Reconstruction of lake-water salinity from fossil diatom assemblages in saline lakes of the Vestfold Hills, Antarctica.

by

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&

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"From a drop of water, a logician could infer the possibility of an Atlantic or Niagara, without having seen or heard of one or the other."

Sherlock Holmes

A Study in Scarlet
Sir Arthur Conan Doyle

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university, and to the best of my knowledge contains no copy or paraphrase of material previously published or written by another person, except where due reference is made in the text.

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Abstract

Polar lake environments provide an essentially undistubed ecosystem to research and their water chemistries are often the result of climatic influences throughout their histories. Salinity, in particular, has a clear relationship with changing precipitation and evaporation in polar lake environments, thus changes in lakewater salinity can be related to the climatic regime of polar lakes basins. By exploring thc rclationship between diatom assemblages and limnological environmental variables in Antarctic saline lakes, fossil diatom assemblages enable palaeo-lake water variables in these lake ecosystems to be quantified.

Canonical correspondence analysis of the relationship between surface sediment diatom assemblages and measured limnological variables in thirty-three coastal Antarctic lakes revealed that salinity accounted for a significant amount of the variation in the distribution of these diatom assemblages, revealing its value for limnological inference models in this coastal Antarctic region.

A weighted-averaging regression and calibration transfer function developed from this diatom-salinity relationship enables the reconstruction of past lakewater salinity from fossil diatom assemblages. Application of this palaeosalinity reconstruction tool to four lake sediment cores collected from lakes representative of the range of current salinities in the Vestfold Hills (fresh to markedly hypersaline) allows the timing and extent of the salinity development of these currently different lake environments to be determined.

Diatom stratigraphy of two lakes currently characterised by hypersaline and marine epilimnion lakewater salinity respectively revealed distinct changes in lake history. Initial lake assemblages are indicative of a freshwater community. Subsequent assemblages represent marine inlet and saline lake assemblages respectively. In both cores, core bottom assemblages produced a lakewater salinity of the order of 3 ‰ while core top assemblages produced a saline lakewater salinity of the order of 60 ‰. Diatom stratigraphy of the currently hyposaline lake revealed a history of continual salinity increase (of the order of 3 ‰ to 25 ‰) in this basin. Conversely, diatom stratigraphy of the freshwater lake revealed little salinity change throughout the core (~ 1 ‰ fluctuation) demonstrating the greater sensitivity of the saline lakes investigated as palaeoclimatic recorders.

Salinity has a clear relationship with changing precipitation and evaporation in polar lake environments. Therefore, changes in lakewater salinity allow inferences to be made about the changes in a lake basins local climate. Cycles of increasing and decreasing salinity within one of the saline lake cores demonstrates the effectiveness of the diatom-salinity transfer function as a proxy for inferring changes in water level and effective precipitation. Palaeolake precipitation estimates from these salinity and water level reconstructions show no significant trends in precipitation are detectable throughout the past ~ 700 years. There is certainly no identifiable increase in precipitation in the past two centuries as would be expected with anthropogenically influenced warming in such a region, revealing the usefulness of this tool for palaeoclimatic analyses in Antarctic limnological regions.

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Chapter 1: Introduction

1.1 The Problem

Historical records show that local, regional and global climates fluctuate in response to both natural and anthropogenic influences. The focus of much current climate change research is therefore on both present and past climate variability. A method of looking beyond instrumentally-measured climate change is needed to determine if past trends can allow future change to be predicted in a reliable and informative manner.

Detailed ecosystem-climate change research is critical for the development of accurate climate change models. Many lakes provide an undisturbed ecosystem to research and their water chemistries are often the result of climatic influences throughout their histories. Such research has been carried out in most lake provinces with a noticeable lack in continental Antarctica. Climate change is often detected first in the polar regions and these regions often have a disproportionate influence on global climatic processes. The absence of climate change analysis from the unique lake ecosystems of Antarctica needs to be addressed urgently.

The natural variability of past and present climate change needs to be understood before future climate changes can be predicted. The determination of natural climate change baselines will allow future changes in climate to be assessed in terms of their potential for benefit or detriment to biological systems worldwide.

Current predictive models suggest that increases in global anthropogenic greenhouse gases will be manifested as an increase in precipitation in coastal Antarctic regions (Kattenberg *et al.*, 1996). Warmer temperatures will lead to a more vigorous hydrological cycle which also suggests a possibility for more extreme rainfall events (Houghton *et al.*, 1996). It is not possible based on current knowledge to determine whether recent climate change in east Antarctic coastal areas are natural or influenced by anthropogenic processes.

1.2 Rationale for Current Research

Lakes in arid and semi-arid regions of the world respond particularly rapidly to climate-driven hydrological change. Fluctuations in the balance between precipitation and evaporation result in both changes in lake level and in the concentration or dilution of dissolved salts (Last & Slezak, 1988). Due to the sensitivity of lakewater chemistry to even small changes in the climate of these regions, salt lakes and their sedimentary biological communities are particularly well suited as sources of palaeoclimatic information (Williams 1981; Last & Schweyen 1983; Evans 1993). Fluctuations in water chemistry variables are recorded in a variety of palaeolimnological indicators, including the community composition of diatoms (Juggins *et al.*, 1994).

Diatoms are one of the most useful biological indicators. Fossil diatoms leave a record of past water chemistry, especially palaeosalinity, and also contribute to the measure of water level and climate change. Their use in reconstructing limnological variables, particularly pH (Gasse & Tekaia, 1983; Flower, 1986; Whitmore, 1989; Birks *et al.*, 1990; Cumming *et al.*, 1994), nutrients (Hall & Smol, 1992; Bennion, 1994; Zeeb *et al.*, 1994), and salinity (Fritz, 1990; Cumming & Smol, 1993; Fritz *et al.*, 1991; 1993; 1994; Wilson *et al.*, 1994; Gasse *et al.*, 1995) is well documented. They have been used extensively in temperate and tropical regions for reconstructing past changes in water chemistry and show great potential for studying environmental change in the Antarctic (Bjorck *et al.*, 1991; Wasell & Håkansson, 1993; Jones *et al.*, 1993; Jones & Juggins, 1995). The use of algal taxa as palaeoclimatic indicators is of special value in high latitudes because many other palaeolimnological methods, such as palynology, are often of limited usefulness in these environments (e.g. low concentrations of spores or pollen) (Smol *et al.*, 1995).

Antarctic lake sediment contains records from environments with little historical anthropogenic disturbance and allows current water chemistry-diatom relationships to be explored, documented and related to natural environmental variability. The natural variability of past climate change can thus be documented and related to modern climate change for a more complete understanding of the consequences of future climate changes and their impact on local Antarctic regions.

Continental Antarctic lakes are known from many eastern Antarctic ice-free regions, including the Syowa Oasis (e.g. Tominaga & Fukui, 1981), the Larsemann Hills (e.g. Gillieson, 1991), the Vestfold Hills (e.g. Pickard, 1986) and the Bunger Hills (e.g. Kaup *et al.*, 1993). The Vestfold Hills provides a particularly wide range of lakewater environments in which to investigate the response of diatom assemblages to past lakewater chemistries. As the ice sheet retreated from the Vestfold Hills, melt water and sea water filled the pre-existing low areas to form the lakes which are present today. The current water level and chemistry of each lake is a result of a limited number of factors: meteorological input (direct and from catchment area snow melt), and the loss through evaporation and ablation (Gibson & Burton, 1996). The variety of water chemistries that occur in the lakes of the Vestfold Hills are used to explore the relationships that exist between diatom assemblages and water chemistry gradients. These relationships are then used to hindcast changes in the water chemistry of these systems from fossil diatom assemblages. Emphasis is placed on lake sediments as archives of climate change.

1.3 Objectives

The primary objective of this thesis is to use fossil diatom assemblages to quantify palaeo-lakewater variables in Antarctic lakes. This is done by:

1) exploring relationships between recent diatom assemblages and limnological environmental parameters;

2) determining which lake characteristics are most strongly related to the composition of surface sediment diatom assemblages;

3) modelling the response of the variables identified in 2) to allow these parameters to be calculated from the relative percentage of diatom species in lake sediment samples; and

4) extending this correlation to fossil sediment samples allowing palaeoenvironmental parameters to be estimated.

1.4 Limitations

Limitations of the research carried out herein are primarily contributed to by the nature of collecting from, analysing and understanding the Antarctic ecosystem. Logistical difficulties restricted contemporary lake sediment and water sampling to 33 lakes from an area of well over 300 lakes. Similarly, environmental variable sampling was restricted to salinity, nutrients and major ions although it is known that other environmental and biological factors, e. g. light penetration and grazing, have an effect on the diatom population of a lake.

