. 2: SEM view

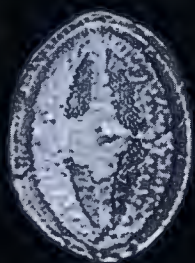
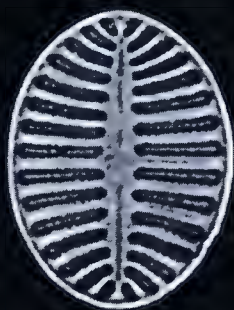
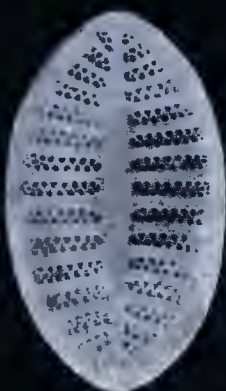
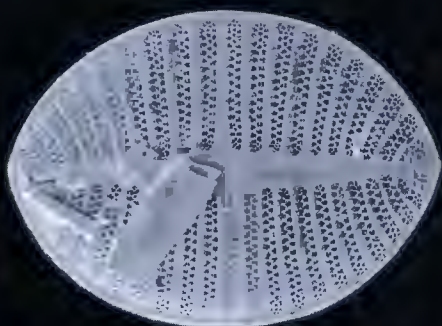
Figs. 3 - 5      *Cocconeis fasciolata* (Ehrenberg) Brown

Fig. 3: SEM view

Figs. 4 - 5: LM views

Figs. 6 - 8:      *Cocconeis schuettii* Van Heurck

Scale = 10  $\mu\text{m}$



**Plate 5**

Figs. 1 - 2:     *Diploneis splendida* (Gregory) Cleve

Scale bar = 10  $\mu\text{m}$ .



1



2

## Plate 6

Figs. 1 - 2: *Diploneis* sp. c

Fig. 3: *Entomoneis* sp. a

Figs. 4 - 5: *Entomoneis* sp. b  
SEM view

Figs. 6 - 7: *Fallacia marnieri* (Manguin) Lange-Bertalot

Scale bar = 10  $\mu\text{m}$ .





1



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**Plate 7**

Figs. 1 - 3: *Fragilariopsis curta* (Van Heurck) Hustedt

Figs. 4 - 5: *Fragilariopsis cylindrus* (Grunow) Kreiger

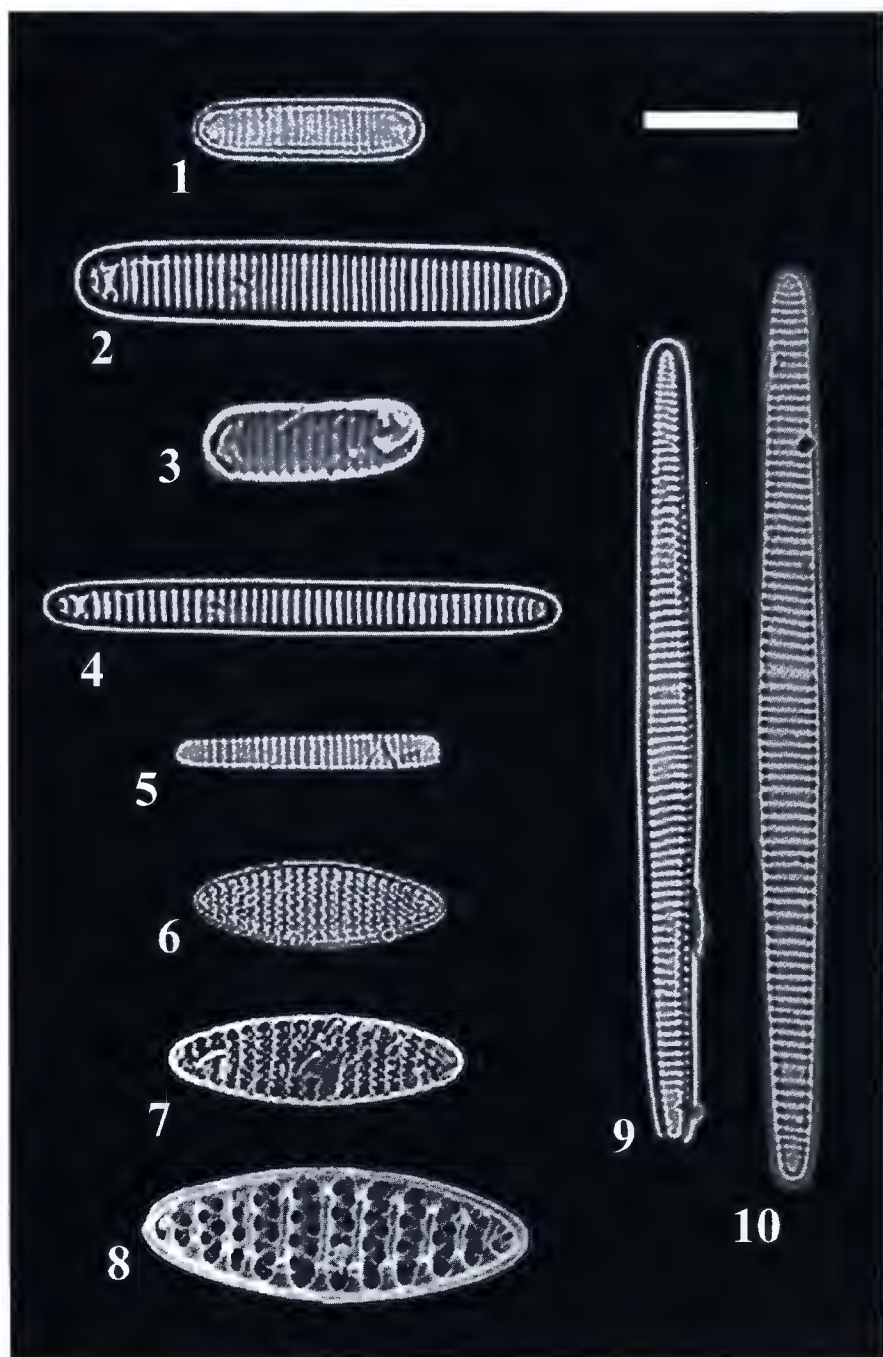
Figs. 6 - 8: *Fragilariopsis kergulensis* (O'Meara) Hustedt

Fig. 6: LM view

Figs. 7-8: SEM view

Figs. 9 - 10: *Fragilariopsis obliquecostata* (Van Heurck) Hasle

Scale bar = 10  $\mu\text{m}$ .



**Plate 8**

Figs. 1 - 2: *Fragilariopsis rhombica* (O'Meara) Hustedt

Fig. 1: LM view

Fig. 2: SEM view

Fig. 3 - 4: *Fragilariopsis ritscheri* Hustedt

Fig. 3: SEM view

Fig. 4: LM view

Fig. 5: *Fragilariopsis sublinearis* (Van Heurck) Heiden

LM view

Scale bar = 10  $\mu\text{m}$ .



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**Plate 9**

Figs. 1 - 2:     ***Gyrosigma*** sp. a

Scale bar = 10  $\mu\text{m}$ .



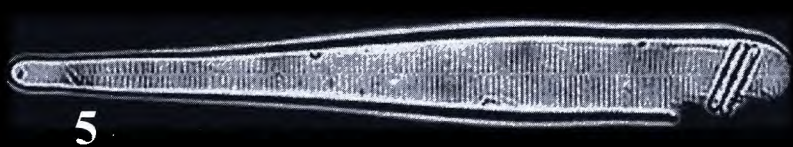
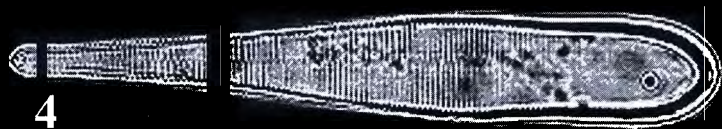
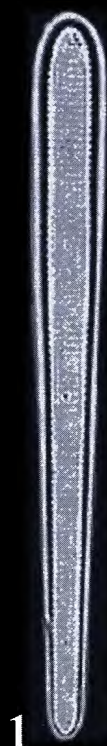
**Plate 10**

Figs. 1 - 2      *Licmophora antarctica*  
Scale bar = 10  $\mu\text{m}$

Fig. 3          *Licmophora* sp. b  
SEM view  
Scale bar = 5  $\mu\text{m}$

Figs. 4 - 5      *Licmophora belgicae*  
Scale bar = 10  $\mu\text{m}$





**Plate 11**

Figs. 1 - 3: *Navicula directa* (W. Smith) Ralfs

Fig. 1: SEM view

Figs. 2 - 3: LM views

Figs. 4 - 5: *Luticola muticopsis* (Van Heurck) Mann

Figs. 6 - 7: *Navicula perminuta* Grunow

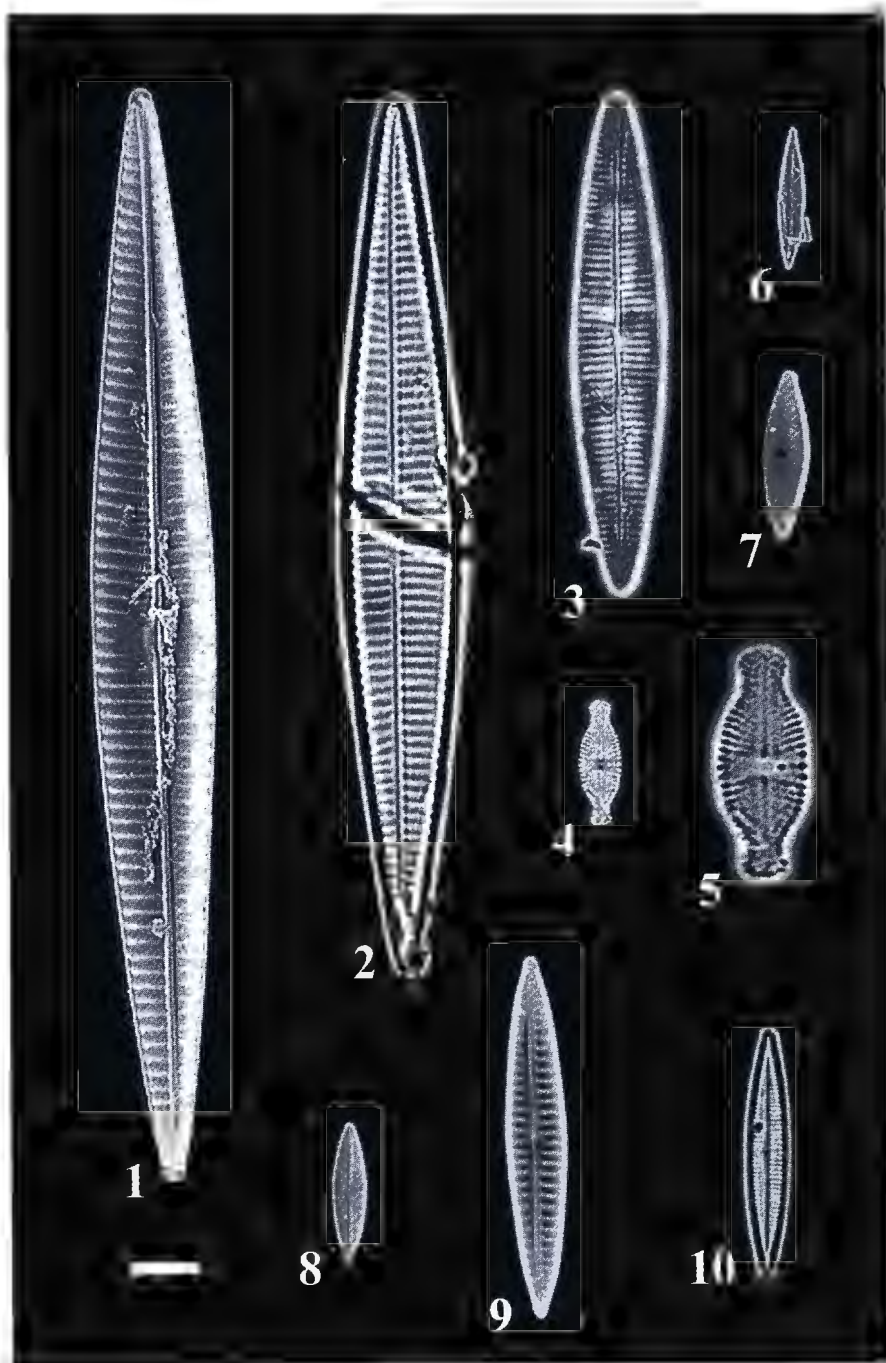
Figs. 8 - 10: *Navicula* sp. a (Van Heurck) Patrick

Fig. 8: LM view

Fig. 9: SEM view

Fig. 10: LM view

Scale bar = 10  $\mu\text{m}$ .



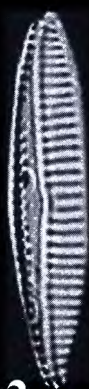
## Plate 12

- Figs. 1-3: *Navicula* sp. b  
Figs. 1-2: LM views  
Fig. 3: SEM view
- Figs. 4-6: *Navicula* sp. c
- Figs. 7-8: *Navicula* aff. *glaciei* Van Heurck  
SEM views

Scale bar = 10  $\mu$ m.



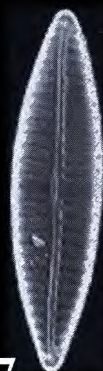
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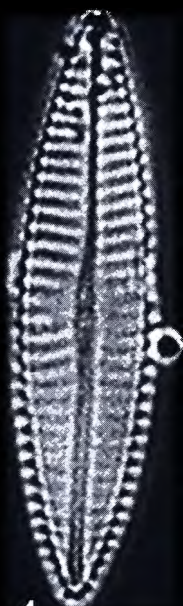
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3



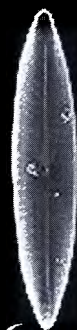
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8



**Plate 13**

Figs 1 - 3:        *Nitzschia dubia* var. *australis* Pergallo

Scale bar = 10 μm.



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3



## Plate 14

Figs. 1 - 2: *Nitzschia* sp. b

Figs. 3 - 4: *Nitzschia* sp. a

Figs. 5 - 6: *Pinnularia quadratarea* (A. Schmidt) Cleve

Fig. 7 - 8: *Pinnularia quadratarea* var. *constricta* (Østrup) Heiden

Scale = 10  $\mu$ m





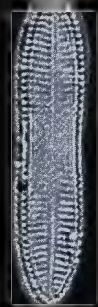
3



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8

## Plate 15

- Figs. 1 - 5:     ***Planothidium delicatula*** (Kützing) Grunow  
Fig. 1. SEM view of *Planothidium robustum* Manguin  
Figs. 2 - 4. LM views of *Planothidium* spp.  
Fig. 5. SEM view of *Planothidium septentrionalis*

Scale = 10  $\mu\text{m}$



## Plate 16

Figs. 1 - 2: *Pleurosigma elongatum* W. Smith

Figs. 3 - 4: *Pleurosigma* aff. *obscurum* W. Smith emed. Sterrenburg

Figs. 5 - 6: *Pleurosigma* sp. a

Scale = 20  $\mu\text{m}$



**Plate 17**

Figs. 1 - 2: *Parlibellus* sp. a

Figs. 3 - 4 *Pseudogomphonema kamtschatica* (Grunow) Medlin

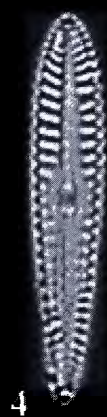
Figs. 5 - 7 *Pseudostaurosira* cf. *brevistriata* (Grunow in Van Heurck) Williams  
and Round

Figs. 5 and 6: SEM views

Fig. 7: LM view

Figs. 8 - 9: *Stauroneis wislouchii* Poretzky and Anisimowa

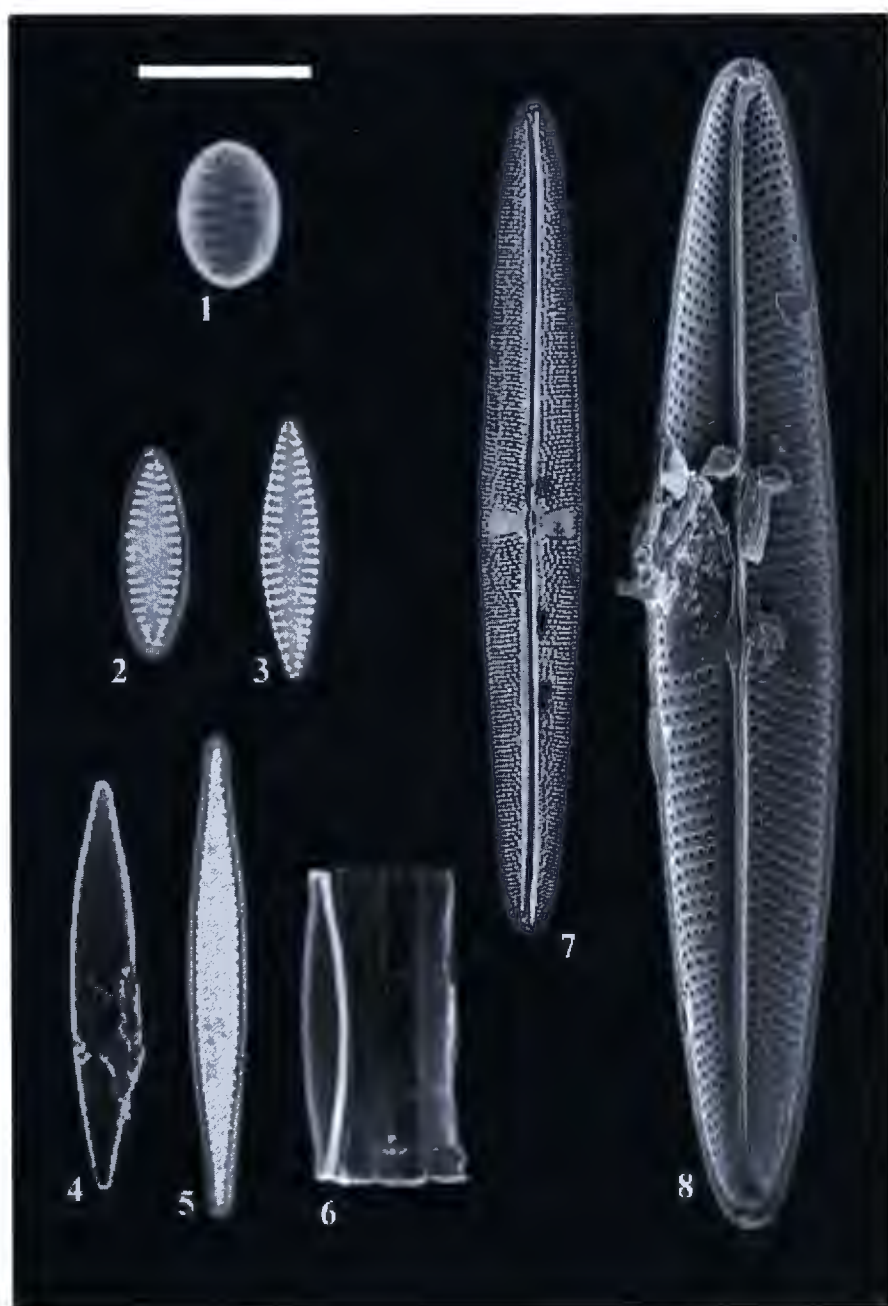
Scale = 10  $\mu\text{m}$



**Plate 18**

- Fig. 1: *Staurosira construens* var. *venter* (Ehrenberg) Hamilton  
SEM view  
Scale bar = 10  $\mu$ m.
- Figs. 2 - 3: *Staurosira construens* var. *pumila* (Grunow) Kingston  
Scale bar = 10  $\mu$ m.
- Figs. 4 - 6: *Synedropsis* cf. *recta* Hasle, Medlin and Syvertsen  
Fig. 8: SEM girdle view  
Fig. 9: LM valve view  
Fig. 10: SEM valve view  
Scale bar = 50  $\mu$ m.
- Figs. 7 - 8: *Trachyneis aspera* (Ehrenberg) Cleve  
Fig. 13: LM view  
Fig. 14: SEM view  
Scale bar = 40  $\mu$ m.