1.5 Structure of Thesis

Antarctic limnological and palaeolimnological research is introduced and reviewed. The environmental reconstruction techniques necessary to extract palaeo-lakewater variables from the lake biota is then discussed and, finally, each objective as researched is documented and discussed in turn.

Chapter 2: Literature Review

2.1 Limnology

2.1.1 Introduction

The term limnology is derived from the Greek word limne meaning pool, marsh or lake, and was first defined by F. A. Forel (1892) as "the oceanography of lakes" (Cole, 1983). Many adaptations of this definition have been coined resulting in the modern definition of limnology as "the study of lakes, including their animal and plant life, the physical and chemical features of their waters, characteristics of the bottom sediment, and the relations of these to the physical, chemical, and biological features of the catchment area" (Birks & Birks, 1980).

A lake is the result of a number of factors including its geological origin, climatic processes in the catchment area since its development, physical lake structure, chemical processes and biological community dynamics. Cole (1983), Goldman & Horne (1983) and Taub (1984) discuss the possible geological origins of lake basins, the possible physical structures lakes may adopt, the chemical processes effecting lake basins and the biological dynamics of lake ecosystems.

The effect of climate, both present and past, on a lake basin and in particular water chemistry and biotic responses to changes in climate influenced variables is the primary focus herein.

This type of research can be carried out in a variety of lake environments but as saline lakes are common in coastal Antarctic provinces and as saline lake systems are simple, natural models of ecosystem structure and function (Walker, 1973) research herein focuses on saline lake ecosystems.

2.1.2 Antarctic Limnology

Approximately 98% of the Antarctic continent is ice-covered and there are few ice-free sites suitable for the development of inland waters (Heywood, 1984). Descriptive limnology of the Antarctic region began after the International Geophysical Year (1957) when a number of permanent research stations were established (Hobbie, 1984). Some of the preliminary limnological investigations of Antarctic lakes carried out include Armitage & House (1962) and Goldman (1970) in the area of McMurdo Sound, Tominaga & Fukui (1981) and Murayama *et al.* (1988) in the vicinity of the Japanese Antarctic Syowa Station, Bardin & Le Flat (1966) in the Schirmacher Ponds area of Queen Maud Land, Heywood (1977a), Heywood (1983) and Kieffer & Copes (1983) in the Antarctic Peninsula and offshore islands region and Matsubaya *et al.* (1979), Gibson *et al.* (1989) and Torii *et al.* (1989) in the ice-free areas of the Soya Coast, the Vestfold Hills and the Southern Victoria Land of Antarctica.

Hobbie (1984), Vincent & Ellis-Evans (1989) and Vincent (1987) discuss Antarctic lakes in terms of polar lake ecosystems, comparing and contrasting them with Arctic systems. Heywood (1972, 1977b) gives a comprehensive overview of the formation, evolution and maintenance of purely Antarctic lake environments. He categorises them into lakes and pools of the Continental ice sheet e.g. Vostok (78° 27' S, 106° 52' E); the Continental inland ice-free areas e.g. South Victoria Land (77° 00'S, 162° 52'E), Schirmacherosen (Schirmacher Ponds) (70° 45'S, 11° 40'E) and Bunger Hills (66° 17'S, 100° 47'E); the Continental coastal areas and adjacent islands e.g. Ross Island (77° 30'S, 168° 00'E), Ongul Island (69° 01' S, 39° 32'E) and the Vestfold Hills (68° 33'S, 78° 15' E); and the Antarctic Peninsula and offshore islands e.g. Marguerite Bay , west coast of peninsula (68° 30'S, 69° 00'E), Hope Bay, east coast of peninsula (63° 24' S, 57° 00'E), and Signy Island, South Orkney Islands (60° 43' S, 45° 38'E) (Figure 1).

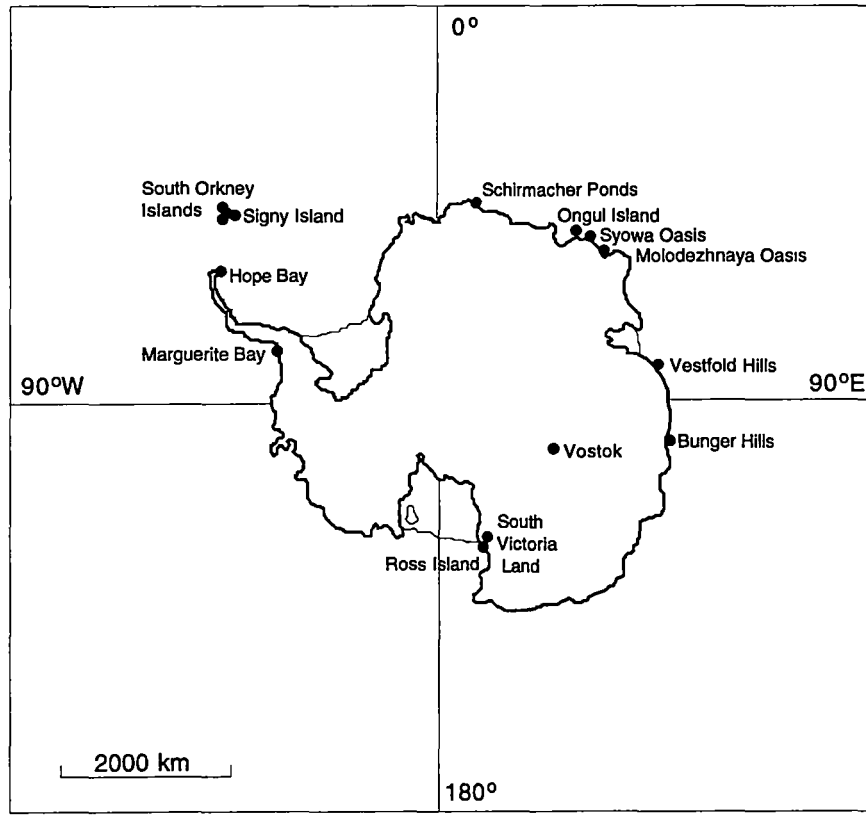

Figure 1: Location of the inland water-bodies discussed in the text.

Of these locations, lakes within the Dry Valleys (e.g. Torii *et al.*, 1980; Vincent, 1981; Wharton *et al.*, 1989; Lizotte & Priscu, 1992; Andersen *et al.*, 1993; Chinn, 1993; Lyons & Mayewski, 1993; Matsumoto, 1993; Wharton *et al.*, 1993; Doran *et al.*, 1994) and the maritime Antarctic (e.g. Simonov, 1973; Heywood, 1977a; Reynolds, 1981; Drago, 1983; Heywood, 1983; Kieffer & Copes, 1983; Ellis-Evans, 1985; Hawes, 1985; Ellis-Evans, 1990; Hawes, 1990; Ellis-Evans, 1991; Guilizzoni *et al.*, 1992) dominate the literature.

However, the many lakes that occur in other ice-free areas, including the Vestfold Hills, Larsemann Hills, Bunger Hills, Schirmacher Ponds and Syowa Oasis are just as interesting. The literature describing the lakes within such regions has been summarised by Bardin & Le Flat (1966), Heywood (1972, 1977b), Burton (1981a,b), Tominaga & Fukui (1981), Wright & Burton (1981), Gillieson *et al.* (1990) and Kaup *et al.* (1993) although many other reports exist for individual lakes within these regions (e.g. Kerry *et al.*, 1977; Burton & Barker, 1979; Burch, 1988; Franzmann *et al.*, 1988; Heath, 1988; Ingole & Parulekar, 1990; Laybourn-Parry & Marchant, 1992a; Lewis, 1994). These oases contain within them important limnological regions which are ideal for the investigation of a wide variety of physical, chemical and biological processes. Lakes within these regions are closed systems for most of each year and are apparently affected by fewer anthropogenic external influences than lakes in lower latitudes. Studies of these habitats with restricted environmental variables and inter-specific relationships have the potential to reveal basic ecological principles more readily than studies conducted in more complex ecosystems (Heywood, 1972). Often the most useful method of advancing limnological knowledge is to utilise comparative studies of different types of lakes within one geographical area, or lake district (Goldman & Horne, 1983). The Vestfold Hills, being the largest presently accessible ice-free lake district in the Australian Antarctic Territory, provides just such an opportunity to research saline lake systems and the response of their biota to changing limnological parameters in a relatively climatically sensitive region.