**Plate 19**

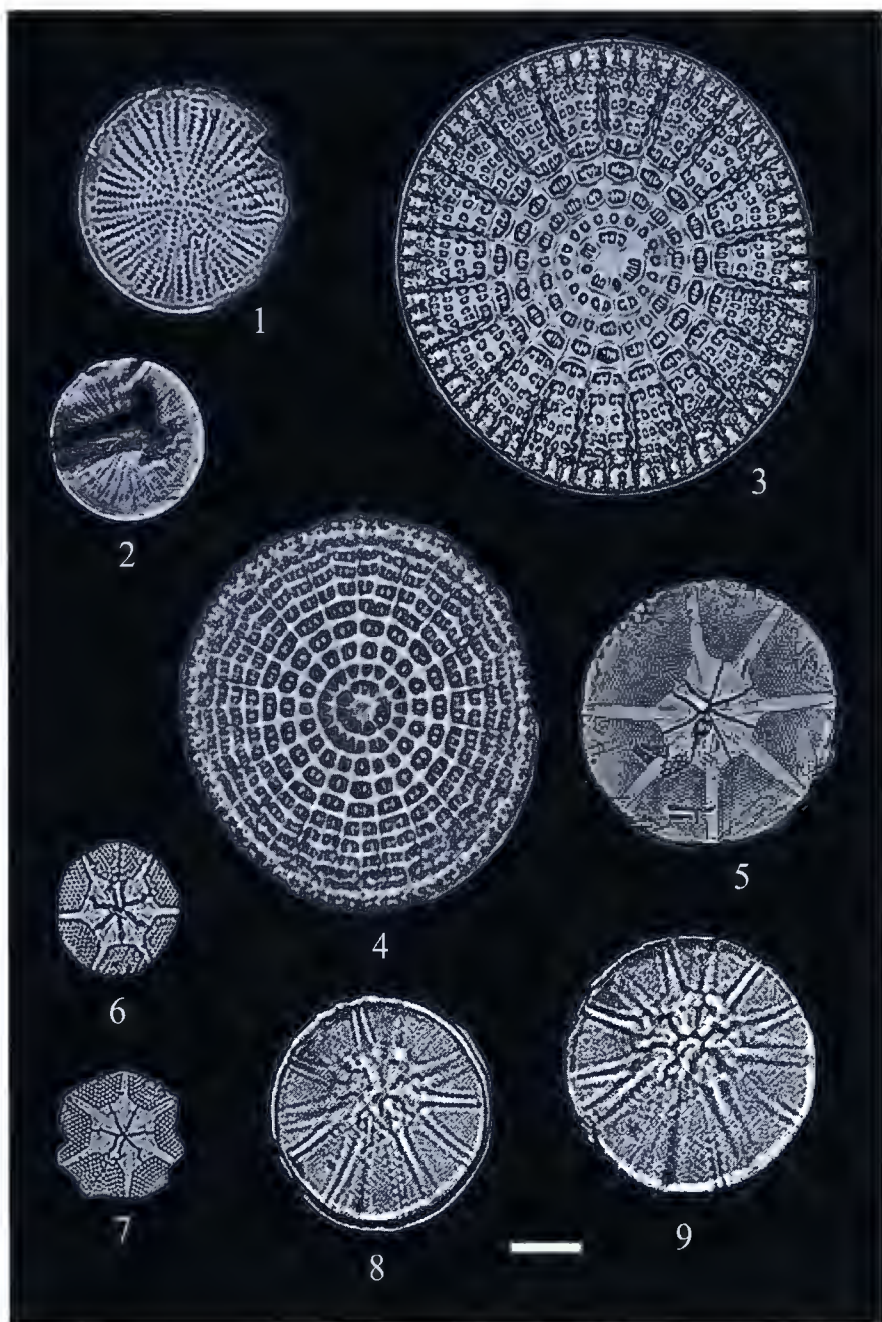
Figs. 1 - 2:     *Actinocyclus actinchilus* (Ehrenberg) Simonsen  
Scale bar = 5  $\mu\text{m}$

Figs. 3 - 4:     *Arachnoidiscus* sp. a  
Scale bar = 50  $\mu\text{m}$

Fig. 5:         *Asteromphalus hookeri* Ehrenberg  
Scale bar = 10  $\mu\text{m}$

Figs. 6 - 7:     *Asteromphalus* sp. a  
Scale bar = 30  $\mu\text{m}$

Figs. 8 - 9:     *Asteromphalus* sp. b  
Scale bar = 30  $\mu\text{m}$



**Plate 20**

Figs. 1 - 2: *Biddulphia areolata*  
SEM views  
Scale bar = 10  $\mu$ m

Fig. 3: *Catacombas camtschatica* (Grunow) Williams and Round  
SEM view  
Scale bar = 10  $\mu$ m

Figs. 4 - 6: *Dactyliosolen antarcticus* Castracane  
Fig. 4: SEM view  
Figs. 5 - 6: LM views  
Scale bar = 10  $\mu$ m

Figs. 7 - 9: *Eucampia antarctica* (Castracane) Manguin  
Figs. 7, 9: LM views  
Fig. 8: SEM view  
Scale bar = 10  $\mu$ m

Figs. 10 - 11: *Paralia sulcata* (Ehrenberg) Cleve  
Scale bar = 10  $\mu$ m

Figs. 12 - 13: *Melosira* sp. a  
Scale bar = 10  $\mu$ m

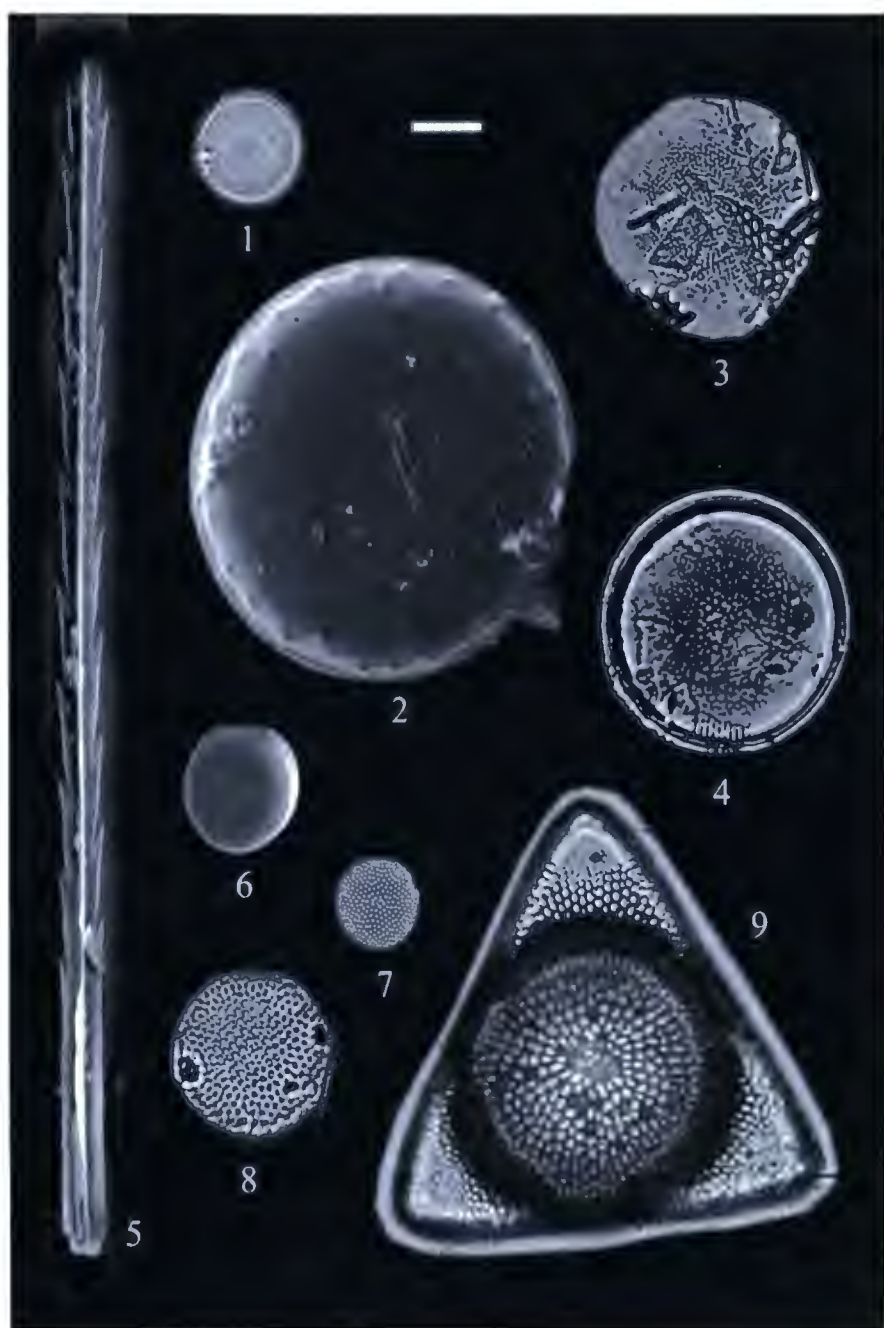
Figs. 14 - 15: *Thalassionema gelida*  
Scale bar = 25  $\mu$ m  
  
Scale bar = 10  $\mu$ m



**Plate 21**

- Figs. 1 - 2:     ***Porosira* sp. a**  
Fig. 1: LM view  
Scale bar = 10  $\mu$ m  
Fig. 2: SEM view  
Scale bar = 1.5  $\mu$ m
- Fig. 3:     ***Porosira glacialis* (Grunow) Jørgensen**  
Scale bar = 10  $\mu$ m
- Fig. 4:     ***Porosira pseudodenticulata* (Hustedt) Jousé**  
Scale bar = 10  $\mu$ m
- Fig. 5:     ***Thalassiothrix antarctica* Schimper ex Karsten**  
SEM view  
Scale bar = 10  $\mu$ m
- Figs. 6 - 7:     ***Thalassiosira gracilis* var. *expecta* (Van Lindingham) Fryxell and  
Hasle**  
Scale bar = 10  $\mu$ m
- Fig. 8:     ***Thalassiosira antarctica* Comber**  
Scale bar = 10  $\mu$ m
- Fig. 9:     ***Trigonium arcticum***  
Scale bar = 10  $\mu$ m





## Appendix 2

Sampling details and  $\text{Pb}^{210}$  results pertaining to Chapter 6.





Australian Nuclear Science and Technology Organisation  
PMB 1 Menai, NSW, 2234, Australia.

Contact: Andrew Jenkinson  
Telephone: (02) 9717 3478  
E-mail: avj@ansto.gov.au

## CERTIFICATE OF ANALYSIS

Client Name: **Beck Scouller**  
Client Institution: **Australian Antarctic Division**

Project Title: **2001rc0140**  
Core Description: **Sparkes #1**

Sampling Date: **0-Jan-00**  
ANSTO Ref: **0**

Row No.	Depth		ANSTO ID	Activity of Po-210 as at 0-Jan-00			Activity of Ra-226 as at 0-Jan-00			Activity of Excess Pb-210 as at 0-Jan-00			Note - This table of excess Pb-210 has not been adjusted for sand, silt or clay content. (adjusted data, if applicable, can be found at the end of this sheet).
	(cm)	(cm)		(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	
12	0.3	+/- 0.3	c411	10.70	+/- 0.30	2.8	2.46	+/- 0.10	4.2	8.24	+/- 0.31	3.8	
13	2.5	+/- 0.3	c412	4.92	+/- 0.17	3.6	1.84	+/- 0.09	4.9	3.08	+/- 0.20	6.4	
14	3.7	+/- 0.3	c413	3.20	+/- 0.13	3.9	1.78	+/- 0.09	5.0	1.41	+/- 0.15	10.9	
15	4.9	+/- 0.3	c414	2.62	+/- 0.11	4.0	2.16	+/- 0.10	4.8	0.45	+/- 0.15	32.7	
16	6.1	+/- 0.3	c415	2.39	+/- 0.10	4.0	2.07	+/- 0.08	4.0	0.32	+/- 0.13	39.5	
17	8.3	+/- 0.3	c416	2.15	+/- 0.06	2.9	2.07	+/- 0.10	4.7	0.08	+/- 0.12	140.8	
18	9.5	+/- 0.3	c417	2.16	+/- 0.04	1.7	2.95	+/- 0.14	4.8	-0.79	+/- 0.15	-18.6	
19	11.3	+/- 0.3	c418	2.38	+/- 0.04	1.5	1.41	+/- 0.08	4.0	0.97	+/- 0.07	6.9	
20	14.9	+/- 0.3	c419	2.70	+/- 0.08	3.0	2.13	+/- 0.09	4.1	0.58	+/- 0.12	20.6	
21	17.9	+/- 0.3	c420	3.04	+/- 0.09	3.0	2.83	+/- 0.12	4.3	0.21	+/- 0.15	73.8	
22	20.3	+/- 0.3	c421	3.58	+/- 0.10	2.9	3.30	+/- 0.13	3.9	0.28	+/- 0.17	58.6	
23	24.75	+/- 0.25	c422	3.14	+/- 0.09	3.0	2.69	+/- 0.11	4.2	0.46	+/- 0.15	32.1	
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<b>Po-210 Activities</b>			
Highest	10.6984	dpm/g	
Lowest	2.1530	dpm/g	
Mean	3.5820	dpm/g	
Number	12		

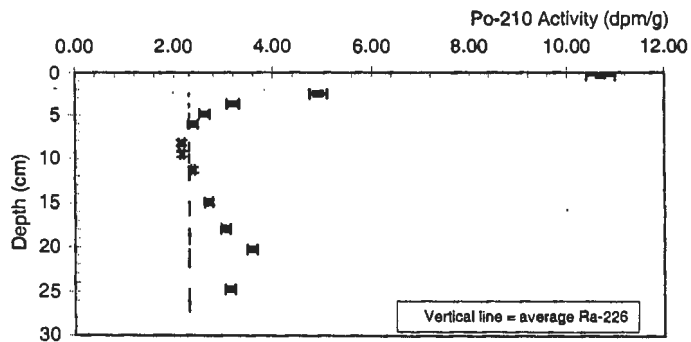
  

<b>Ra-226 Activities</b>			
Highest	3.2954	dpm/g	
Lowest	1.4105	dpm/g	
Mean	2.3073	dpm/g	
Number	12		

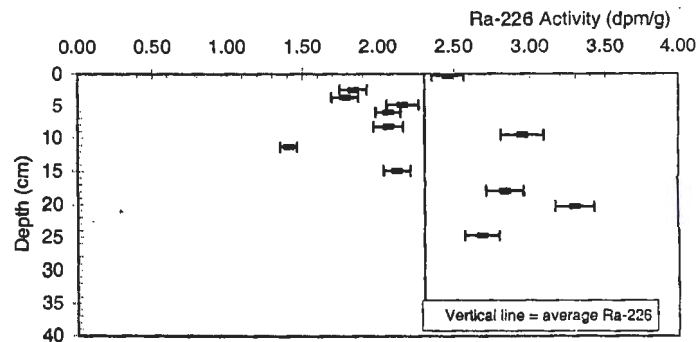
  

<b>Excess Pb-210 Activities</b>			
Highest	8.2371	dpm/g	
Lowest	-0.7862	dpm/g	
Mean	1.2747	dpm/g	
Number	12		

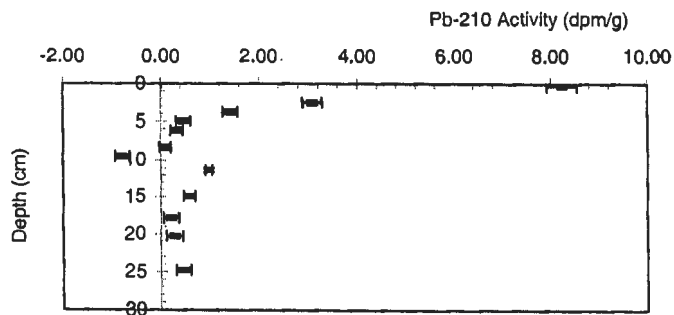
**Plot of Po-210 Activity vs Depth**



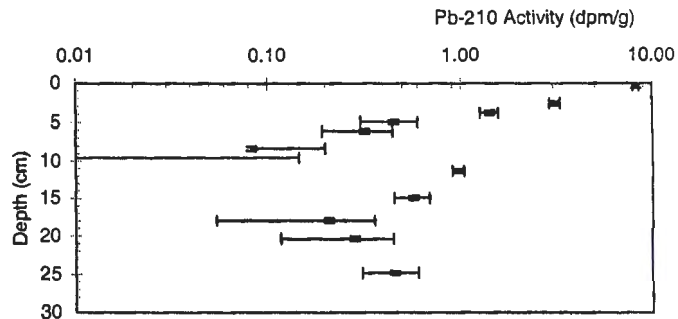
**Plot of Ra-226 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**