2.1.3 Limnology of the Vestfold Hills

The Vestfold Hills form a ~ 400 km^2 ice-free area on the Ingrid Christensen Coast of the Australian Antarctic Territory, Eastern Antarctica (68°25' S - 68°40 S, 77°50' E - 78°35' E)(Figure 1). They are an ice-free oasis, sparsely vegetated by algae, mosses and lichens, and are kept free of ice and snow by ablation and melting in summer (Heywood, 1984).

The geology of the Vestfold Hills is described by Collerson & Sheraton (1986). They have a low-lying but rugged topography with a maximum elevation of 158 m a.s.l. (Gore, 1992). The geomorphology of the Vestfold Hills is divided between the east, characterised by relatively fresh, unweathered rock, rugged relief, and sparse glacial sediment and aeolian debris, and the west, with contrasting subdued relief, intensely weathered rock, and abundant accumulations of glacial and aeolian debris (Adamson & Pickard, 1986a, b; Gore *et al.* 1996). Prominent relict marine terraces, approximately 6000 years old and now at 6 m a.s.l., testify to the marine conditions prevailing in much of the Vestfold Hills following the retreat of the ice-sheet in the early Holocene (Bird *et al.*, 1991; Peterson *et al.*, 1988).

The climate of this area is cold, dry and windy (Table 1), largely determined by the interaction of dry katabatic winds from the continental plateau and moist oceanic winds moving in from the north-east (Heywood, 1984).

Table 1

Climatic variables for Davis Station*, Vestfold Hills, Antarctica.

	Maximum	Mean	Minimum
Annual Temperature (°C)	-7.5	-10.2	-12.9
Monthly Temperature (°C)	0.5	-	-18.0
Annual Wind Speed (ms^{-1})	-	5.0	-
Annual Relative Humidity (%)	90	62	-
Annual Precipitation ($mmyr^{-1}$)	-	69	-

* = Data collated from Commonwealth Bureau of Meteorology (1961), Kerry et *al.* (1977), Burton & Campbell (1980), Streten (1986) and Heywood (1984).

Burton & Campbell (1980) and Streten (1986) discuss and summarise the general climate of this region which can be characterised as intermediate between polar continental and sub-polar maritime climates (Fitzsimons, 1990).

A prominent feature of the Vestfold Hills is the numerous lakes (more than 300) which range in size, depth, salinity and history (Figure 2). Approximately 8 % of the area is occupied by fresh water lakes and 2 % occupied by saline and hypersaline lakes (Adamson & Pickard, 1986a). Many of the saline and hypersaline lakes were formed following the end of the last period of glaciation (~ 8000 years B.P.), originating from sea water trapped in basins after isostatic land uplift, caused by the recession of the continental ice cap, from the region. Their present salinity depends on the period since isolation, size of the basin and water balance in the basin (Adamson & Pickard, 1986a).

Detailed physical, chemical and biological publications are available for many of these lakes (e.g. Burton & Barker, 1979; Hand, 1979; Matsubaya *et al.*, 1979; Burton, 1981a,b; Wright & Burton, 1981; Burch, 1988; Burke & Burton, 1988; Butler *et al.*, 1988; Franzmann *et al.*, 1988; Heath, 1988; Masuda *et al.*, 1988; Torii *et al.*, 1988; Gibson *et al.*, 1989; Matsumoto, 1989; van den Hoff *et al.*, 1989; James *et al.*, 1990; Bird *et al.*, 1991; Franzmann, 1991; Gibson *et al.*, 1991; Franzmann & Dobson, 1992; Franzmann & Rohde, 1992; Roberts *et al.*, 1993; James *et al.*, 1994; Perriss *et al.*, 1995; Gibson & Burton, 1996 and Roberts & McMinn, 1996).

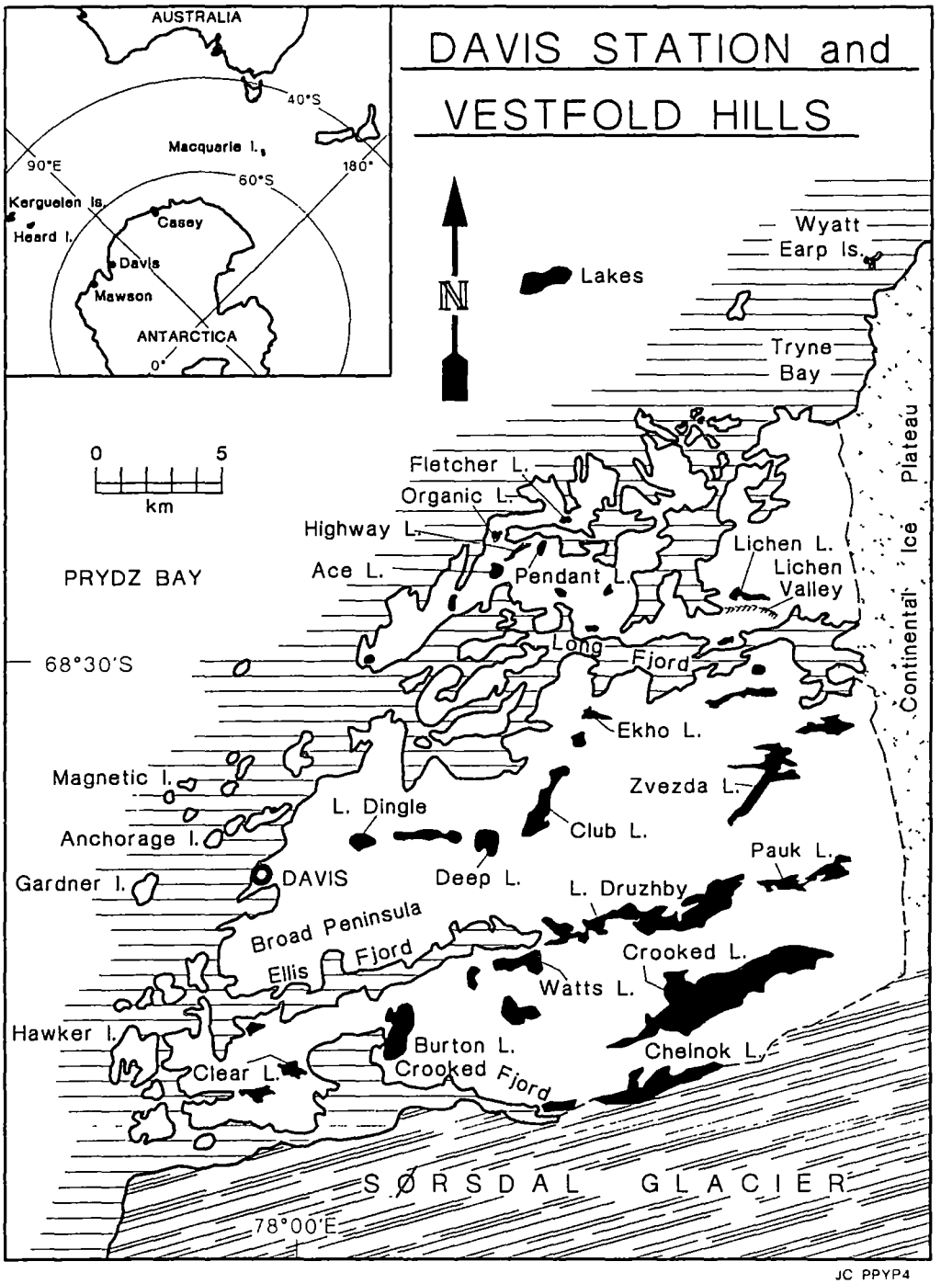

Figure 2: The Vestfold Hills, Antarctica.

A comparison with saline lakes in another east Antarctic oasis, the Bunger Hills, shows that the Vestfold lakes have a wider range of ionic and nutrient water chemistry components (Kaup *et al.* 1993). Consequently, the Vestfold Hills provides the unique opportunity to investigate the response of diatoms to large gradients of water chemistry variables, particularly salinity, in a coastal Antarctic environment.

2.2 Palaeolimnology

2.2.1 Introduction

The sediments deposited within a lake are composed of minerogenic, biological and chemical materials that vary with the seasons and with regional and global climate changes (Reid & Wood, 1976). By researching the changes in lake sediments over time, climatic causes of these changes can be determined. The study of past lake environments, palaeolimnology, is therefore formally defined as "the understanding of the sequential changes and their causal relationships that bodies of water have experienced during their history (Frey, 1964)" (Birks & Birks, 1980).

Because long term instrumental data does not exist for past climate analysis, high resolution palaeoclimatic reconstructions can be used to interpret the palaeohydrological signals preserved in the sediment record of closed-basin lakes (Cumming & Smol, 1993). Palaeolimnological research is often the only way to obtain palaeoclimate information and can therefore provide for a better understanding of past environments and place future climate change within a natural climate variability context.