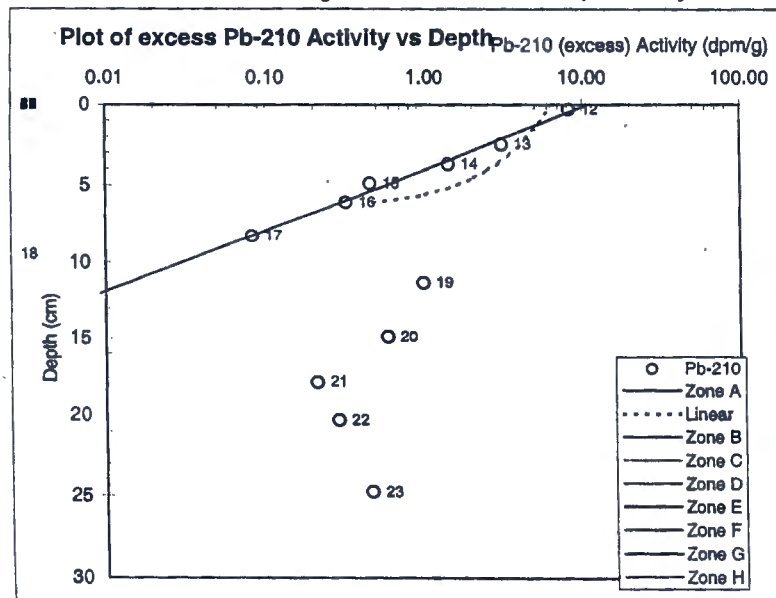


## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: **Unaltered for sand, silt or clay content**



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

Sedimentation Rate				Correlation Coefficient
Linear Relationship				
Row No.	Depth		(%)	(r <sup>2</sup> )
12 17	0 - 9 Zone A =	0.149 +/- 0.044 cm/year	29.6	0.7599
Exponential Relationship				
Row No.	Depth		(%)	(r <sup>2</sup> )
12 17	0 - 9 Zone A =	0.053 +/- 0.005 cm/year	10.3	0.9882
0 0	Zone B =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000
0 0	Zone C =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000
0 0	Zone D =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000
0 0	Zone E =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000
0 0	Zone F =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000
0 0	Zone G =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000
0 0	Zone H =	#DIV/0! +/- #DIV/0! cm/year	###	0.0000

**Note:** A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs



[illegible]

Row No.	Activity of Excess Pb-210 as at 0-Jan-00			
	(dpm/g)		(dpm/g)	(%)
12	8.24	+/-	0.31	3.8
13	3.08	+/-	0.20	6.4
14	1.41	+/-	0.15	10.9
15	0.45	+/-	0.15	32.7
16	0.32	+/-	0.13	39.5
17	0.08	+/-	0.12	140.8
18	0.00	+/-	0.15	#####
19	0.97	+/-	0.07	6.9
20	0.58	+/-	0.12	20.6
21	0.21	+/-	0.15	73.8
22	0.28	+/-	0.17	58.6
23	0.46	+/-	0.15	32.1
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## Constant Initial Concentration (CIC) Model

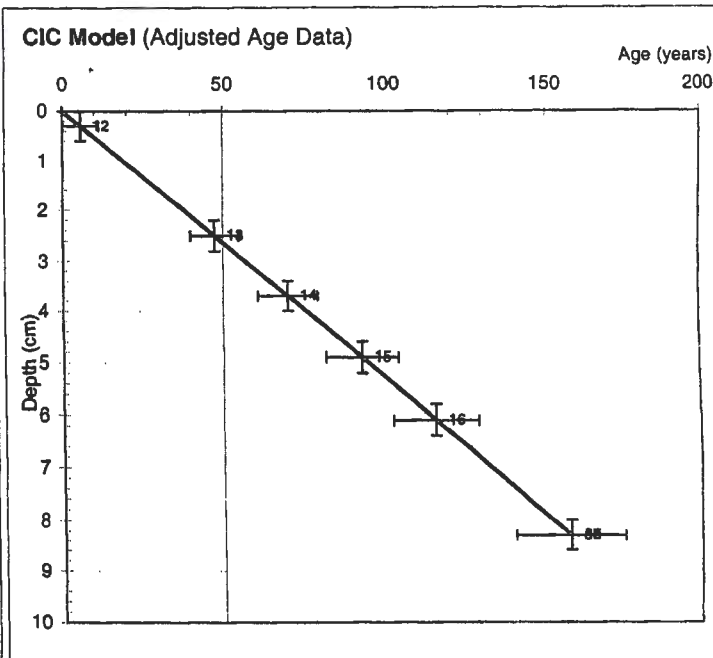
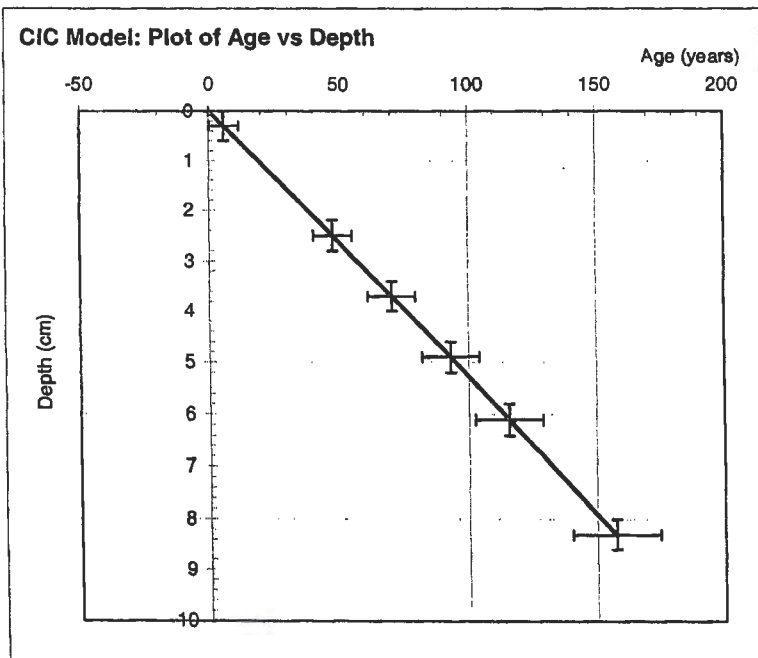
### Cautionary Note

In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.

**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

### Adjusted Age Data

The graph below has been constructed by eliminating any "negative a" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.



Sparkes Bay Core 2



Australian Nuclear Science and Technology Organisation  
PMB 1 Menai, NSW, 2234, Australia.

Contact: Andrew Jenkinson  
Telephone: (02) 9717 3478  
E-mail: avj@ansto.gov.au

## CERTIFICATE OF ANALYSIS

**Client Name:** Beck Scouller  
**Client Institution:** Australian Antarctic Division

**Project Title:** 2001rc0147  
**Core Description:** Sparkes #2

**Sampling Date:** 0-Jan-00  
**ANSTO Ref:** 0

Row No.	Depth		ANSTO ID	Activity of Po-210 as at 0-Jan-00			Activity of Ra-226 as at 0-Jan-00			Activity of Excess Pb-210 as at 0-Jan-00		
	(cm)	(cm)		(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)
12	0.15	+/- 0.15	c462	5.78	+/-	0.10	1.62	+/-	0.08	4.7	4.17	+/- 0.13
13	1.35	+/- 0.15	c483	2.10	+/-	0.06	1.64	+/-	0.07	4.0	0.46	+/- 0.09
14	2.85	+/- 0.25	c484	2.55	+/-	0.07	2.42	+/-	0.11	4.4	0.13	+/- 0.13
15	4.85	+/- 0.25	c485	1.79	+/-	0.05	1.88	+/-	0.08	4.7	0.12	+/- 0.09
16	6.95	+/- 0.25	c466	1.81	+/-	0.03	2.31	+/-	0.11	4.6	-0.50	+/- 0.11
17	8.775	+/- 0.175	c467	2.68	+/-	0.06	2.62	+/-	0.12	4.6	0.07	+/- 0.13
18	10.18	+/- 0.175	c468	2.87	+/-	0.05	2.85	+/-	0.12	4.0	0.02	+/- 0.12
19	12.63	+/- 0.175	c469	3.19	+/-	0.11	2.74	+/-	0.12	4.2	0.45	+/- 0.16
20	15.75	+/- 0.25	c470	2.60	+/-	0.04	1.92	+/-	0.10	5.4	0.68	+/- 0.11
21	19	+/- 0.5	c471	3.52	+/-	0.06	2.62	+/-	0.11	4.1	0.90	+/- 0.12
22	21.25	+/- 0.25	c472	2.61	+/-	0.04	2.20	+/-	0.09	4.2	0.41	+/- 0.10
23	26.45	+/- 2.25	c473	3.04	+/-	0.05	1.16	+/-	0.05	4.2	1.88	+/- 0.07
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**Note** - This table of excess Pb-210 has not been adjusted for sand, silt or clay content.

(adjusted data, if applicable, can be found at the end of this sheet).

**Po-210 Activities**

Highest 5.7837 dpm/g  
Lowest 1.7937 dpm/g  
Mean 2.8786 dpm/g  
Number 12

**Ra-226 Activities**

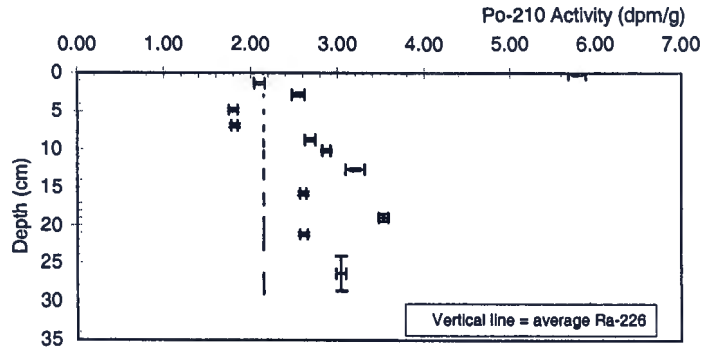
Highest 2.8477 dpm/g  
Lowest 1.1558 dpm/g  
Mean 2.1473 dpm/g  
Number 12

**Excess Pb-210 Activities**

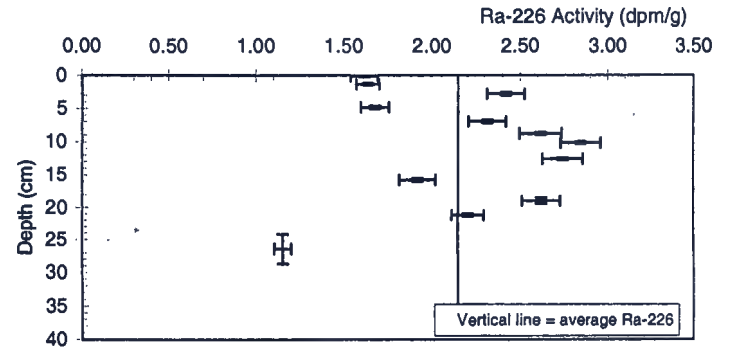
Highest 4.1679 dpm/g  
Lowest -0.5018 dpm/g  
Mean 0.7313 dpm/g  
Number 12



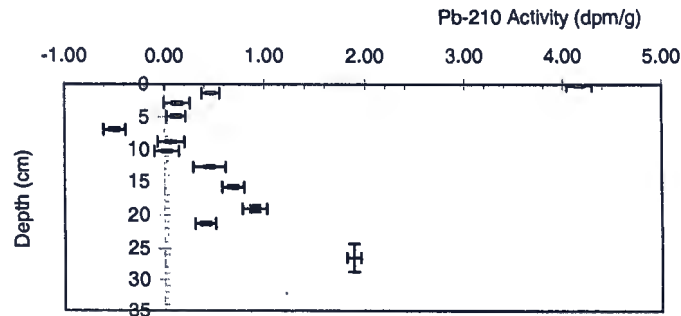
**Plot of Po-210 Activity vs Depth**



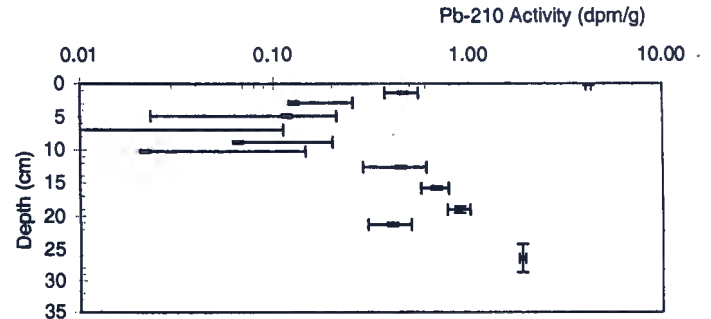
**Plot of Ra-226 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**

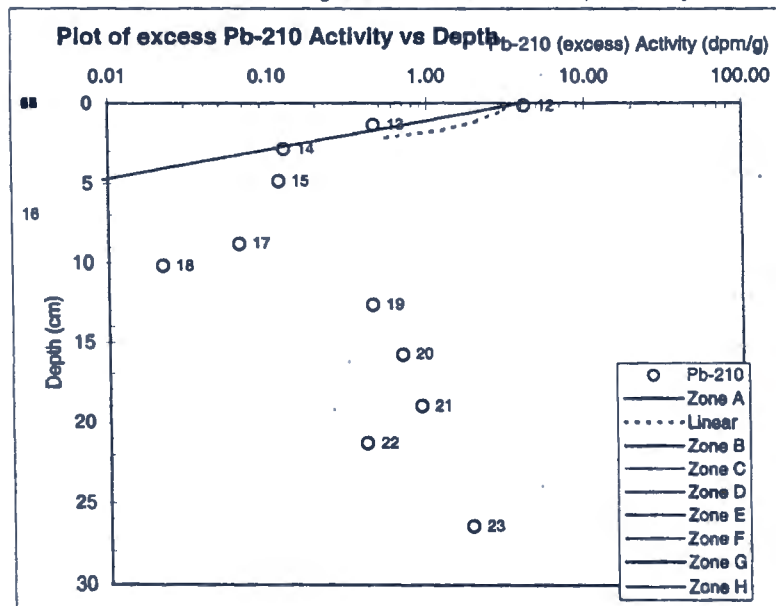


## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: **Unaltered for sand, silt or clay content**



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

		Sedimentation Rate		Correlation Coefficient	
		Linear Relationship		(%)	(r <sup>2</sup> )
Row No.	Depth				
12 14	0 - 3 Zone A =	0.057 +/-	0.037 cm/year	64.2	0.7595
Exponential Relationship					
Row No.	Depth			(%)	(r <sup>2</sup> )
12 14	0 - 3 Zone A =	0.024 +/-	0.020 cm/year	81.3	0.9556
0 0	Zone B =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone C =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone D =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone E =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone F =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone G =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone H =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000

**Note:** A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs.



[illegible]

Row No.	Activity of Excess Pb-210 as at 0-Jan-00			
	(dpm/g)		(dpm/g)	(%)
12	4.17	+/-	0.13	3.1
13	0.46	+/-	0.09	19.4
14	0.13	+/-	0.13	101.7
15	0.12	+/-	0.09	80.1
16	0.00	+/-	0.11	#####
17	0.07	+/-	0.13	204.4
18	0.02	+/-	0.12	569.2
19	0.45	+/-	0.16	35.8
20	0.68	+/-	0.11	16.0
21	0.90	+/-	0.12	13.6
22	0.41	+/-	0.10	25.0
23	1.88	+/-	0.07	3.7
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## Constant Initial Concentration (CIC) Model

### Cautionary Note

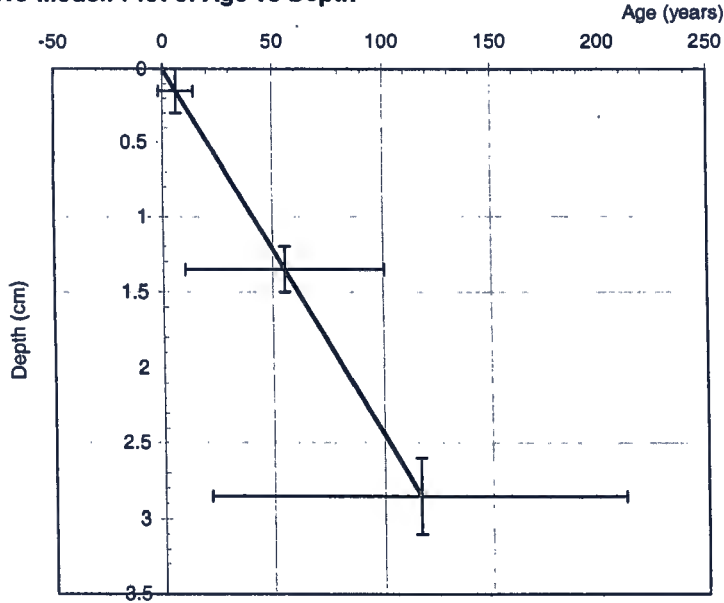
In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.

**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

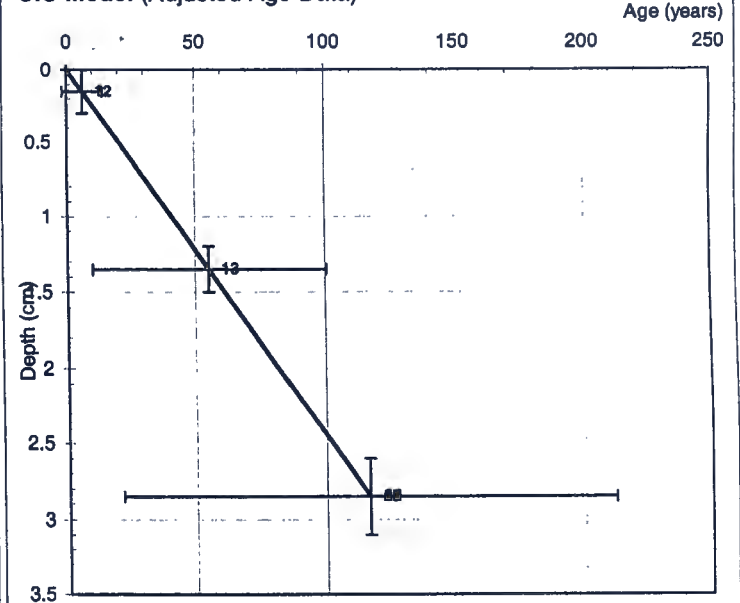
### Adjusted Age Data

The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.

CIC Model: Plot of Age vs Depth



CIC Model (Adjusted Age Data)



Shannon Bay



Australian Nuclear Science and Technology Organisation  
PMB 1 Menai, NSW, 2234, Australia.