Proxy data for palaeolimnological climate reconstruction can be derived from many sources including pollen (e.g. Birks & Birks, 1980), chrysophycean algae (e.g. Zeeb *et al.*, 1994), and diatoms (e.g. Smol, 1988). Aquatic organisms are particularly good indicators of changing climates because a climatic change will influence the water chemistry of a lake, to which these organisms respond. The prospect of global warming has focused particular attention on the role of using such proxies in producing quantitative reconstructions of climate related limnological variables. These reconstructions allow climate-model predictions to be assessed and placed in context of natural climate variability (Fritz *et al.*, 1991). Unless natural variability of past climate is documented it will not be possible to recognise and assess anthropogenically related effects on climate above and beyond natural variability (eg. greenhouse effect) (Smol, 1988). Polar regions are particularly important for such research as they are often the first to show signs of hemispheric climatic change, and they do so to the greatest degree (Smol, 1988). Equally, climatic shifts in high latitudes often have more profound effects on other regions (Smol, 1988).

2.2.2 Antarctic Palaeolimnology

The Antarctic region is a key repository of palaeoenvironmental information important for understanding global climatic evolution and its causes, the development of the cryosphere, and sea level history (Kennett & Barron, 1992).

Antarctic palaeolimnological research to date is again dominated by the Dry Valleys and the maritime Antarctic. Much is now known about the Dry Valley lakes in terms of their origin (e.g. Torii *et al.*, 1989), evolution (e.g. Lyons & Mayewski, 1993), past chemical and physical environments (e.g. Gumbley *et al.*, 1974; Wharton *et al.*, 1989) and assosicated biological composition (e.g. Simmons *et al.*, 1993) culminating in inferences about the climate change in the lakes of this unique area (e.g. Wilson *et al.*, 1974; Wharton *et al.*, 1992; Smith & Friedman, 1993; Doran *et al.*, 1994; Spaulding *et al.*, 1997). Maritime Antarctic research has similarly focussed on the evolution of the lakes within this region (e.g. Mäusbacher *et al.*, 1989; Xie *et al.*, 1989) and thier biological communities (e.g. Schmidt *et al.*, 1990; Li & Zhang, 1992; Hodgson & Johnston, 1997) with the view to produce inferences about the maritime palaeoclimatic environment (e.g. Zale & Karlén, 1989; Björck *et al.*, 1991, 1993; Appleby *et al.*, 1995; Jones & Juggins, 1995).

Other palaeolimnological programs have been concentrated around the east Antarctic limnological provinces such as the Schirmacher Oasis (e.g. Makeyev, 1973), the Larsemann Hills (e.g. Gillieson *et al.*, 1990; Gillieson, 1990, 1991), the Bunger Hills (e.g. Verkulich & Melles, 1992) and the Vestfold Hills (section 2.2.3).

2.2.3 Palaeolimnology of the Vestfold Hills

Previous palaeolimnological investigations carried out in the Vestfold Hills have focussed on the origin of the saline waters (e.g. Masuda *et al.*, 1988), their evolution (Bird *et al.*, 1991) and changing biological compositions (e.g. Volkman *et al.*, 1986; Wasell, 1993) and the palaeolimnological evolution of some individual lakes in the region including Watts Lake (e.g. Pickard *et al.*, 1986), Nicholson Lake (Bronge, 1989, 1992; Wasell, 1993) and Ace, Highway and Organic Lakes (Bird *et al.*, 1991) as well as some Taynaya Bay and Ellis Fjord samples (Bird et al., 1991).

The present study adds to the palaeolimnological research in this region with the analysis of lake cores collected from each of the peninsulas in the Vestfold Hills (Long, Broad and Mule) and representing each of the present day salinity categories (i.e. freshwater, hyposaline, marine and hypersaline).

2.3 Diatom-Water Chemistry Relationships

2.3.1 Diatoms

i. Introduction

Diatoms (Bacillariophyceae) are unicellular algae characterised by a silica outer shell or frustule (Round *et al.*, 1990). Their frustules are generally well preserved and abundant in Antarctic saline lake sediments (although this is not the general case for saline lakes) and as individual taxa are characteristic of different lakewater conditions the occurrence and abundance of fossil frustules in lake sediments can be used to reconstruct past water chemistry.

Saline lake diatom literature focuses heavily on African lakes (e.g. Shoeman & Archibald, 1976; Gasse & Tekaia, 1983; Gasse *et al.*, 1995) although current North American literature (e.g. Fritz *et al.*, 1991, 1993; Dixit *et al.*, 1991, 1993; Cumming & Smol, 1993; Wilson *et al.*, 1994) is improving the balance. Fritz *et al.* (1993) and Juggins *et al.* (1994) provide excellent reviews of current regional diatom-saline lake research projects. The most noticeable research gap in these reviews is the saline lake diatom flora of Antarctica.

ii. Antarctic Communities

Diatom flora's form conspicuous elements of the microbial communities of many polar marine environments and are particularly abundant members of the algal flora of Antarctic saline lakes. However, few comprehensive taxonomic studies have been carried out in Antarctic communities. Earlier investigators described the variability of diatoms occurring at specific sites. For example, Fukushima (1970) found 49 diatom taxa in South Georgia (54° 13' S, 36° 33' W), and 32 in the Shinnan Rocks Area (67° 57' S, 44° 29' E). At Kasumi Rock (67° 57' S, 49° 29' E) 33 species of diatoms were found in 8 lakes, 2 lakes at Molodezhnaya Station (67° 40' S, 45° 50' E) had 5 diatom species. Ten species were found at Mirny Station (66° 33' S, 93° 01' E), 13 at McMurdo Station on Ross Island (77° 32' S, 166° 12' E) and 11 on Cape Barne , Ross Island (77° 32' S, 166° 12' E). Cape Evans (77° 32' S. 166° 12' E) and Cape Royds (77° 32' S, 166° 12' E), Ross Island revealed 15 and 21 species of diatoms respectively. Later studies (e.g. Drouet, 1973; Prescott, 1979) have expanded upon these observations with the more recent review by Jones (1996) leading to the most comprehensive list of diatom occurrences from Antarctic inland waters to date. The present study addresses the lack of fully documented diatom flora from continental Antarctic lake provinces, providing the first comprehensive study of the diatom flora of the Vestfold Hills. Full taxonomic details of all taxa encountered are presented in Appendicies 3 and 4.

iii. Antarctic Palaeocommunities

Most Antarctic sediments contain a large number of diatom species (Birks *et al.*, 1990). In addition, the rapid chemical response to hydrological change means that the changing diatom stratigraphy of Antarctic saline lake sediments can provide a sensitive, high resolution record of climate change, without the time lags characteristic of many other palaeoclimate proxies (Fritz *et al.*, 1991).

There are, however, some difficulties involved with using Antarctic diatom palaeocommunities including dissolution, breakage or reworking. Unfavourable preservational conditions in either the laboratory or the field environment will destroy or diminish the palaeoecological value of any sedimentary diatom record (Flower, 1993). Other limitations are discussed in Kamatani (1971), Marshall & Warakomski (1980), Berner (1980), Rippey (1983) and McMinn (1995). However, dissolution was found to be the only problem affecting the preservation of fossil diatoms in certain sections of the Vestfold Hills lake cores.

2.3.2 Water Chemistry

i. Introduction

A large number of variables determine the size and composition of diatom communities (e.g. light–Patrick, 1977; turbidity–Dean *et al.*, 1984; hydrological conditions–Bradbury, 1987; pH–Birks *et al.*, 1990; salinity–Fritz et al, 1991; water-current direction and velocity–Molloy, 1992; nutrient levels–Hall & Smol, 1992 and temperature–Pienitz *et al.*, 1995) but there is a particularly well documented literature concerning the response of individual species to pH (Gasse & Tekaia 1983, Charles & Whitehead 1986, Birks *et al.* 1990), nutrient (Whitemore 1989, Hall & Smol 1992; Jones & Juggins, 1995) and salinity (Juggins, 1988; Fritz *et al.* 1991, 1993) gradients. Due to their simplicity i.e. predominantly closed lake systems without the disturbance effects of higher plants and animals, fewer structural forces influence the algal communities in Antarctic lakes than in most other places on earth (Hansson & Håkansson, 1992). The survival of biota in an Antarctic lake environment is therefore predominantly a result of the lakewater salinity concentration and composition, the availability of nutrients and light, the pH environment and the extent and duration of ice cover with its associated restricted exchange of gases (Parker *et al.*, 1972; Heywood, 1984; Perrin *et al.*, 1987). Average temperatures in Antarctic lakes rarely rise to more than a few degrees above freezing and it is unlikely that slight interannual differences in water temperatures would elicit a direct response in the biotic community (Smol, 1988). Of the remaining variables which influence the biota,

dissolved oxygen, ice cover and/or duration and the consequent light environment (in addition to the water chemistry of the lake) are all strongly affected by salinity. As a consequence, stress imposed on lake biota by salinity is thought to be the principal determinant of species composition in saline waters (Cumming & Smol, 1993).

ii. Lakewater Salinity in the Vestfold Hills

Salinity alters several processes occurring within a lake. Saline lakes stratify easily and require more wind energy to destroy thermal stratification than freshwater lakes at the same temperature. High salt concentrations also lower both the freezing point and the temperature at which the water reaches its maximum density (Bearman, 1989). At high salinity, this amounts to several degrees Celsius and is sufficient to keep some Antarctic salt lakes from freezing. When combined with high temperature, high salt concentrations also restrict the solubility of gases such as oxygen and carbon dioxide (Borowitzka, 1981).

Additional stresses of the Antarctic environment such as low temperatures, and an extremely variable light environment from constant light in summer months to total darkness in winter months, mean that whilst Antarctic saline lakes do support algae and other organisms, and although their populations may be large in some lakes, the range of species is generally much smaller than in lakes of similar salinity in temperate regions (Wright and Burton, 1981).

It has also been shown that the composition of diatom communities in many lake environments is controlled not only by salinity but also by brine type (Gasse *et al.* 1983). However, the diatom response to changes in brine type is much weaker than the response to the salinity gradient and this remains to be demonstrated for Antarctic lake provinces. The composition of the salts in the coastal Antarctic lakes and ponds is mostly similar to that in seawater (11 ions: Cl^-, SO_4^{2-}, HCO_3^-, Br^-, $H_2BO_3^-$, F^-, Na^+, Mg^{2+}, Ca^{2+}, K^+ & Sr^{2+} make up 99.9% of the dissolved constituents of total salinity, the anions account for 21.861 ‰ while cations account for 12.621 ‰ (Bearman, 1989)). The few experimental studies performed on algae suggest that the concentration of major anions (Cl^-, SO_4^{2-}, HCO_3^-) and osmotic pressure can affect growth rates (e.g. Sugihara & Kilham, 1977) and that differing cation concentrations affect the kinetics of phosphate uptake (e.g. Healey, 1973; Rigby *et al.*, 1980). More research will be needed to determine whether there is a causative basis for correlations between cation and anion concentrations and diatom community structure in Antarctic lakes.

Salinity is ideally suited as a climatic factor to reconstruct in Antarctic palaeolimnological investigations as it has a clear relationship with the net water balance of a region. Salinity variability between lakes in the Vestfold Hills depends almost entirely on the local balance between precipitation and evaporation, which is

climatically controlled. Salinity increases if water is withdrawn by evaporation or ablation; and it will decrease if water is added by precipitation. This "water budget" (the net result of water inputs and water losses) records the change in climatic forces on a lake basin. The reconstruction of past fluctuations in salinity and lake levels in saline lakes can then provide a framework for understanding modern hydrologic conditions and a tool for predicting future hydrologic responses to climate change (Fritz, 1990).

iii. Other Water Chemistry Variables

Other variables which may influence the diatom communities within the saline lakes of the Vestfold Hills include the nutrient, light and pH environment.

The major nutrients in all aquatic systems are nitrogen and phosphorus. Silicate is also important in systems where diatoms are abundant. These three nutrients can become limiting to diatom growth when demand becomes greater than supply. Most nutrient research in the Antarctic has been limited to the Southern Ocean and coastal waters with nutrient levels in the Southern Ocean south of the Polar Front found to be generally high (Dieckmann *et al.*, 1991) fluctuating little even after substantial phytoplankton blooms (El Sayed *et al.*, 1983). However, McMinn *et al.* (1995) measured some of the lowest nutrient levels found in the Antarctic region within a fjord in the Vestfold Hills. Nutrient levels were initially highest near the mouth of the fjord, and decreased towards the head with silicate, nitrate and phosphate ranging from 23 to 51 μM, 10 to 26 μM and 1.1 to 2.1 μM respectively. Perrin *et al.* (1987) also documented significantly lower nutrient concentrations during summer blooms at a coastal site near Davis, Prydz Bay, with silicate of 10.4 μM, nitrate 1.4 μM and phosphate 0.32 μM. These are comparable with the minimum concentrations observed by McMinn *et al.* (1995) in Ellis Fjord (3.9, 0.4 and 0.2 μM respectively). Consequently, although nutrients of the Southern Ocean are rarely limiting, the effects of nutrient loading and depletion can be significant in Antarctic coastal environments and enclosed or semi-enclosed bodies of water where there are either processes available for the addition of nutrients or where there is a restricted nutrient pool which may become significantly depleted (McMinn and Hodgson, 1993).

Nutrient levels occurring within the epilimnion of the lakes sampled herein are as low, and lower, than those reported by Perrin *et al.* (1987) and McMinn *et al.* (1995) and generally fit Torii *et al.*'s (1988) descriptions of nutrient characteristics in coastal Antarctic saline lakes. Nutrient limitation, therefore, may influence the distribution and composition of the diatom assemblages within these lake systems.

Ice cover and duration, which are also influenced by salinity, play a major role in determining the wind and light environment of Antarctic lakes. Ice cover eliminates wind generated currents within a lake (Ragotzkie & Likens, 1964; Wharton *et al.*,

1989) and greatly restricts exchange of gases between the water column and atmosphere (Craig *et al.*, 1992) and sediment deposition into the water column below (Squyres *et al.*, 1991; Wharton *et al.*, 1993). An increase in the opacity of ice also greatly restricts light penetration to the lake Wharton *et al.*, 1993). Hobbie (1984) found that if lake ice contains bubbles or inclusions of frozen snow, 20 cm will reduce incident light (visible wavelengths) by 50 % and this will also serve to preclude certain algae from these lakes.

The pH of a lake can also have a large effect on the lake biota. When the pH of a lake falls below 4 or 5, the species diversity is severely restricted (Goldman and Horne, 1983). The hydrogen-ion concentration also controls the chemical state of many lake nutrients, including carbon dioxide, as well as influencing other important plant nutrients such as phosphate, ammonia, iron, and trace metals (Goldman and Horne, 1983).

Although the pH and light environments, as well as the extent and duration of the seasonal ice cover, have important influences on the water chemistry of an Antarctic lake they are not as prominent an influence as salinity and were not measured and therefore not considered herein.

2.4 Palaeolimnological Reconstruction of Lakewater Variables

2.4.1 Transfer Functions

The response of a diatom community to changes in the limnological environment can be quantitatively modelled. These "transfer functions" allow inferences of past lake environments to be made from fossil diatom communities. A transfer function is therefore a model of the ecological responses of diatoms to their current environment that can be used to infer past environmental conditions from diatom indicators in past sediments.

Transfer function techniques were first applied to marine plankton by Imbrie & Kipp (1971), to tree ring data by Fritts *et al.* (1971) and to terrestrial pollen by Webb & Bryson (1972). Following these applications diatom transfer functions have become extensively used tools for the reconstruction of various water chemistry variables throughout the world's limnological provinces.

The first step in a transfer function involves collecting and establishing relationships between present-day diatom species and environmental variables from a set of study lakes (a training or calibration set) (Hall & Smol, 1992). The modelled response of the diatom assemblage to the environmental gradients measured provides the basis upon which the second part of the transfer function, calibration, builds. If the distributions of diatom taxa are strongly related to a particular environmental variable, realistic reconstructions of that variable should be possible from the fossil diatom species composition of sediment core samples (ter Braak, 1987b).

Numerous researchers have used transfer functions as tools for hindcasting environmental variables, with many concentrating on single variables such as pH (Gasse & Tekaia, 1983; Birks *et al.*, 1990), specific nutrients (Hall & Smol, 1992; Bennion, 1994) and salinity (Fritz *et al.*, 1991, 1993, 1994; Cumming & Smol, 1993; Wilson *et al.*, 1994). Of these, Cumming & Smol (1993) comprehensively describe the development of diatom-based salinity inference models, thier advantages, pitfalls and possible applications and Fritz *et al.* (1991, 1993) apply diatom-based salinity inference models to specific climate change questions in the northern Great Plains of North America (with the development of a climate change inference tool for Devils Lake, North Dakota).