Contact: Andrew Jenkinson  
Telephone: (02) 9717 3478  
E-mail: avj@ansto.gov.au

## CERTIFICATE OF ANALYSIS

Client Name: **Beck Scouller**

Project Title: **2001rc0142**

Sampling Date

**0-Jan-00**

Client Institution. **Australian Antarctic Division** Core Descriptio. **Shannon**

ANSTO Ref:

**0**

Row No.	Depth			ANSTO ID	Activity of Po-210 as at 0-Jan-00				Activity of Ra-226 as at 0-Jan-00				Activity of Excess Pb-210 as at 0-Jan-00			
	(cm)		(cm)		(dpm/g)		(dpm/g)	(%)	(dpm/g)		(dpm/g)	(%)	(dpm/g)		(dpm/g)	(%)
12	2	+/-	2	c428	6.88	+/-	0.11	1.6	1.29	+/-	0.06	4.9	5.60	+/-	0.13	2.3
13	18	+/-	2	c429	2.75	+/-	0.06	2.2	0.86	+/-	0.04	5.0	1.89	+/-	0.07	4.0
14	30	+/-	2	c430	1.55	+/-	0.04	2.4	0.84	+/-	0.04	5.0	0.71	+/-	0.06	7.9
15	42	+/-	2	c431	1.03	+/-	0.02	2.4	0.78	+/-	0.04	4.9	0.26	+/-	0.05	17.8
16	62	+/-	2	c432	0.96	+/-	0.03	2.8	0.77	+/-	0.04	5.1	0.19	+/-	0.05	25.4
17	76	+/-	2	c433	0.87	+/-	0.03	3.5	0.70	+/-	0.03	4.8	0.16	+/-	0.05	27.8
18	88	+/-	2	c434	0.93	+/-	0.03	2.9	1.12	+/-	0.08	6.8	-0.19	+/-	0.08	-41.8
19	104	+/-	2	c435	0.85	+/-	0.03	3.0	1.26	+/-	0.12	9.6	-0.41	+/-	0.12	-30.3
20	137.5	+/-	2.5	c436	1.08	+/-	0.03	2.7	1.78	+/-	0.15	8.5	-0.70	+/-	0.15	-22.1
21	177.5	+/-	2.5	c437	0.98	+/-	0.03	2.8	0.23	+/-	0.02	8.7	0.75	+/-	0.03	4.5
22	220	+/-	5	c438	0.86	+/-	0.03	3.4	1.26	+/-	0.10	7.8	-0.41	+/-	0.10	-25.3
23	262.5	+/-	2.5	c439	1.10	+/-	0.04	3.3	0.91	+/-	0.07	7.4	0.19	+/-	0.08	40.3
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**Note** -This table of excess Pb-210 has not been adjusted for sand, silt or clay content. (adjusted data, if applicable, can be found at the end of this sheet).

**Po-210 Activities**

Highest 6.8829 dpm/g  
Lowest 0.8522 dpm/g  
Mean 1.6528 dpm/g  
Number 12

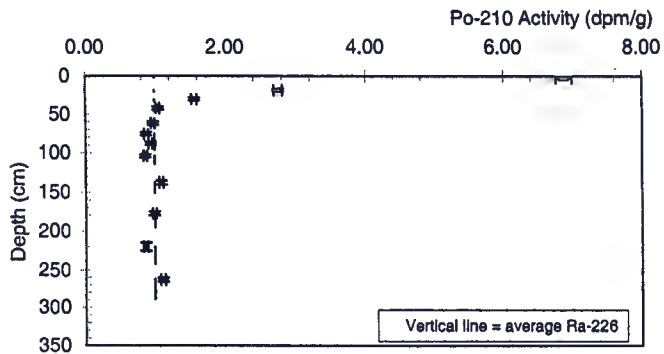
**Ra-226 Activities**

Highest 1.7757 dpm/g  
Lowest 0.2294 dpm/g  
Mean 0.9835 dpm/g  
Number 12

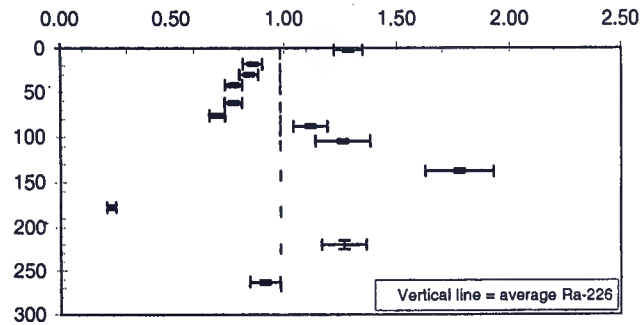
**Excess Pb-210 Activities**

Highest 5.5964 dpm/g  
Lowest -0.6960 dpm/g  
Mean 0.6693 dpm/g  
Number 12

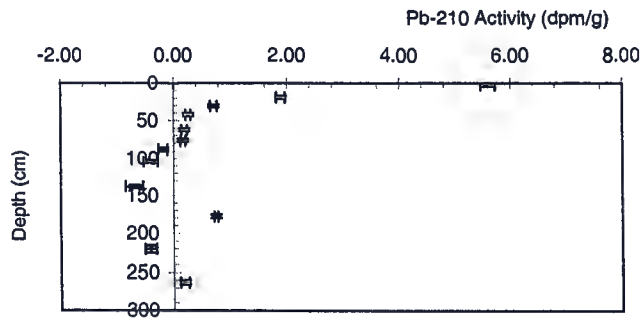
**Plot of Po-210 Activity vs Depth**



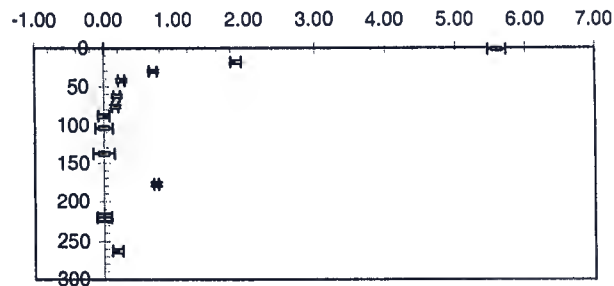
**Plot of Ra-226 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**

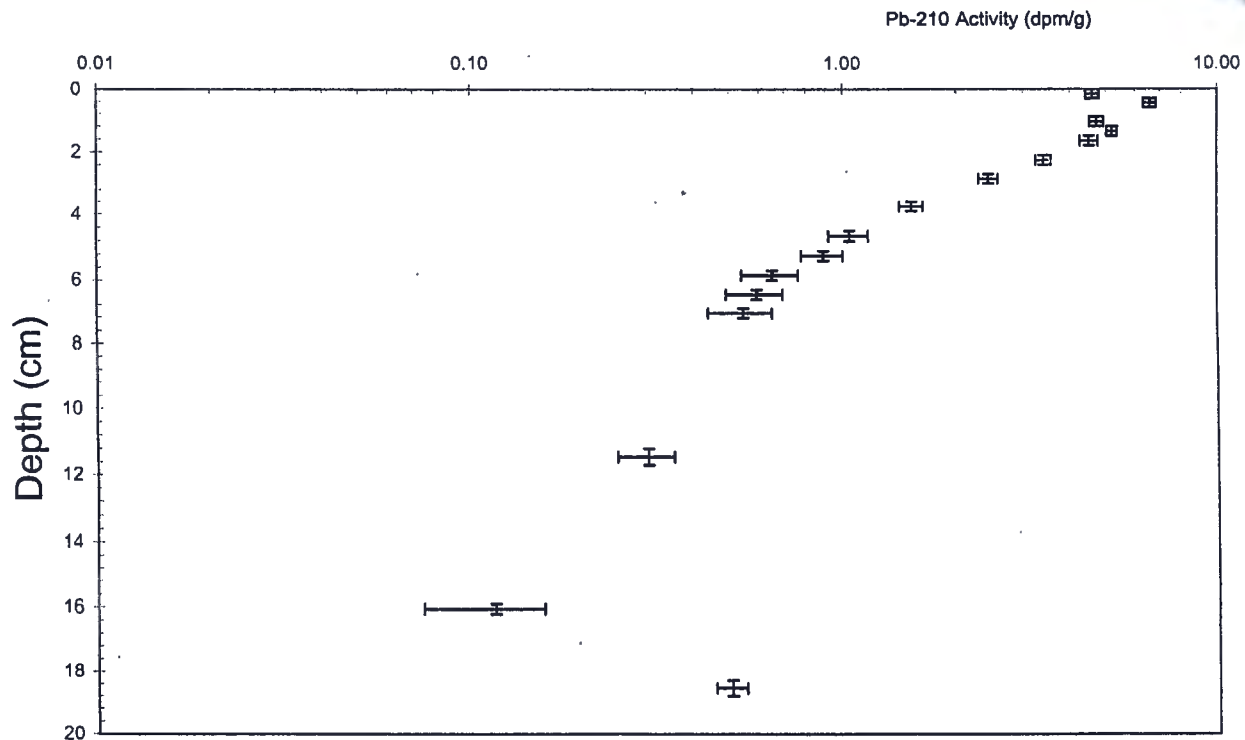


**Plot of Excess Pb-210 Activity vs Depth**





## Plot of Excess Pb-210 Activity vs Depth

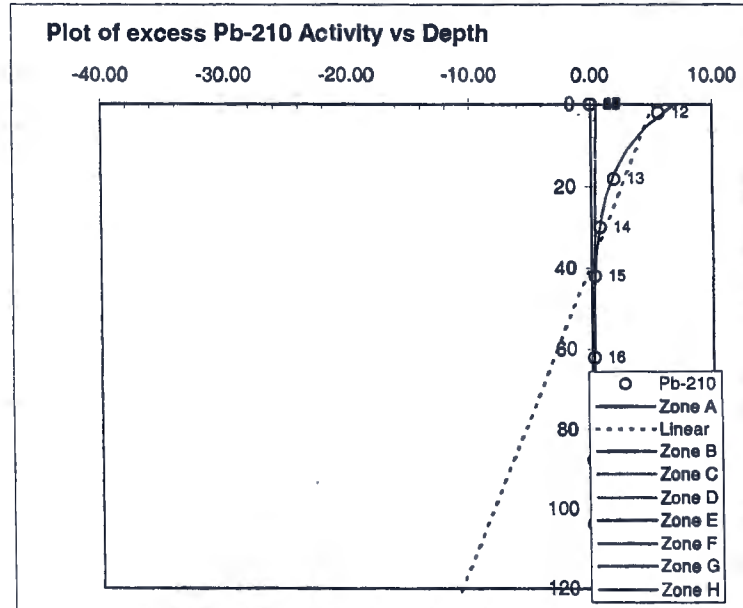


## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: **Unaltered for sand, silt or clay content**



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

Row No.	Depth	Sedimentation Rate		Correlation Coefficient	
		Linear Relationship		(%)	(r <sup>2</sup> )
12 15	0 - 44 Zone A =	0.871 +/-	0.233 cm/yr	26.7	0.8895
Exponential Relationship					
12 15	0 - 44 Zone A =	0.404 +/-	0.019 cm/yr	4.8	0.9970
15 17	40 - 78 Zone B =	2.302 +/-	1.013 cm/yr	44.0	0.9877
0 0	Zone C =	#### +/-	#DIV/0! cm/yr	#DIV/0!	0.0000
0 0	Zone D =	#### +/-	#DIV/0! cm/yr	#DIV/0!	0.0000
0 0	Zone E =	#### +/-	#DIV/0! cm/yr	#DIV/0!	0.0000
0 0	Zone F =	#### +/-	#DIV/0! cm/yr	#DIV/0!	0.0000
0 0	Zone G =	#### +/-	#DIV/0! cm/yr	#DIV/0!	0.0000
0 0	Zone H =	#### +/-	#DIV/0! cm/yr	#DIV/0!	0.0000

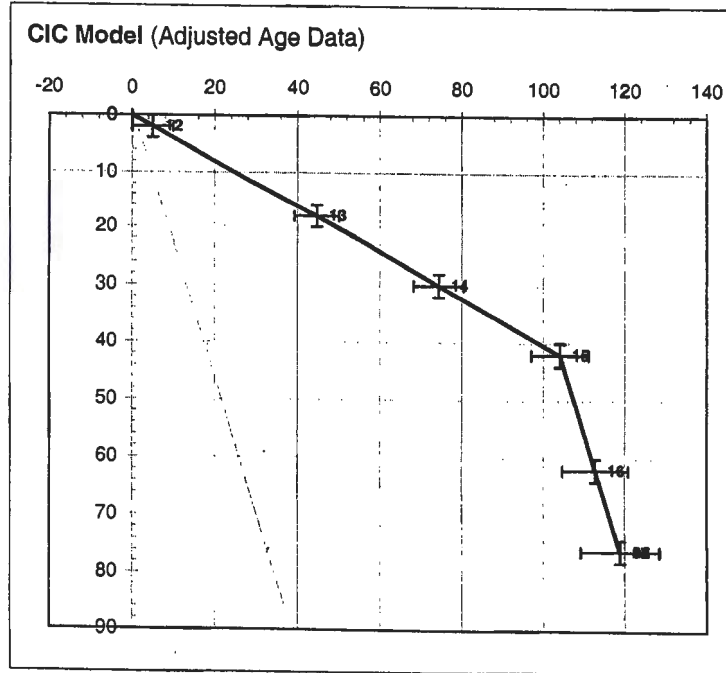
**Note:** A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs.

[illegible]

**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

### Adjusted Age Data

The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.



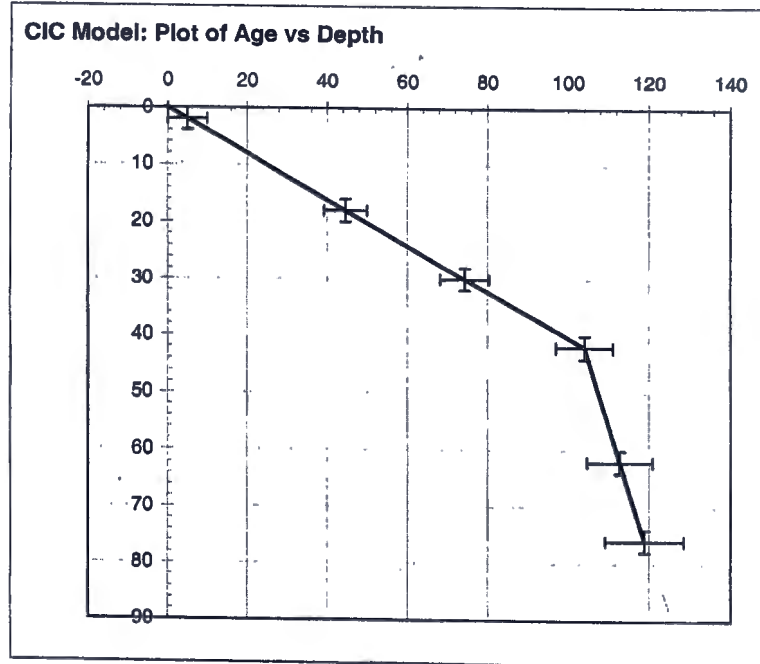
The Excess Pb-210 data below has been derived from a set of **Unaltered original data** and forms the basis of all the plots

Row No.	Activity of Excess Pb-210 as at 0-Jan-00		
	(dpm/g)	(dpm/g)	(%)
12	5.60 +/-	0.13	2.3
13	1.89 +/-	0.07	4.0
14	0.71 +/-	0.06	7.9
15	0.26 +/-	0.05	17.8
16	0.19 +/-	0.05	25.4
17	0.16 +/-	0.05	27.8
18	0.00 +/-	0.08	#####
19	0.00 +/-	0.12	#####
20	0.00 +/-	0.15	#####
21	0.75 +/-	0.03	4.5
22	0.00 +/-	0.10	#####
23	0.19 +/-	0.08	40.3
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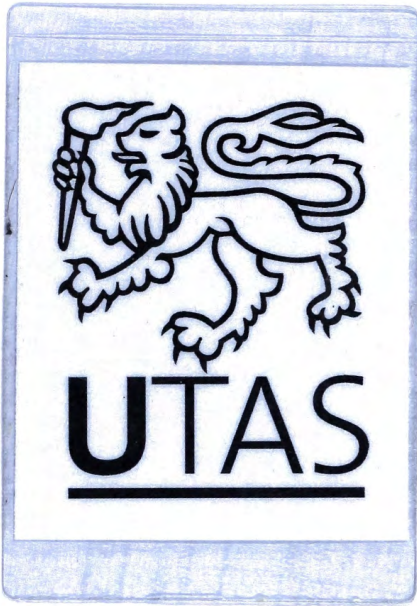
## Constant Initial Concentration (CIC) Model

### Cautionary Note

In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.



*Brown Bay Core 1*



Australian Nuclear Science and Technology Organisation  
PMB 1 Menal, NSW, 2234, Australia.

Contact: Andrew Jenkinson  
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E-mail: avj@ansto.gov.au

## CERTIFICATE OF ANALYSIS

**Client Name:** Beck Scouller  
**Client Institution:** Antarctic Division

**Project Title:** 2001RC0134, 2000RC0041  
**Core Descriptive:** Brown Bay Outer #1

**Sampling Date:** 0-Jan-00  
**ANSTO Ref:** 0

Row No.	Depth		ANSTO ID	Activity of Po-210 as at 0-Jan-00			Activity of Ra-226 as at 0-Jan-00			Activity of Excess Pb-210 as at 0-Jan-00			Note
	(cm)	(cm)		(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	
12	0.45	+/- 0.15	A058	3.35	+/-	0.09	2.8	0.56	+/-	0.06	11.4	2.79	+/- 0.11 4.1
13	0.75	+/- 0.15	A039	2.70	+/-	0.15	5.4	0.58	+/-	0.08	12.9	2.12	+/- 0.16 7.8
14	1.35	+/- 0.15	A059	1.18	+/-	0.04	3.2	0.64	+/-	0.07	10.2	0.54	+/- 0.08 14.2
15	1.65	+/- 0.15	c393	1.01	+/-	0.02	2.0	0.76	+/-	0.04	4.9	0.25	+/- 0.04 17.2
16	2.55	+/- 0.15	A060	0.89	+/-	0.03	2.8	0.51	+/-	0.05	9.1	0.38	+/- 0.05 14.1
17	3.15	+/- 0.15	A041	0.97	+/-	0.04	3.6	0.65	+/-	0.06	9.1	0.33	+/- 0.07 20.9
18	4.05	+/- 0.15	A061	0.83	+/-	0.02	3.0	0.57	+/-	0.05	9.0	0.26	+/- 0.06 22.3
19	4.65	+/- 0.15	A042	0.72	+/-	0.02	3.4	0.56	+/-	0.05	9.2	0.15	+/- 0.06 36.8
20	5.55	+/- 0.15	A062	0.57	+/-	0.01	2.5	0.49	+/-	0.02	4.6	0.07	+/- 0.03 65.4
21	5.85	+/- 0.15	A043	0.54	+/-	0.02	4.0	0.73	+/-	0.08	11.1	0.19	+/- 0.08 75.4
22	6.45	+/- 0.15	A058	0.54	+/-	0.03	3.8	0.53	+/-	0.06	11.2	0.09	+/- 0.06 158.0
23	7.05	+/- 0.15	A044	0.72	+/-	0.04	2.6	0.64	+/-	0.07	10.7	0.08	+/- 0.07 91.6
24	10	+/- 0.15	c395	0.65	+/-	0.01	2.3	0.65	+/-	0.06	4.4	0.07	+/- 0.08 45.8
25	11.95	+/- 0.15	A040	0.81	+/-	0.03	2.7	0.78	+/-	0.08	9.6	0.08	+/- 0.08 273.4
26	5.25	+/- 0.15	A062	0.51	+/-	0.02	4.0	0.52	+/-	0.05	9.4	0.01	+/- 0.05 45.5
27				NOT USED									
28													
29													
30													
31													
32													
33													
34													
35													

**Note** -This table of excess Pb-210 has not been adjusted for sand, silt or clay content. (adjusted data, if applicable, can be found at the end of this sheet).

### Po-210 Activities

Highest 3.3494 dpm/g  
Lowest 0.5062 dpm/g  
Mean 1.0636 dpm/g  
Number 15

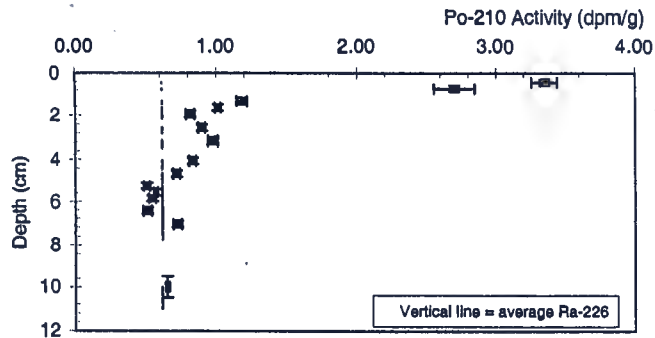
### Ra-226 Activities

Highest 0.7821 dpm/g  
Lowest 0.4947 dpm/g  
Mean 0.6114 dpm/g  
Number 15

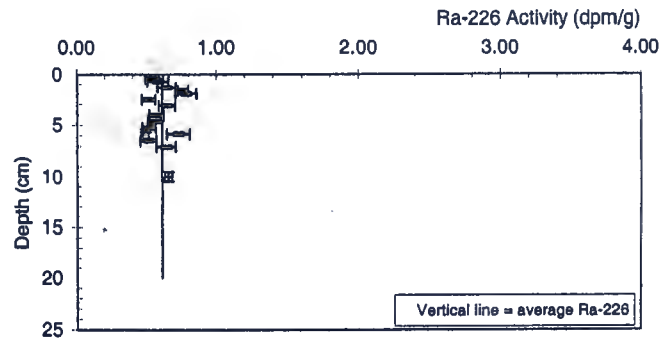
### Excess Pb-210 Activities

Highest 2.7921 dpm/g  
Lowest -0.1851 dpm/g  
Mean 0.4522 dpm/g  
Number 15

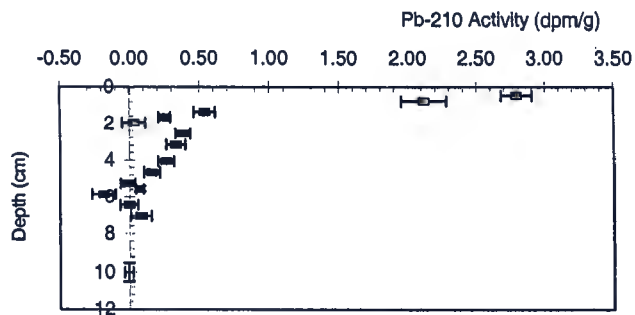
**Plot of Po-210 Activity vs Depth**



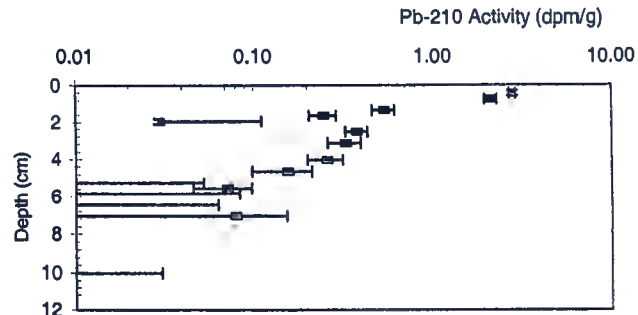
**Plot of Ra-226 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**



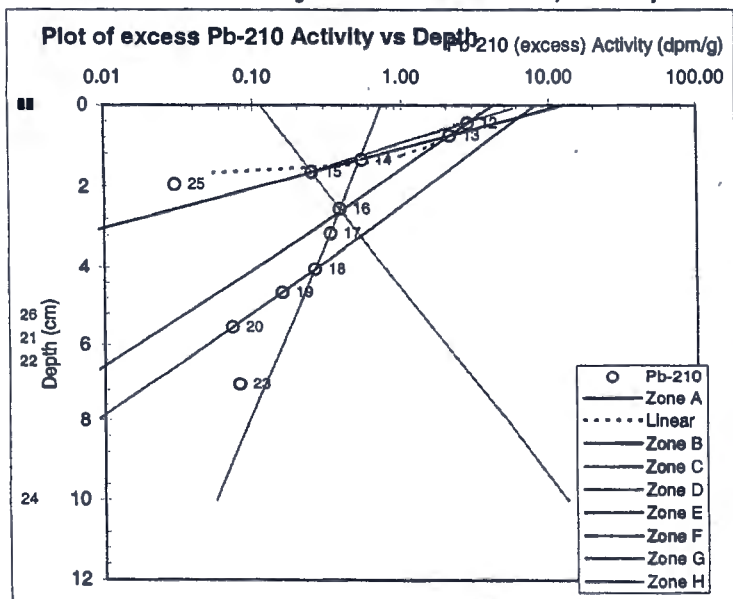


## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: **Unaltered for sand, silt or clay content**



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

Row No.	Depth	Sedimentation Rate		Correlation Coefficient	
		Linear Relationship	(%)	(r <sup>2</sup> )	
12 13	0 - 1	Zone A = 0.038 +/- 0.000 cm/ye	0.0	1.0000	
Exponential Relationship					
12 13	0 - 1	Zone A = 0.034 +/- 0.000 cm/ye	0.0	1.0000	
13 15	1 - 2	Zone B = 0.013 +/- 0.004 cm/ye	32.7	0.9991	
15 16	2 - 3	Zone C = -0.066 +/- 0.000 cm/ye	0.0	1.0000	
16 18	2 - 4	Zone D = 0.120 +/- 0.009 cm/ye	7.8	0.9992	
18 20	4 - 6	Zone E = 0.037 +/- 0.000 cm/ye	0.7	1.0000	
0 0		Zone F = #DIV/0! +/- #DIV/0! cm/ye	####	0.0000	
0 0		Zone G = #DIV/0! +/- #DIV/0! cm/ye	####	0.0000	
0 0		Zone H = #DIV/0! +/- #DIV/0! cm/ye	####	0.0000	

**Note:** A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs.

### Constant Initial Concentration (CIC) Model

### Calculated Sediment Age versus Depth Profile

In the case where Zone A incorporates a 'mixed surface layer' the zone immediately below this (Zone B) is used to construct the Age versus Depth profile.

[illegible]

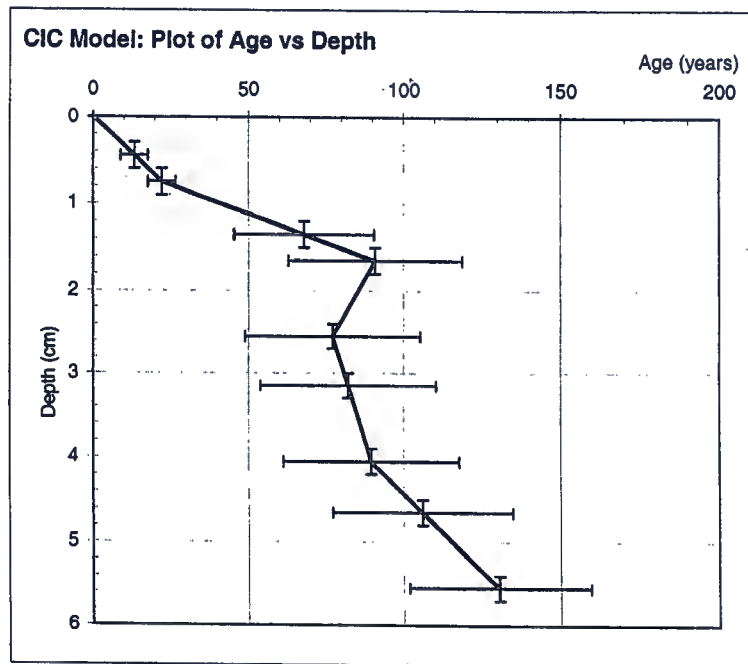
The Excess Pb-210 data below has been derived from a set of **Unaltered original data** and forms the basis of all the plots

Row No.	Activity of Excess Pb-210 as at 0-Jan-00			
	(dpm/g)	(dpm/g)	(%)	
12	2.79 +/-	0.11	4.1	
13	2.12 +/-	0.16	7.8	
14	0.54 +/-	0.08	14.2	
15	0.25 +/-	0.04	17.2	
16	0.38 +/-	0.05	14.1	
17	0.33 +/-	0.07	20.9	
18	0.26 +/-	0.06	22.3	
19	0.15 +/-	0.06	36.8	
20	0.07 +/-	0.03	35	
21	0.00 +/-	0.08	84005	
22	0.00 +/-	0.06	63561	
23	0.08 +/-	0.07	92	
24	0.00 +/-	0.03	30665	
25	0.03 +/-	0.08	273	
26	0.00 +/-	0.05	52723	
27				
28				
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30				
31				
32				
33				
34				
35				

## Constant Initial Concentration (CIC) Model

### Cautionary Note

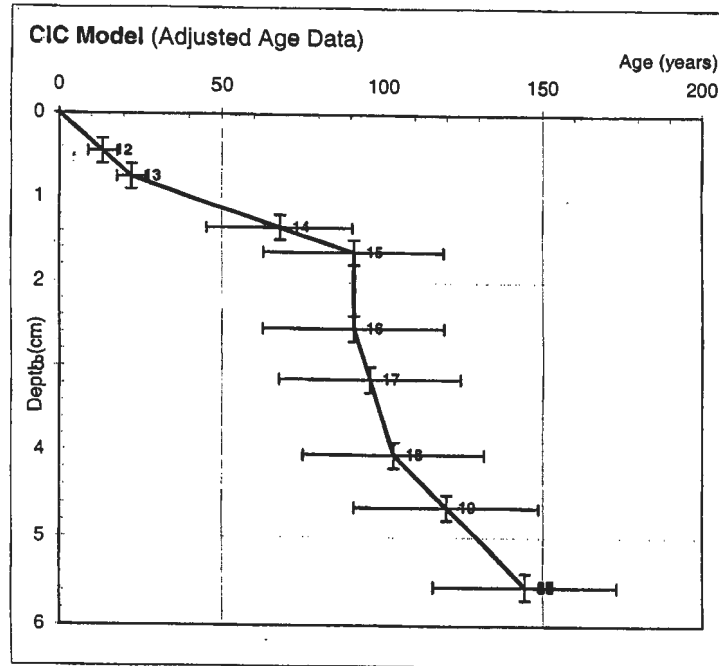
In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.



**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

### Adjusted Age Data

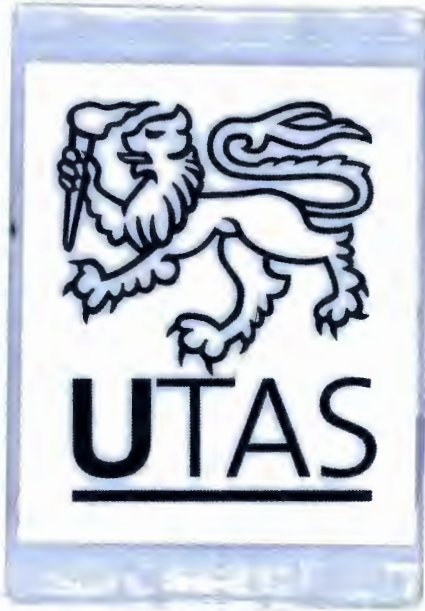
The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.



**Note** - If required the Cumulative Age Change data can be overwritten to force a manual age adjustment.

Original Age	Age Change	Cumulative Age Change	Adjusted Age Data		
			(year)	(year)	(%)
			0	0	
13.3	0	0	13.3 +/-	4.4	33.3
22.2	0	0	22.2 +/-	4.4	20.0
68.0	0	0	68.0 +/-	22.5	33.1
90.8	0	0	90.8 +/-	28.0	30.8
77.1	13.72762	13.72762	90.8 +/-	28.2	31.0
82.1	0	13.72762	95.8 +/-	28.2	29.5
89.6	0	13.72762	103.3 +/-	28.3	27.4
106.0	0	13.72762	119.7 +/-	28.8	24.1
130.6	0	13.72762	144.3 +/-	28.8	20.0

*Brown Bay Core 2*



**Australian Nuclear Science and Technology Organisation**  
PMB 1 Menai, NSW, 2234, Australia.

**Contact:** Andrew Jenkinson  
**Telephone:** (02) 9717 3478  
**E-mail:** [avj@ansto.gov.au](mailto:avj@ansto.gov.au)

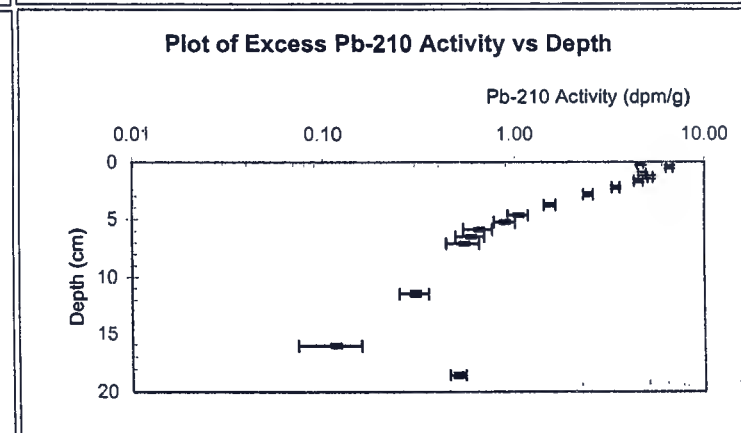
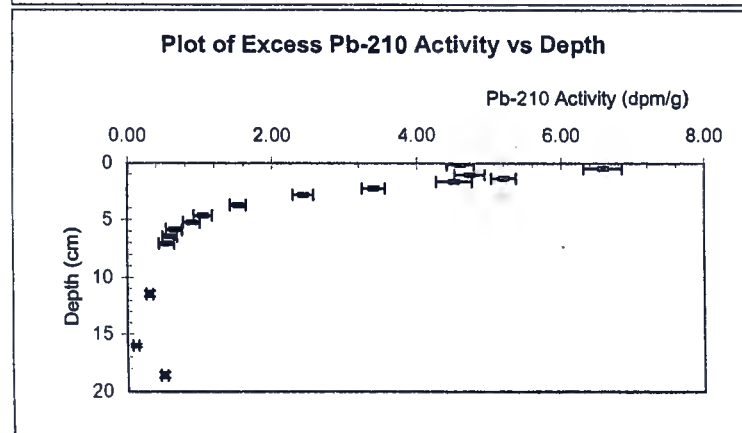
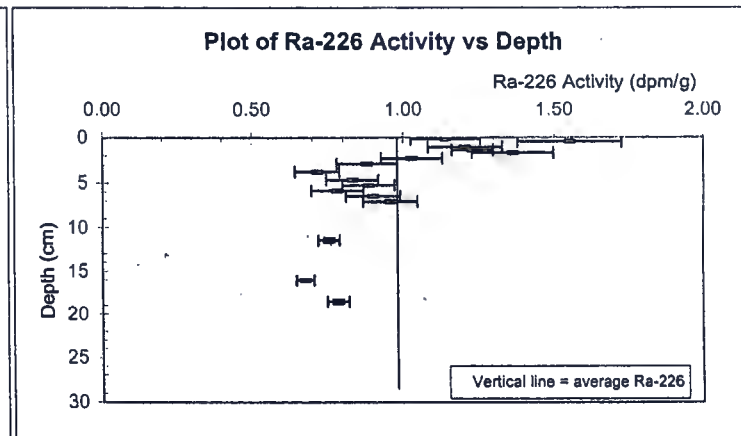
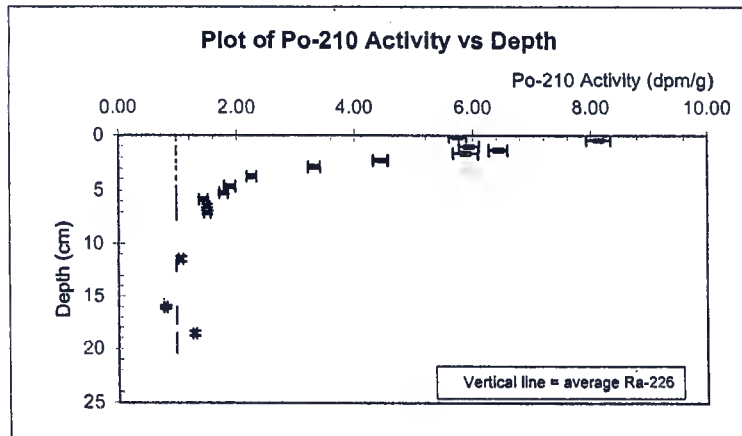
## CERTIFICATE OF ANALYSIS