The relationship between diatoms and water chemistry in the surface sediments of saline lakes herein is explored so that variables of past lakewater chemistry can be reconstructed from the fossil diatoms deposited throughout the lakes of the Vestfold Hills (a comprehensive discussion of the assumptions and general theory of transfer functions, and a guide to choosing between the most common multivariate statistical techniques currently available for creating transfer functions is included in Appendix 1).

2.4.2 Modern Analogue Matching

An alternative method to the transfer function of reconstructing palaeolake water chemistry is that of Modern Analogue Matching. This technique differs from the transfer function approach in the way the relationship between diatoms and water chemistry is constructed. Transfer functions are based on a specific prediction equation, whereas the modern analogue matching approach is based on the fit of fossil samples to the environmental gradient being reconstructed by direct comparison between modern and fossil diatom assemblages. A close modern analogue for each fossil sample is looked for in the training set. The modern sample most similar to the fossil sample in question is found and the past environmental variable to be inferred is that of the closest modern sample's environmental variable.

Although the analogue matching technique is an intuitive one, a key assumption is that the analogue dataset (training dataset) contains examples of all the diatom assemblages being analysed (Bartlein & Whitlock, 1993). For this reason, the water chemistry variable being reconstructed is calculated from the mean or weighted mean of the values of up to the ten closest modern analogues. A choice on how many modern analogues to use to reconstruct the variable can then be made on the basis of the correlation and RMSE of each approach.

One problem associated with both the transfer function and the modern analogue technique is the occasional lack of a modern analogue for a fossil assemblage. This is dealt with by the transfer function technique by extrapolation and by the modern analogue technique of identification of a "no analogue" situation. Bartlein & Whitlock (1993) advise that as the transfer function approach has the intrinsic merit of being statistically optimal when the assumptions underlying the approach are not violated and is based on a formal statistical model, this approach is preferable whenever uncertainties arise in a reconstructed value.

2.4.3 Statistical Techniques Applied Herein

Reliable reconstruction of lake-water chemistry variables from the relative abundance of diatom taxa in a sample requires a good statistical relationship between the diatoms and the variable to be reconstructed (ter Braak 1987a). For this reason alone it is very important to choose the most applicable statistical application to get the most realistic model (see Appendix 1 for further discussion). The large environmental gradients measured in the Vestfold Hills training dataset necessitates the assumption of a non-linear species response model and therefore weighted averaging based statistical techniques are employed. A direct gradient analysis ordination technique (CCA) has been chosen for an initial exploration of the training dataset. The application of a direct gradient technique to the training dataset will identify the relative influence of the measured multiple environmental variables on the diatom species distributions.

Once significant explanatory variables are identified, weighted averaging regression and calibration will enable the development of transfer functions that quantitatively infer these variables based on the species composition of core sediments. Modern analogue matching is also employed to provide an alternative palaeolimnological reconstruction for comparison with the transfer function reconstruction. Both techniques are used herein but the transfer function is given more weight in cases of conflict.

2.3.4 Accuracy of Palaeoecological Reconstruction Methods

The accuracy of palaeoecological reconstruction techniques is most commonly assessed by determining a) the correlation (r^2) between the measured value of a given water-chemistry variable against the reconstructed value calculated from the surficial sediment data and b) the reliability of the reconstructed environmental estimates as assessed by prediction errors. The root mean square of the error (RMSE) is commonly used as a measure of the predictive abilities of modern training sets (Birks, 1994). However, RMSE is invariably underestimated when based solely on the training set (ter Braak & van Dam, 1989; Birks *et al.*, 1990). Jackknifing or bootstrapping, computer intensive means of sub-sampling the original dataset to determine possible bias and to estimate statistical accuracy (Dixon, 1993; Manly, 1993), can be used to derive an unbiased overall RMSE of prediction (RMSEP) for the training set with the lower the value of both the RMSE and the RMSEP giving the highest degree of predicability (Birks *et al.*, 1990).

Chapter 3: Methods

3.1 Sample Collection and Preparation

Thirty-three lakes were chosen for the construction of the training dataset for the Vestfold Hills (Figure 3). Some of the limnological characteristics of these lakes are given in Tables 2 and 3. Surface sediment diatom samples and epilimnion water samples were collected from these lakes during November and December 1992, and November and December 1994. The lakes were chosen to provide a representative sample of the diatom taxa from fresh (0.5 ‰) through to hypersaline (165 ‰) lake habitats in the Vestfold Hills region. Markedly hypersaline lakes (> 250 + ‰) were unable to be sampled due to their lack of a stable ice cover.

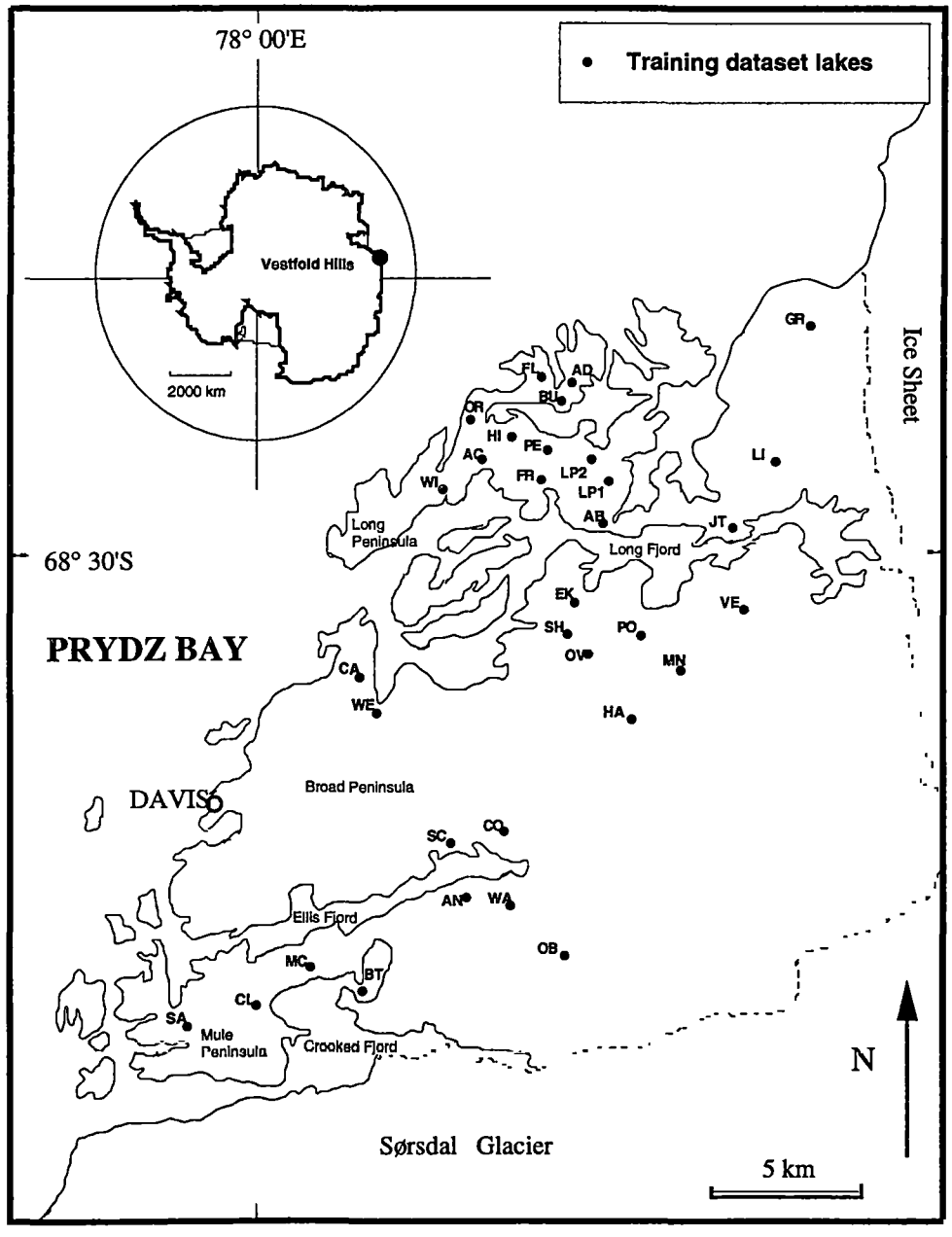

Figure 3: Distribution of sample sites in the training dataset. Lake codes correspond to those in Table 2 and 3.

Four lake cores were chosen for palaeolimnological analyses (Figure 4). These lake cores were selected for analysis both on the basis of their present salinity: fresh (Cat Lake), hyposaline (Lake McCallum), marine (Ace Lake) and hypersaline (Anderson Lake) and on the basis of their geographical position: at least one from each of the peninsulas (Long, Broad and Mule) within the Vestfold Hills.