**Client Name:** Beck Scouller  
**Client Institution:** Australian Antarctic Division

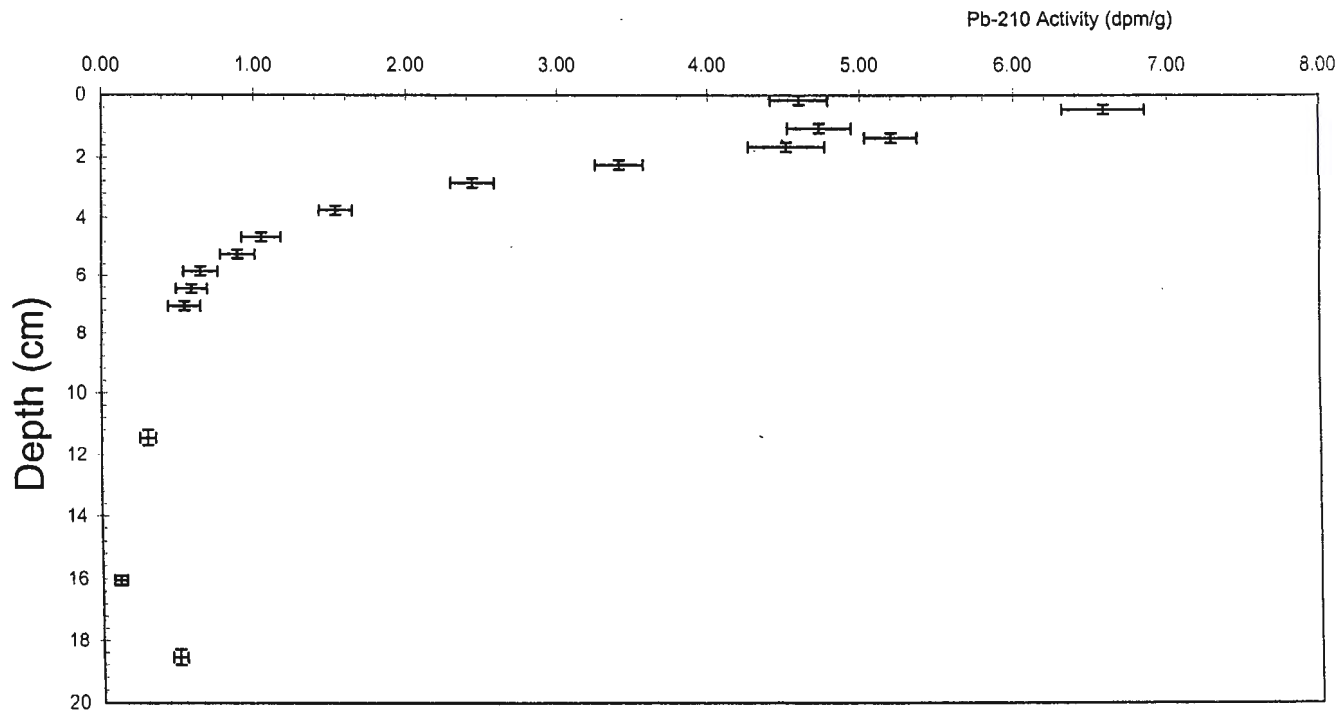
Project Title: 2001rc0135, 2001RC0042  
Core Description: Brown Bay Outer #2

Sampling Date 0-Jan-00  
ANSTO Ref: 0

[illegible]



## Plot of Excess Pb-210 Activity vs Depth



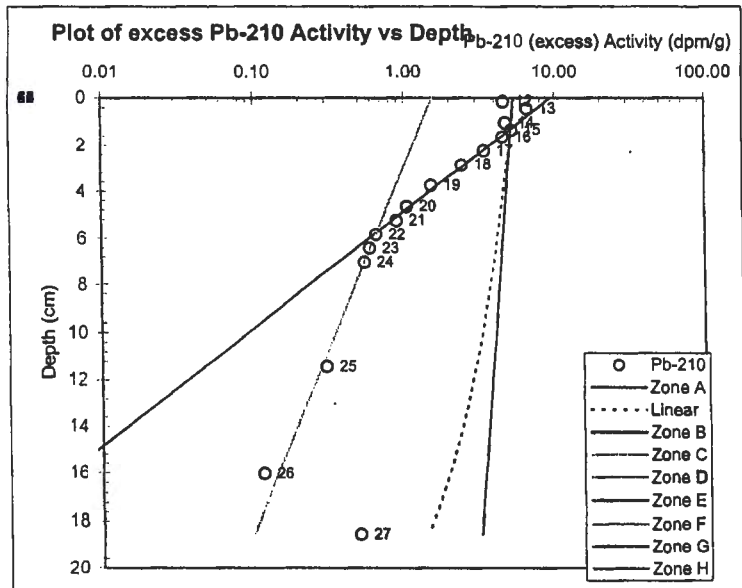


## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: Unaltered for sand, silt or clay content



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

Sedimentation Rate				Correlation Coefficient	
Linear Relationship					
Row No.	Depth			(%)	(r^2)
12 15	0 - 2 Zone A =	0.561 +/-	2.983 cm/year	531.7	0.0174
Exponential Relationship					
Row No.	Depth			(%)	(r^2)
12 15	0 - 2 Zone A =	1.090 +/-	8.204 cm/year	752.3	0.0093
15 22	1 - 6 Zone B =	0.067 +/-	0.003 cm/year	4.4	0.9957
22 24	6 - 7 Zone C =	0.209 +/-	0.012 cm/year	5.9	0.9988
0 0	Zone D =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone E =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone F =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone G =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone H =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000

Note: A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs.

### Constant Initial Concentration (CIC) Model

### Calculated Sediment Age versus Depth Profile

In the case where Zone A incorporates a 'mixed surface layer' the zone immediately below this (Zone B) is used to construct the Age versus Depth profile.

[illegible]

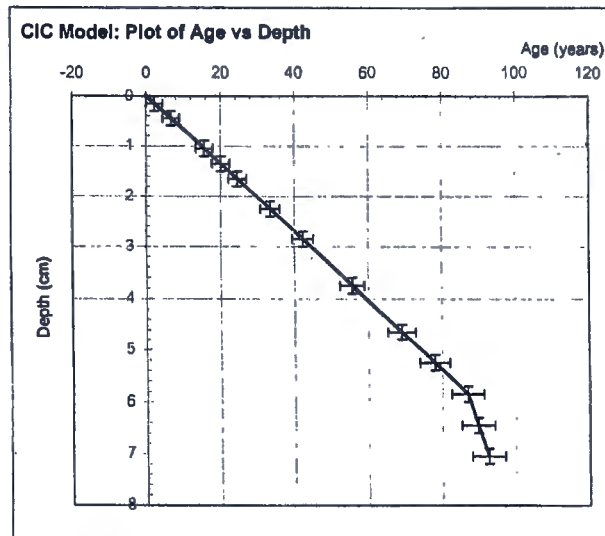
The Excess Pb-210 data below has been derived from a set of Unaltered original data and forms the basis of all the plots

Row No.	Activity of Excess Pb-210 as at 0-Jan-00		
	(dpm/g)	(dpm/g)	(%)
12	4.60 +/-	0.19	4.1
13	6.58 +/-	0.27	4.1
14	4.73 +/-	0.21	4.4
15	5.20 +/-	0.17	3.3
16	4.52 +/-	0.25	5.6
17	3.41 +/-	0.16	4.7
18	2.43 +/-	0.14	5.9
19	1.53 +/-	0.11	7.2
20	1.05 +/-	0.13	12.2
21	0.89 +/-	0.11	12.7
22	0.65 +/-	0.11	17.1
23	0.59 +/-	0.10	17.2
24	0.54 +/-	0.11	19.4
25	0.30 +/-	0.05	17.4
26	0.12 +/-	0.04	35.9
27	0.50 +/-	0.05	9.4
28			
29			
30			
31			
32			
33			
34			
35			

## Constant Initial Concentration (CIC) Model

### Cautionary Note

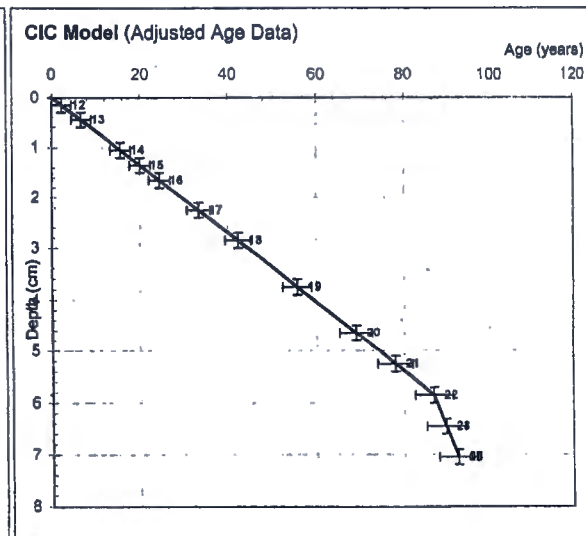
In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.



**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

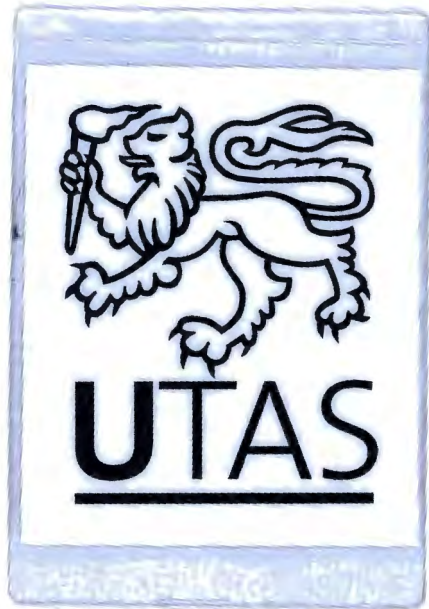
### Adjusted Age Data

The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.



## Appendix 3

Sampling details and  $\text{Pb}^{210}$  results pertaining to Chapter 7.



Brown Bay Core 1



Contact: Andrew Jenkinson  
Telephone: (02) 9717 3478  
E-mail: [avj@ansto.gov.au](mailto:avj@ansto.gov.au)

**Client Name:** Beck Scouller  
**Client Institution:** Australian Antarctic Division

Project Title: 2001rc0135\_2001RC0049  
Core Description: Brown Bay Outer #2

Sampling Date 0-Jan-00  
ANSTO Ref: 0

Row No.	Depth			ANSTO ID	Activity of Po-210 as at 0-Jan-00			Activity of Ra-226 as at 0-Jan-00			Activity of Excess Pb-210 as at 0-Jan-00			Note -This table of excess Pb-210 has not been adjusted for sand, silt or clay content.  (adjusted data, if applicable, can be found at the end of this sheet).			
	(cm)	+/-	(cm)		(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)				
12	0.15	+/-	0.15	A045	5.74	+/-	0.15	2.6	1.14	+/-	0.11	10.1	4.60	+/-	0.19	4.1	(adjusted data, if applicable, can be found at the end of this sheet).
13	0.45	+/-	0.15	A068	8.13	+/-	0.21	2.5	1.55	+/-	0.17	11.2	6.58	+/-	0.27	4.1	
14	1.05	+/-	0.15	A069	5.94	+/-	0.17	2.8	1.21	+/-	0.12	10.2	4.73	+/-	0.21	4.4	
15	1.35	+/-	0.15	c396	6.43	+/-	0.16	2.4	1.23	+/-	0.07	5.5	5.20	+/-	0.17	3.3	
16	1.65	+/-	0.15	A046	5.88	+/-	0.21	3.6	1.36	+/-	0.13	9.9	4.52	+/-	0.25	5.6	
17	2.25	+/-	0.15	A070	4.44	+/-	0.12	2.8	1.03	+/-	0.10	9.9	3.41	+/-	0.16	4.7	
18	2.85	+/-	0.15	A047	3.31	+/-	0.10	3.1	0.88	+/-	0.10	11.4	2.43	+/-	0.14	5.9	
19	3.75	+/-	0.15	A071	2.25	+/-	0.08	3.7	0.72	+/-	0.07	10.1	1.53	+/-	0.11	7.2	
20	4.65	+/-	0.15	A048	1.88	+/-	0.10	5.1	0.83	+/-	0.09	10.3	1.05	+/-	0.13	12.2	
21	5.25	+/-	0.15	A072	1.78	+/-	0.07	4.1	0.88	+/-	0.09	9.8	0.89	+/-	0.11	12.7	
22	5.85	+/-	0.15	A049	1.43	+/-	0.07	5.0	0.78	+/-	0.09	10.9	0.65	+/-	0.11	17.1	
23	6.45	+/-	0.15	A073	1.49	+/-	0.05	3.2	0.90	+/-	0.09	10.0	0.59	+/-	0.10	17.2	
24	7.05	+/-	0.15	A050	1.50	+/-	0.06	3.7	0.96	+/-	0.09	9.4	0.54	+/-	0.11	19.4	
25	11.25	+/-	0.25	c407	0.06	+/-	0.04	3.7	0.75	+/-	0.03	4.6	0.30	+/-	0.05	17.4	
26	16.15	+/-	0.15	c408	0.79	+/-	0.03	0.15	0.68	+/-	0.03	4.4	0.12	+/-	0.04	35.9	
27	18.55	+/-	0.25	c897	1.29	+/-	0.03	2.5	0.78	+/-	0.04	4.5	0.50	+/-	0.05	9.4	
28					No included												
29																	
30																	
31																	
32																	
33																	
34																	
35																	

**Po-210 Activities**

Highest      8.1342 dpm/g

Lowest        0.7917 dpm/g

Mean          3.3338 dpm/g

Number             16

**Ra-226 Activities**

Highest      1.5527 dpm/g

Lowest        0.6760 dpm/g

Mean          0.9803 dpm/g

Number             16

**Excess Pb-210 Activities**

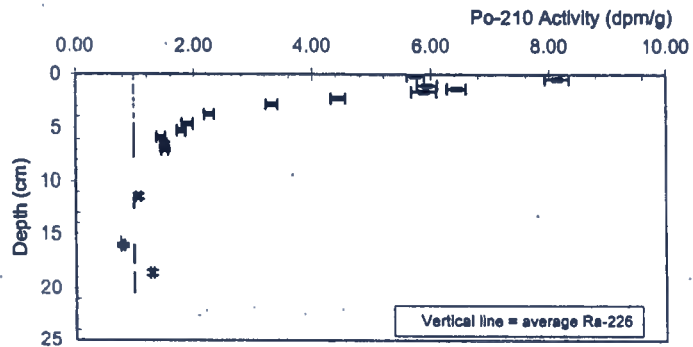
Highest      6.5815 dpm/g

Lowest        0.1157 dpm/g

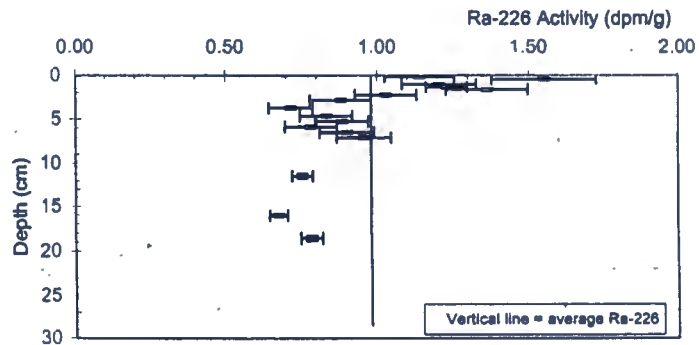
Mean          2.3535 dpm/g

Number             16

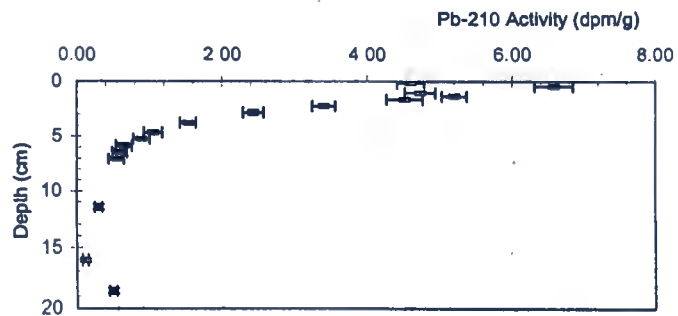
**Plot of Po-210 Activity vs Depth**



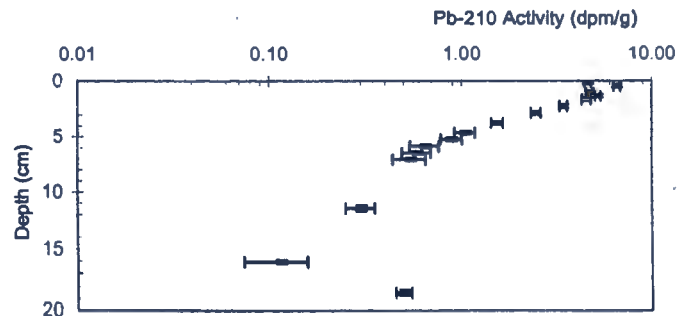
**Plot of Ra-226 Activity vs Depth**



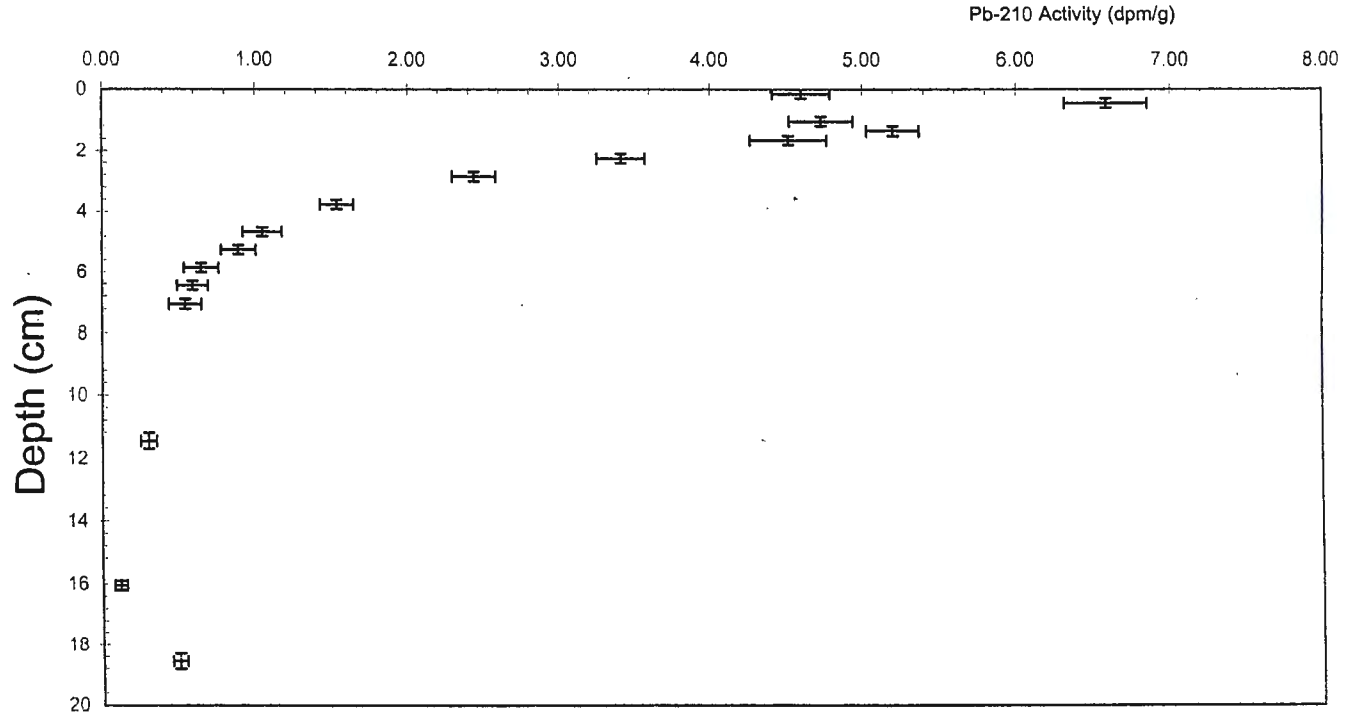
**Plot of Excess Pb-210 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**

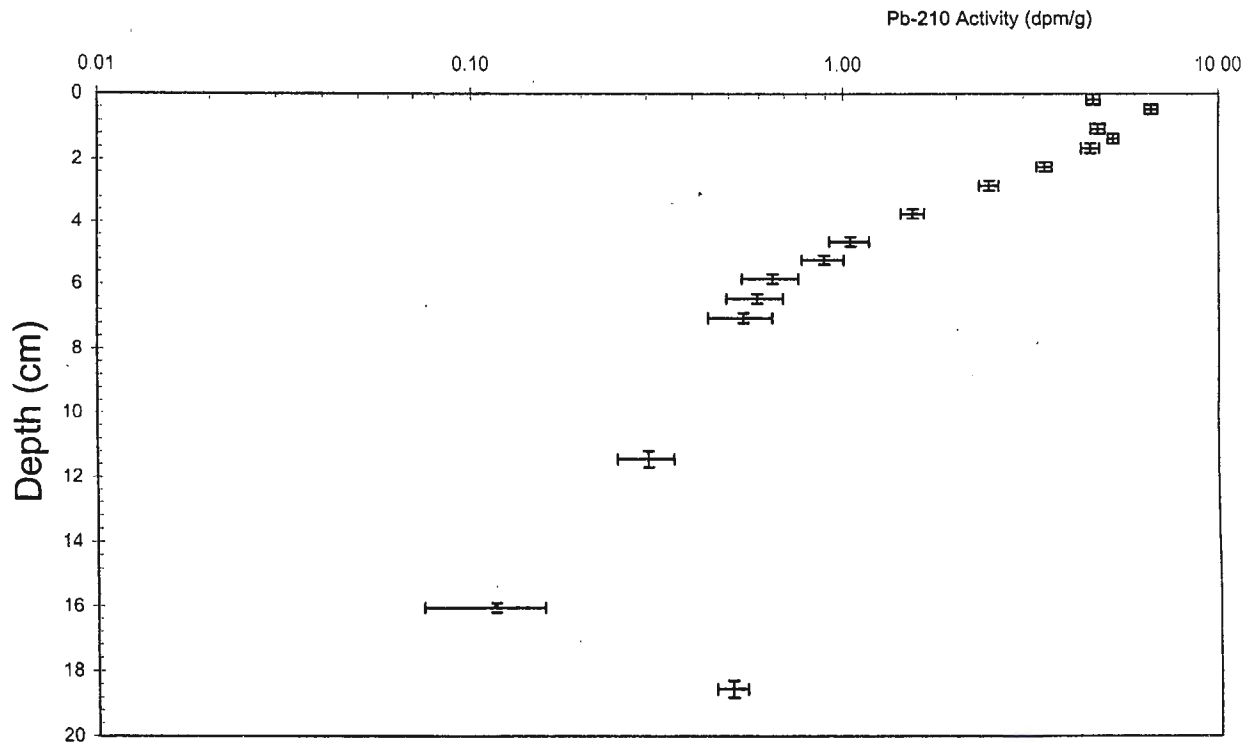


## Plot of Excess Pb-210 Activity vs Depth





## Plot of Excess Pb-210 Activity vs Depth



In the case where Zone A incorporates a 'mixed surface layer' the zone immediately below this (Zone B) is used to construct the Age versus Depth profile.

[illegible]

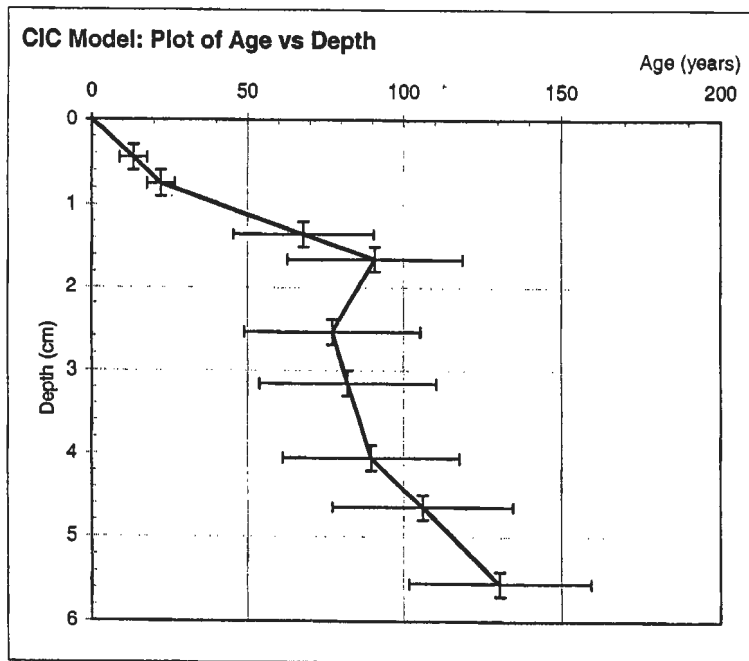
## Constant Initial Concentration (CIC) Model

The Excess Pb-210 data below has been derived from a set of **Unaltered original data** and forms the basis of all the plots

Row No.	Activity of Excess Pb-210 as at 0-Jan-00			
	(dpm/g)	+/-	(dpm/g)	(%)
12	2.79	+/-	0.11	4.1
13	2.12	+/-	0.16	7.8
14	0.54	+/-	0.08	14.2
15	0.25	+/-	0.04	17.2
16	0.38	+/-	0.05	14.1
17	0.33	+/-	0.07	20.9
18	0.26	+/-	0.06	22.3
19	0.15	+/-	0.06	36.8
20	0.07	+/-	0.03	35
21	0.00	+/-	0.08	84005
22	0.00	+/-	0.06	63561
23	0.08	+/-	0.07	92
24	0.00	+/-	0.03	30665
25	0.03	+/-	0.08	273
26	0.00	+/-	0.05	52723
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34				
35				

### Cautionary Note

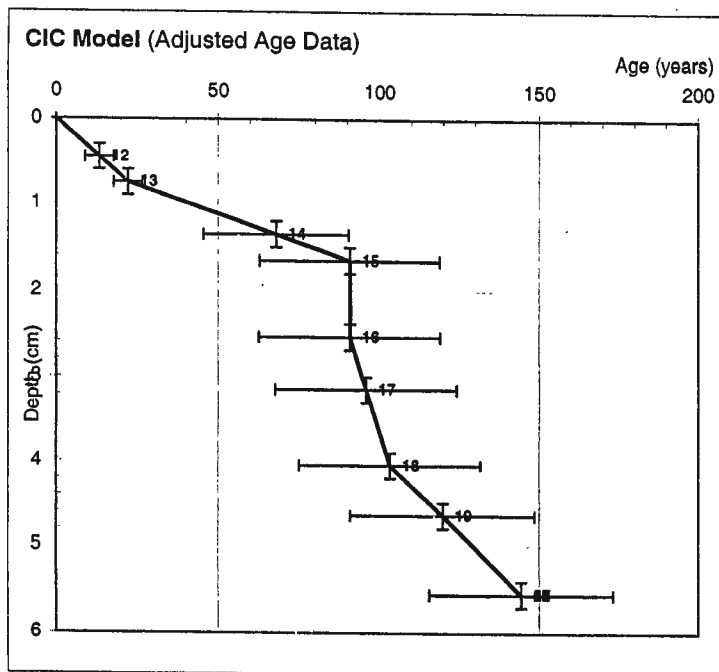
In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.



**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

### Adjusted Age Data

The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.

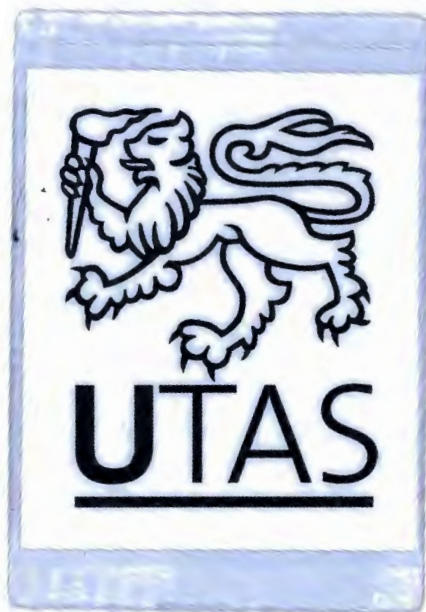


**Note** - If required the Cumulative Age Change

data can be overwritten to force a manual age adjustment.

Original Age	Age Change	Cumulative Age Change	Adjusted Age Data		
			(year)	(year)	(%)
			0	0	
13.3	0	0	13.3 +/-	4.4	33.3
22.2	0	0	22.2 +/-	4.4	20.0
68.0	0	0	68.0 +/-	22.5	33.1
90.8	0	0	90.8 +/-	28.0	30.8
77.1	13.72762	13.72762	90.8 +/-	28.2	31.0
82.1	0	13.72762	95.8 +/-	28.2	29.5
89.6	0	13.72762	103.3 +/-	28.3	27.4
106.0	0	13.72762	119.7 +/-	28.8	24.1
130.6	0	13.72762	144.3 +/-	28.8	20.0

Brown Bay Core 2



## CERTIFICATE OF ANALYSIS

Client Name: **Beck Scouller**  
Client Institution: **Antarctic Division**

Project Title: **2001RC0134, 2000RC0041**  
Core Descriptive **Brown Bay Outer #1**

Sampling Date: **0-Jan-00**  
ANSTO Ref: **0**

Row No.	Depth		ANSTO ID	Activity of Po-210 as at 0-Jan-00			Activity of Ra-226 as at 0-Jan-00			Activity of Excess Pb-210 as at 0-Jan-00		
	(cm)	(cm)		(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)	(dpm/g)	(dpm/g)	(%)
12	0.45	+/- 0.15	A058	3.35	+/- 0.09	2.8	0.56	+/- 0.06	11.4	2.79	+/- 0.11	4.1
13	0.75	+/- 0.15	A039	2.70	+/- 0.15	5.4	0.58	+/- 0.08	12.9	2.12	+/- 0.16	7.8
14	1.35	+/- 0.15	A059	1.18	+/- 0.04	3.2	0.64	+/- 0.07	10.2	0.54	+/- 0.08	14.2
15	1.65	+/- 0.15	c393	1.01	+/- 0.02	2.0	0.76	+/- 0.04	4.9	0.25	+/- 0.04	17.2
16	2.55	+/- 0.15	A060	0.89	+/- 0.03	2.8	0.51	+/- 0.05	9.1	0.38	+/- 0.05	14.1
17	3.15	+/- 0.15	A041	0.97	+/- 0.04	3.6	0.65	+/- 0.06	9.1	0.33	+/- 0.07	20.9
18	4.05	+/- 0.15	A061	0.83	+/- 0.02	3.0	0.57	+/- 0.05	9.0	0.26	+/- 0.06	22.3
19	4.65	+/- 0.15	A042	0.72	+/- 0.02	3.4	0.56	+/- 0.05	9.2	0.15	+/- 0.06	36.8
20	5.55	+/- 0.15	A094	0.57	+/- 0.01	2.6	0.49	+/- 0.02	21.3	0.07	+/- 0.03	35.4
21	5.85	+/- 0.15	A043	0.54	+/- 0.02	4.0	0.76	+/- 0.05	11.1	0.19	+/- 0.08	45.4
22	6.45	+/- 0.15	A063	0.51	+/- 0.05	5.4	0.54	+/- 0.05	11.2	0.00	+/- 0.06	1589.0
23	7.05	+/- 0.15	A044	0.72	+/- 0.06	5.6	0.64	+/- 0.07	10.7	0.08	+/- 0.07	91.6
24	10.15	+/- 0.5	A095	0.65	+/- 0.01	2.6	0.65	+/- 0.01	4.1	0.01	+/- 0.03	451.8
25	11.95	+/- 0.15	A040	0.43	+/- 0.06	6.7	0.76	+/- 0.08	9.6	0.03	+/- 0.08	27.4
26	15.25	+/- 0.15	A062	0.51	+/- 0.02	4.0	0.52	+/- 0.05	9.4	0.01	+/- 0.05	454.5
27				OUT OF SEQUENCE								
28												
29												
30												
31												
32												
33												
34												
35												

**Note** - This table of excess Pb-210 has not been adjusted for sand, silt or clay content. (adjusted data, if applicable, can be found at the end of this sheet).

### Po-210 Activities

Highest 3.3494 dpm/g  
Lowest 0.5062 dpm/g  
Mean 1.0636 dpm/g  
Number 15

### Ra-226 Activities

Highest 0.7821 dpm/g  
Lowest 0.4947 dpm/g  
Mean 0.6114 dpm/g  
Number 15

### Excess Pb-210 Activities

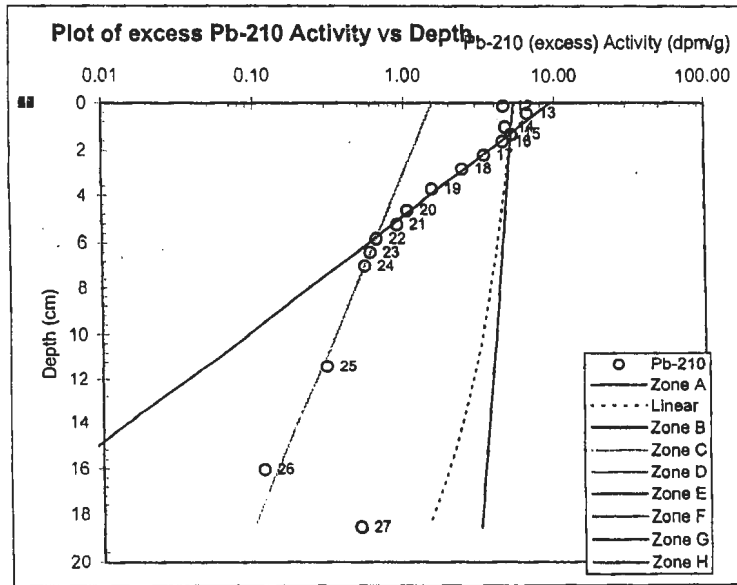
Highest 2.7921 dpm/g  
Lowest -0.1851 dpm/g  
Mean 0.4522 dpm/g  
Number 15

## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: Unaltered for sand, silt or clay content



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

Row No.	Depth	Sedimentation Rate		Correlation Coefficient	
		Linear Relationship		(%)	(r <sup>2</sup> )
12 15	0 - 2 Zone A =	0.561 +/-	2.983 cm/year	531.7	0.0174
Exponential Relationship					
12 15	0 - 2 Zone A =	1.090 +/-	8.204 cm/year	752.3	0.0093
15 22	1 - 6 Zone B =	0.067 +/-	0.003 cm/year	4.4	0.9957
22 24	6 - 7 Zone C =	0.209 +/-	0.012 cm/year	5.9	0.9988
0 0	Zone D =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone E =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone F =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone G =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000
0 0	Zone H =	#DIV/0! +/-	#DIV/0! cm/year	####	0.0000

**Note:** A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs.

### Calculated Sediment Age versus Depth Profile

[illegible]



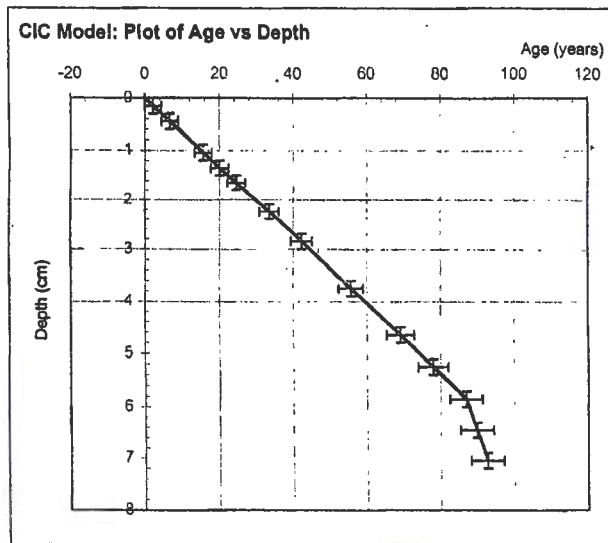
The Excess Pb-210 data below has been derived from a set of Unaltered original data and forms the basis of all the plots

Row No.	Activity of Excess Pb-210 as at 0-Jan-00			
	(dpm/g)	(dpm/g)	(%)	
12	4.60 +/-	0.19	4.1	
13	6.58 +/-	0.27	4.1	
14	4.73 +/-	0.21	4.4	
15	5.20 +/-	0.17	3.3	
16	4.52 +/-	0.25	5.6	
17	3.41 +/-	0.16	4.7	
18	2.43 +/-	0.14	5.9	
19	1.53 +/-	0.11	7.2	
20	1.05 +/-	0.13	12.2	
21	0.89 +/-	0.11	12.7	
22	0.65 +/-	0.11	17.1	
23	0.59 +/-	0.10	17.2	
24	0.54 +/-	0.11	19.4	
25	0.30 +/-	0.05	17.4	
26	0.12 +/-	0.04	35.9	
27	0.50 +/-	0.05	9.4	
28				
29				
30				
31				
32				
33				
34				
35				

## Constant Initial Concentration (CIC) Model

### Cautionary Note

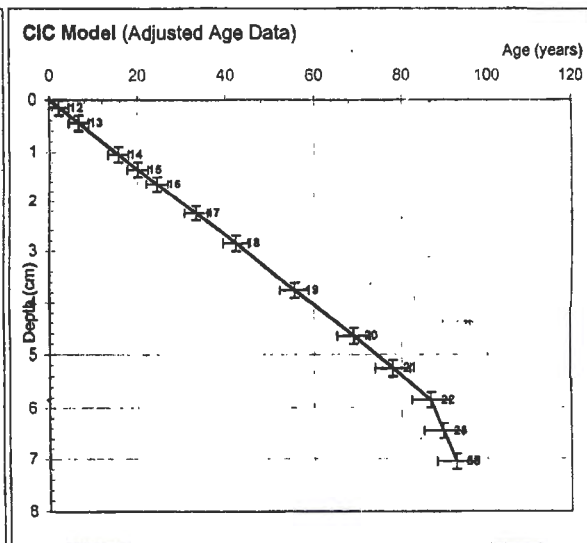
In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.



**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

### Adjusted Age Data

The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.