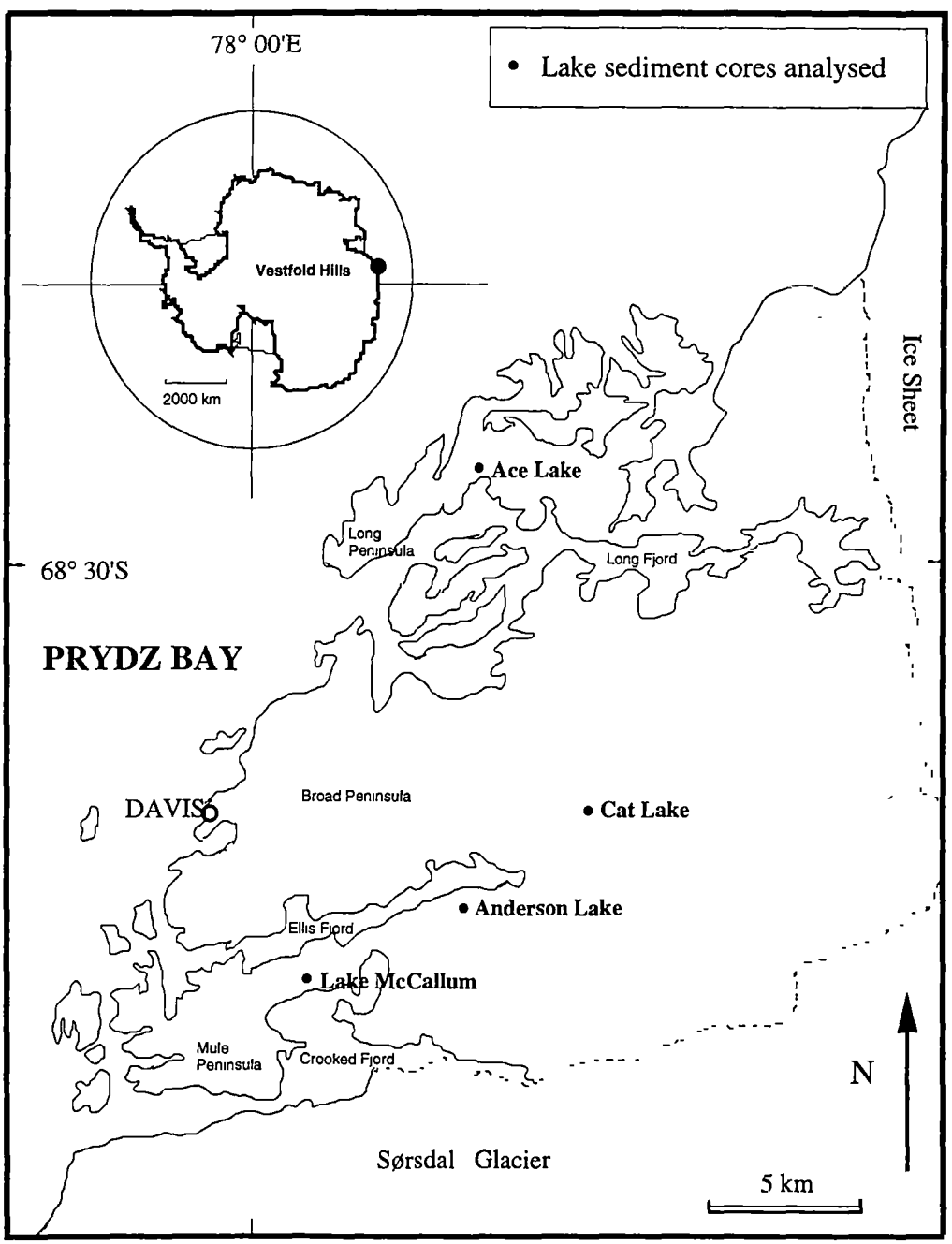

Figure 4: Location of the sediment cores collected from the Vestfold Hills.

3.1.1 Water Chemistry

At each lake, a single midsummer (November - December 1994) water sample was collected in a 2 l Kemmerer bottle from the epilimnion (0 - 2 m depth). Samples were stored in 125 ml polyethylene bottles, frozen at -20°C and returned to the Institute of Antarctic and Southern Ocean Studies, University of Tasmania, for analysis.

Eleven lakewater chemistry variables including salinity, major ionic solutes, and major nutrients were analysed (Table 3). The data recorded here represent a single analysis of summer lakewater chemistry conditions.

Field measurements of electrical conductivity were recorded at 1 m intervals with a submersible data logger (SDL) (Platypus Engineering, Hobart, Tasmania). Salinity was calculated from individual SDL profiles using a conductivity-salinity conversion equation (Fofonoff & Millard 1983). The salinity of the markedly hypersaline lakes sampled (> 100 ‰ at 2 m) was converted in the same manner, although conversion equations are not designed for such high salinity concentrations. These markedly hypersaline lakes were nevertheless included in all analyses, although actual salinity for these lakes could be slightly higher than that determined here. Each lake is categorised by the salinity range encountered: a) from surface to bottom if the lake is of holomictic or uncertain mixing status; or b) within the mixolimnion where meromixis occurs. Lakes were classified as fresh (< 3 ‰), hyposaline (3 - 30 ‰), marine (30 - 35 ‰) and hypersaline (> 35 ‰)(Table 2).

Alkalinity was determined by titration with sulfuric acid using a pH meter to determine the end-point at pH 4.5 and pH 8.3. Non-standard analysis of alkalinity resulted from the small size (125 ml) of the water sample. Alkalinity concentrations represent a single titration value instead of a triplicate titration value and as such should be interpreted with care.

The methodology of Mackereth *et al.* (1978) was followed for the determination of all other ionic concentrations. Sodium and potassium were determined by flame emission photometry. Calcium and magnesium were determined by flame atomic absorption spectrometry. Chloride concentration was estimated by silver nitrate titration with a potassium chromate indicator. Sulfate was determined by precipitation with barium chloride to produce a fine uniform suspension of barium sulfate. The turbidity of the resultant solution was measured at 410 nm. A glycerol/alcohol/acid conditioning agent was added to keep the precipitate in suspension. All ions were determined within ± 0.5 % except for sulphate (with an associated accuracy of ± 2 %) and chloride (with individual accuracies ranging between ± 0.25 % for lower values and ± 0.08 % for results above 10 000 mg l^{-1}).

Nitrate (NO_3^-), phosphate (PO_4^{3-}) and silica (SiO_2) (measured as reactive silicate (H_4SiO_4)) were analysed with an ALPKEM Auto Analyser. Analysis was carried out following the ALPKEM Methodology Manual (1992) with modifications due to the high concentration of salts in 16 of the 33 water samples. To minimise disturbance due to salt differences in the autosampler for the more saline samples (>40 ‰), nitrate and phosphate

analysis required autoanalyser solutions of higher salinity (65 and 145 ‰ respectively) than standard sea water salinity. Silicates were measured with an instrument calibration accuracy of 9.34 μmol l^{-1}, the accuracy of the phosphate measurements were 0.10 μmol l^{-1} (with 0.08 μmol l^{-1} and 0.19 μmol l^{-1} for the higher salinity standard runs of 60 ‰ and 145 ‰ respectively) and the accuracy of the nitrate measurments were 2.49 μmol l^{-1} (with 5.13 μmol l^{-1} and 0.43 μmol l^{-1} for the higher salinity standard runs of 60 ‰ and 145 ‰ respectively).

3.1.2 Surface Sediment Diatom Assemblages

Surface sediment diatom samples (0-2 cm) were collected from the deepest part of each lake with a Glew Corer (20) (Glew 1989) or Ekman Grab (12) (Table 2). The surface sediment represents a mixture of living cells and recent diatom remains that are estimated to represent material accumulated during the 0 to 20 years before sampling (McMinn, unpublished data).

Samples were stored in the dark at 4°C until processing. Three subsamples were extracted and analysed following the methodology of Battarbee (1986). Each subsample was treated with 10% H_2O_2 for 3 days to remove the organic fraction of the sediment. Following 3 centrifuge treatments (2000 RPM for 5 minutes), samples were washed in distilled water. Prepared residues were mounted in Naphrax (a mounting media with a refractive index of 1.72). Diatoms were then identified using a Zeiss Standard 20 light microscope with 100x oil immersion objective and phase contrast illumination. The percentage of each taxon was evaluated by counting 400 valves for each of the 3 replicate subsamples. Diatom species were then expressed as relative abundances (% total diatoms) of the 1200 valves counted per sample and only those present at ≥2% in any single sample (47 species) were included in numerical analyses. Exclusion of rare taxa is on the basis that they may be allochthonous. This numerical dataset (47 species x 33 lakes) is presented in Appendix 2.