Brown Bay Core 3



**Contact:** Andrew Jenkinson  
**Telephone:** (02) 9717 3478  
**E-mail:** [avj@aristc.gov.au](mailto:avj@aristc.gov.au)

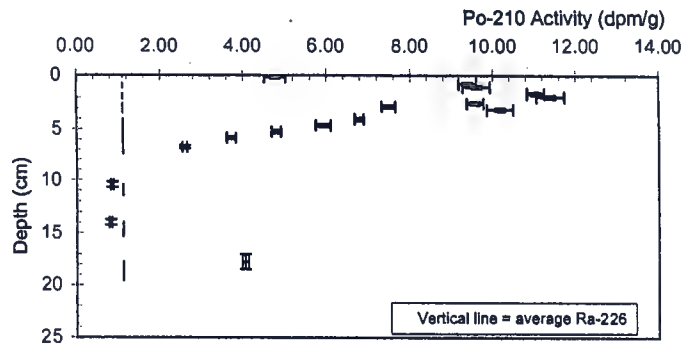
**Client Name:** Beck Scouller  
**Client Institution:** Antarctic Division

Project Title: 2000RC0040, 2001RC0133  
Core Description: Brown Bay Middle core

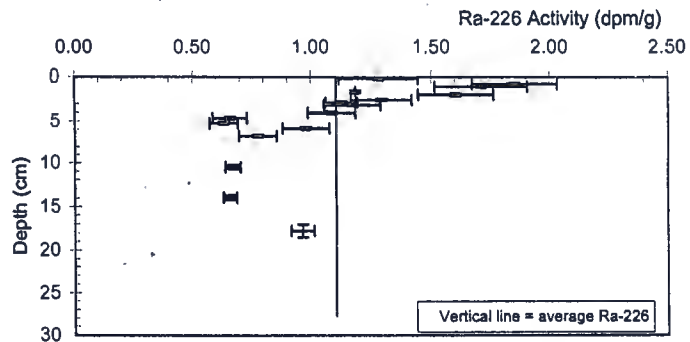
Sampling Date 0-Jan-00  
ANSTO Ref: 0

[illegible]

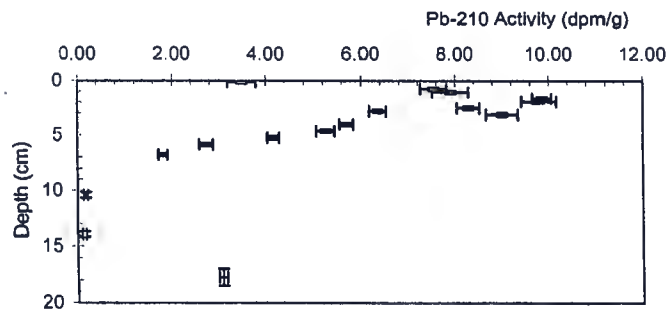
**Plot of Po-210 Activity vs Depth**



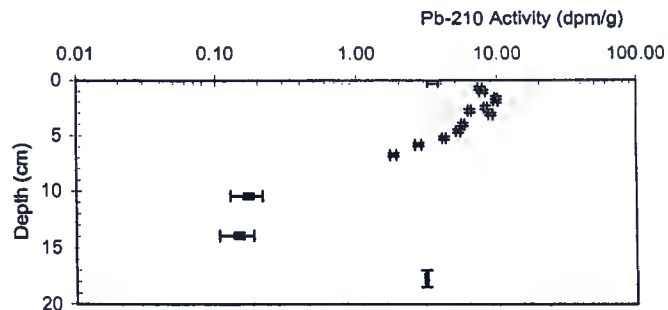
**Plot of Ra-226 Activity vs Depth**



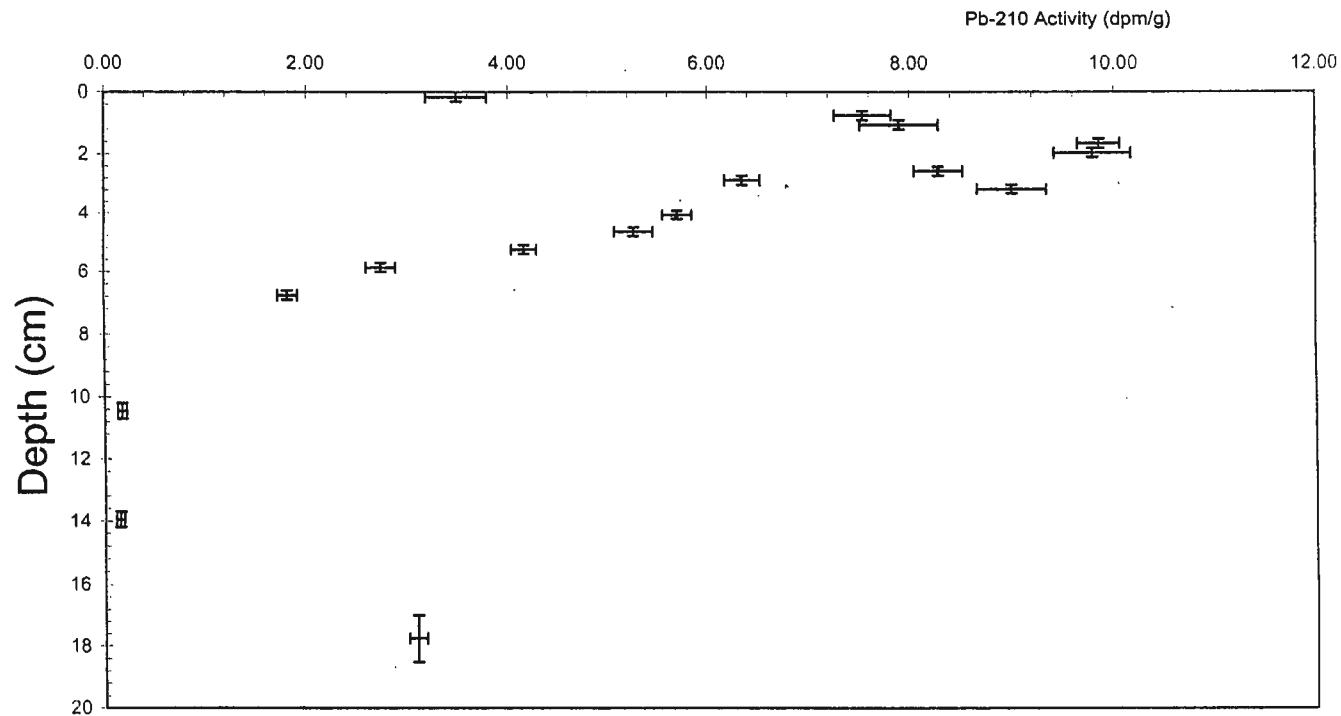
**Plot of Excess Pb-210 Activity vs Depth**



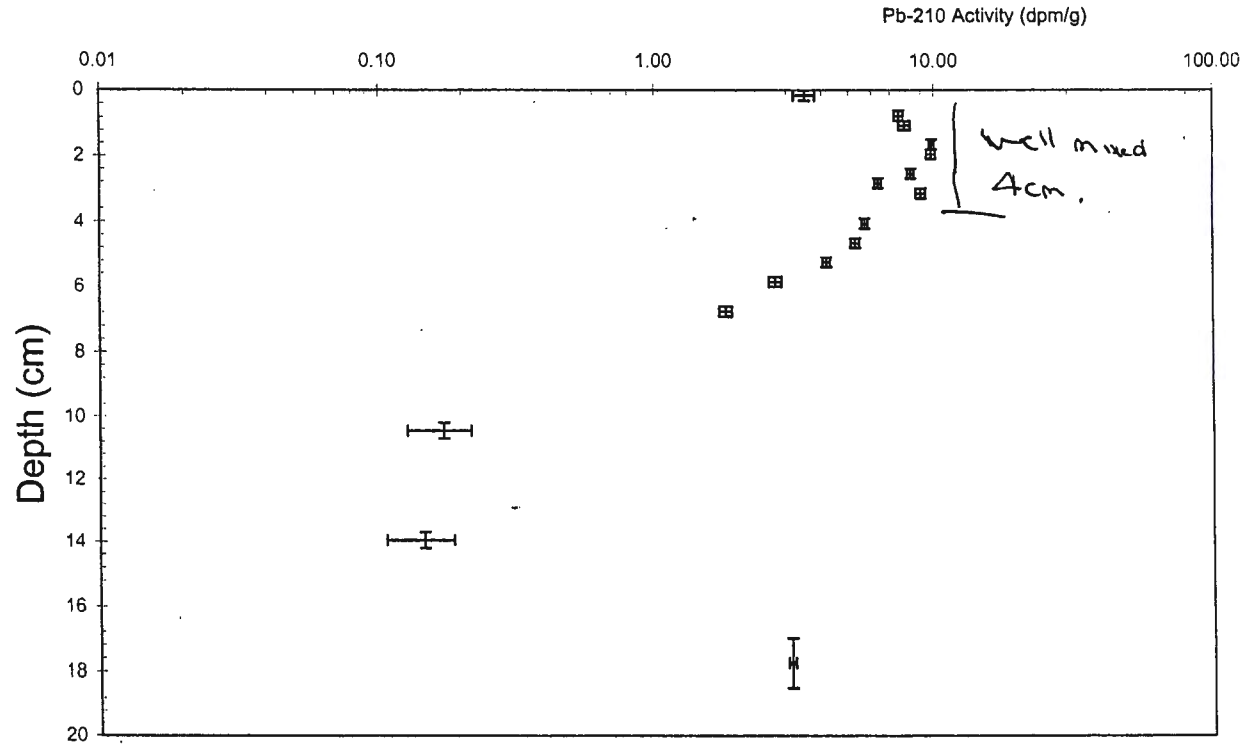
**Plot of Excess Pb-210 Activity vs Depth**



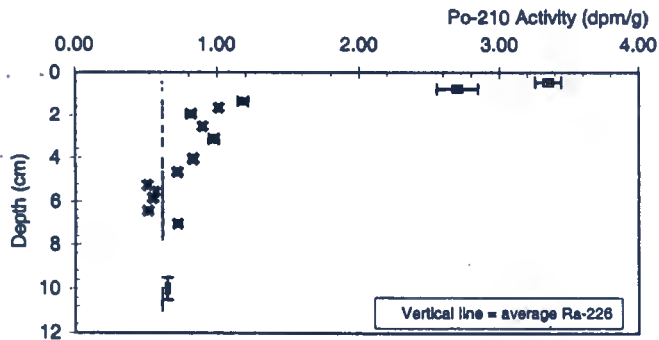
## Plot of Excess Pb-210 Activity vs Depth



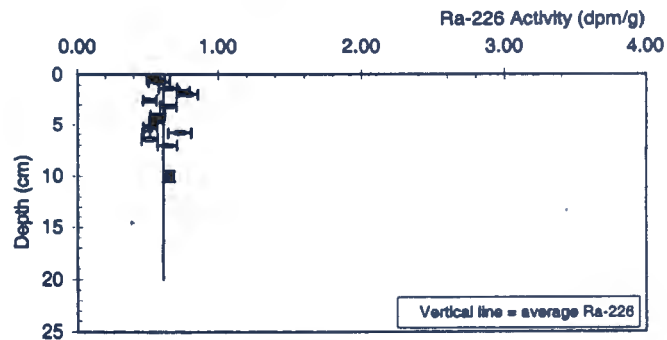
## Plot of Excess Pb-210 Activity vs Depth



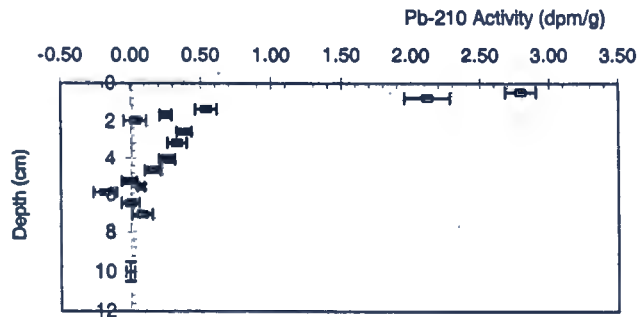
**Plot of Po-210 Activity vs Depth**



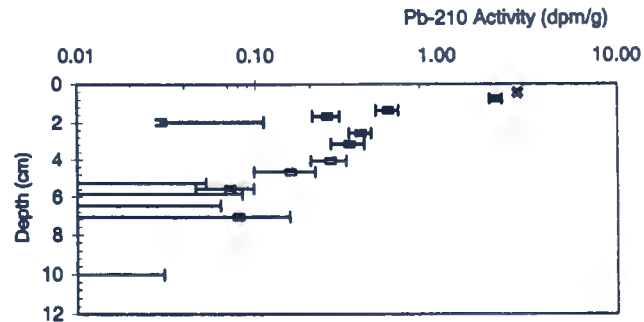
**Plot of Ra-226 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**



**Plot of Excess Pb-210 Activity vs Depth**

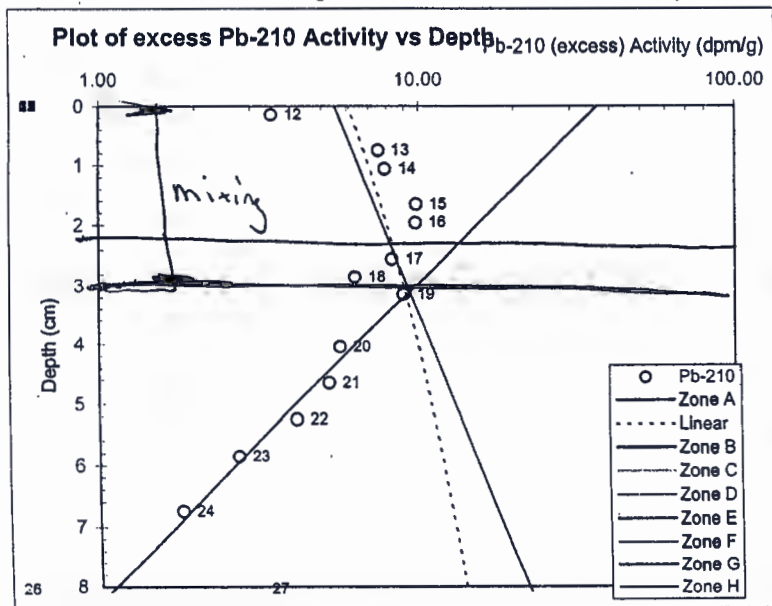


## Constant Initial Concentration (CIC) Model - Stepwise Linear Variant

### Model Assumptions

This model assumes that each horizon in the sediment is derived from material having the same initial excess Pb-210 activity. This would be the case if the Pb-210 flux at the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial excess Pb-210 activity.

Excess Pb-210 data set being used is: Unaltered for sand, silt or clay content



### Model Application

The CIC model is appropriate when input of excess Pb-210 occurs predominantly via the erosion of catchment surfaces. This would be the case for example when a small water body is located in a relatively large catchment area.

### Sedimentation Rate (CIC Model)

		Sedimentation Rate		Correlation Coefficient	
		Linear Relationship			
Row No.	Depth		(%)	(r <sup>2</sup> )	
12 19	0 - 3 Zone A =	-0.138 +/- -0.099 cm/year	71.8	0.2488	
		Exponential Relationship			
Row No.	Depth		(%)	(r <sup>2</sup> )	
12 19	0 - 3 Zone A =	-0.181 +/- -0.098 cm/year	54.2	0.2916	
19 24	3 - 7 Zone B =	0.071 +/- 0.008 cm/year	11.8	0.9775	
0 0	Zone C =	#DIV/0! +/- #DIV/0! cm/year	####	0.0000	
0 0	Zone D =	#DIV/0! +/- #DIV/0! cm/year	####	0.0000	
0 0	Zone E =	#DIV/0! +/- #DIV/0! cm/year	####	0.0000	
0 0	Zone F =	#DIV/0! +/- #DIV/0! cm/year	####	0.0000	
0 0	Zone G =	#DIV/0! +/- #DIV/0! cm/year	####	0.0000	
0 0	Zone H =	#DIV/0! +/- #DIV/0! cm/year	####	0.0000	

**Note:** A Linear Relationship (curved dotted line) is appropriate when a mixed surface layer is evident in Zone A. All other zones will be represented by exponential curves which plot as straight lines on log-linear graphs.



### Constant Initial Concentration (CIC) Model

### Calculated Sediment Age versus Depth Profile

In the case where Zone A incorporates a 'mixed surface layer' the zone immediately below this (Zone B) is used to construct the Age versus Depth profile.

[illegible]

The Excess Pb-210 data below has been derived from a set of Unaltered original data and forms the basis of all the plots

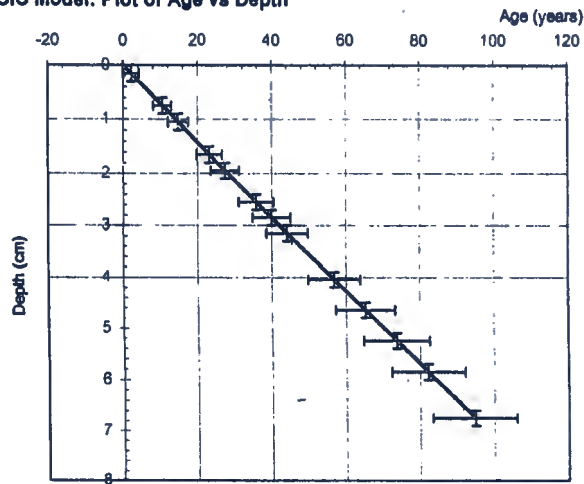
Row No.	Activity of Excess Pb-210 as at 0-Jan-00			
	(dpm/g)	+/-	(dpm/g)	(%)
12	3.49	+/-	0.30	8.7
13	7.54	+/-	0.28	3.7
14	7.90	+/-	0.38	4.9
15	9.85	+/-	0.20	2.1
16	9.79	+/-	0.37	3.8
17	8.28	+/-	0.24	2.9
18	6.39	+/-	0.18	2.8
19	9.01	+/-	0.34	3.8
20	5.70	+/-	0.15	2.6
21	5.26	+/-	0.19	3.7
22	4.16	+/-	0.13	3.0
23	2.73	+/-	0.15	5.4
24	1.81	+/-	0.10	5.3
25	0.17	+/-	0.04	25.8
26	0.15	+/-	0.04	27.3
27	3.08	+/-	0.09	2.9
28				
29				
30				
31				
32				
33				
34				
35				

## Constant Initial Concentration (CIC) Model

### Cautionary Note

In interpreting the graph below it is important to take into consideration the impact of any "horizontal shift or break" in the sedimentation rate regime as observed in the "Plot of Excess Pb-210 versus Depth" profile.

CIC Model: Plot of Age vs Depth



**Bold Numbers** - Numbers in bold refer to row numbers in spreadsheet and are not depths or sample ID's.

### Adjusted Age Data

The graph below has been constructed by eliminating any "negative ages" which the calculations sometimes produce. It is up to the end user to ascertain the appropriateness of such a correction.

CIC Model (Adjusted Age Data)