Diatom taxonomy was determined using both light microscopy (LM) and scanning electron microscopy (SEM). Samples were prepared for SEM by washing in distilled water and filtering onto a 0.8 μm Millipore filter (following the method of Fournier, 1978). The 1992 samples were then examined on a Philips 505 SEM (with spot size of 20 and 50 nm and an accelerating voltage of 20 kV). The 1994 samples were examined on an ElectroScan 2020 Environmental Electron Scanning Microscope (ESEM) with an accelerating voltage of 20 kV.

Diatom identifications are based on the standard volumes of Van Heurck (1962), Patrick & Reimer (1966a,b), Gerloff & Choloky (1970), Krammer & Lange-Bertalot (1986a,b) Round *et al.* (1990). Special attention was given to Australian (John, 1983), polar diatom (Priddle & Fryxell ,1985; Medlin & Priddle, 1990) and Antarctic taxon references (Ko-Bayashi, 1962, 1963 a,b). All taxa encountered are listed in Appendix 3 and illustrated in Appendix 4.

3.1.3 Fossil Diatom Assemblages

Sediment cores from Anderson Lake, Cat Lake and Lake McCallum were taken in November 1991 by members of the Research School of Earth Sciences (RSES), Australian National University (ANU). A modified Livingstone impact piston corer was used to collect the lake cores from selected coring sites (Figures 5 - 8).

Dr. Michael Bird (RSES, ANU) arranged sub-sampling and radiocarbon dating of selected bulk sediment sections of each of these cores which were subsequently sent to the Institute of Antarctic and Southern Ocean Studies for diatom analyses.

The sediment core from Anderson Lake was collected from the northern arm of the lake through a 1.4 m thick ice cover (Figure 5).

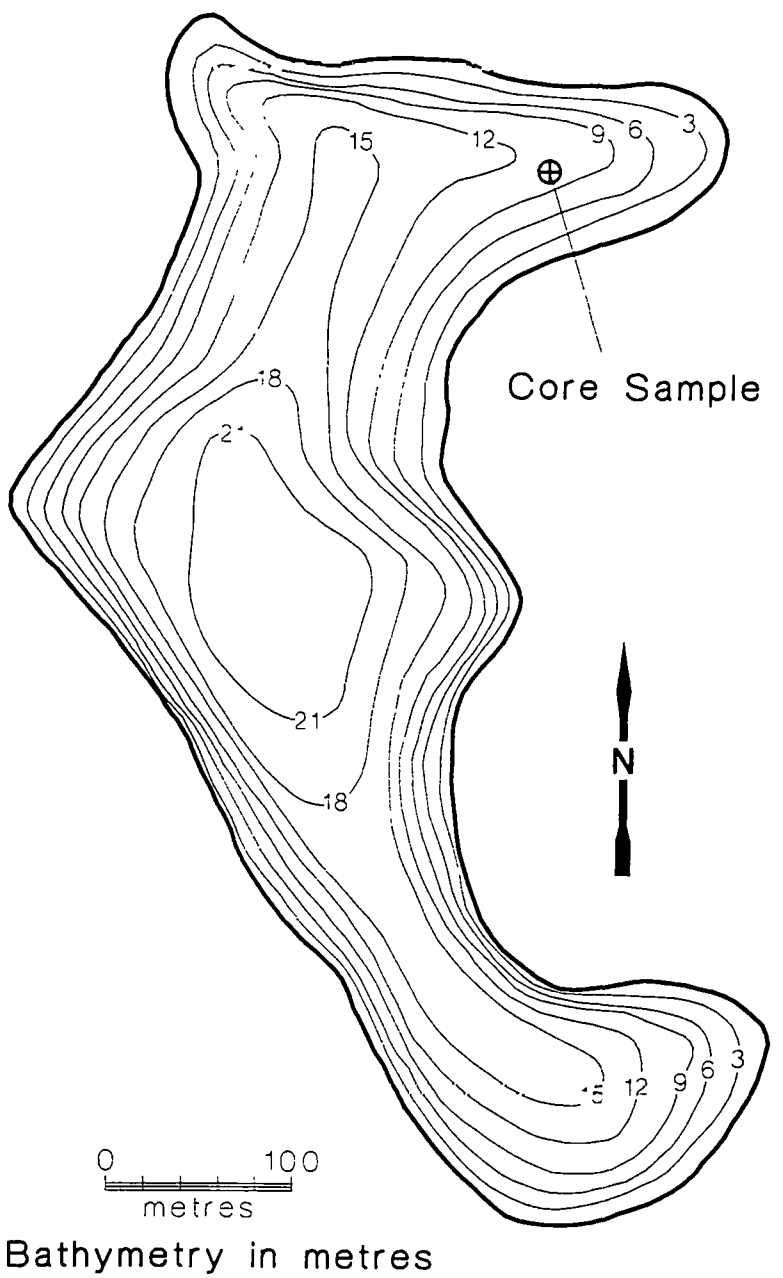

Figure 5: Location of the core sample site within Anderson Lake.

A thick layer of mirabolite covering the deeper parts of the lake bottom could not be penetrated by the corer (three attempts at coring from the deepest part of the lake failed). The core was frozen and divided into approximately 2 cm interval subsamples for diatom analysis. Core sediment extended from the surface to 135.50 cm, although below 109.75 cm dissolution excluded the identification of any diatom species. These highly dissolved basal sediments have been found to be glacial moraine of undetermined age (Lewis, 1994). Uncorrected radiocarbon ages of 6730 ± 200 (ANU-8446), 7110 ± 270 (ANU-8349) and 8450 ± 210 (ANU-8145) for 40, 104 and 111 cm respectively were determined.

The sediment core from Lake McCallum was collected from close to the centre of the lake (at 32 m depth) through a 1.3 m thick ice cover (Figure 6). Core sediment extended from the surface to 124 cm, although below 75 cm dissolution excluded the identification of any diatom species. Subsamples were taken at 5 cm intervals from 0 to 75 cm for diatom analysis. Uncorrected radiocarbon ages of 4690 ± 170 (ANU-8817), 9620 ± 110 (ANU-8348) and 12850 ± 360 (ANU-8550) for 22 - 29, 72 - 78 and 102 - 124 cm respectively were determined.

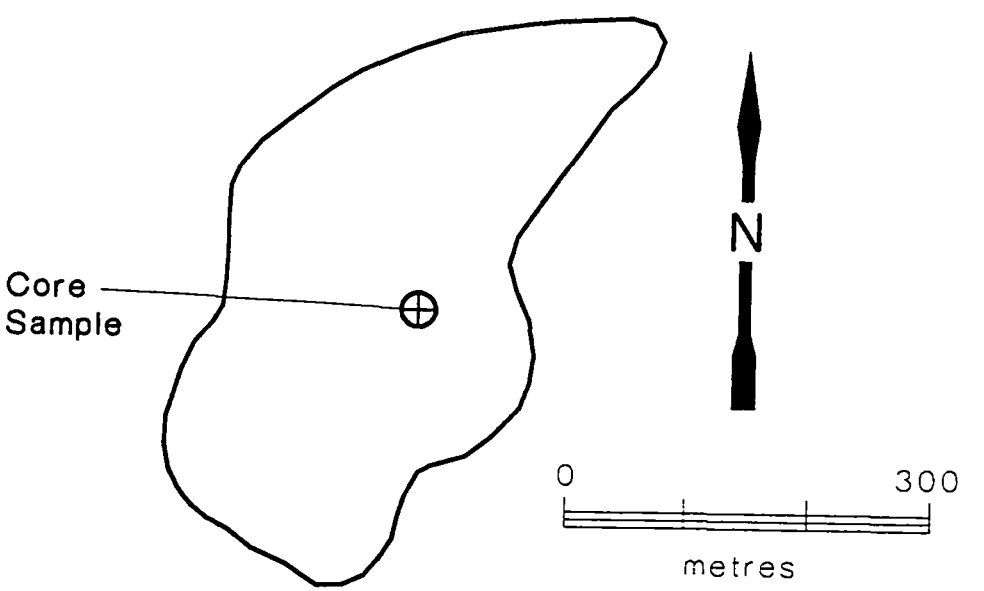

Figure 6: Location of the core sample site within Lake McCallum.

The sediment core from Cat Lake was collected from close to the centre of the lake (at 17.8 m depth) through a 1.7 m thick ice cover (Figure 7).

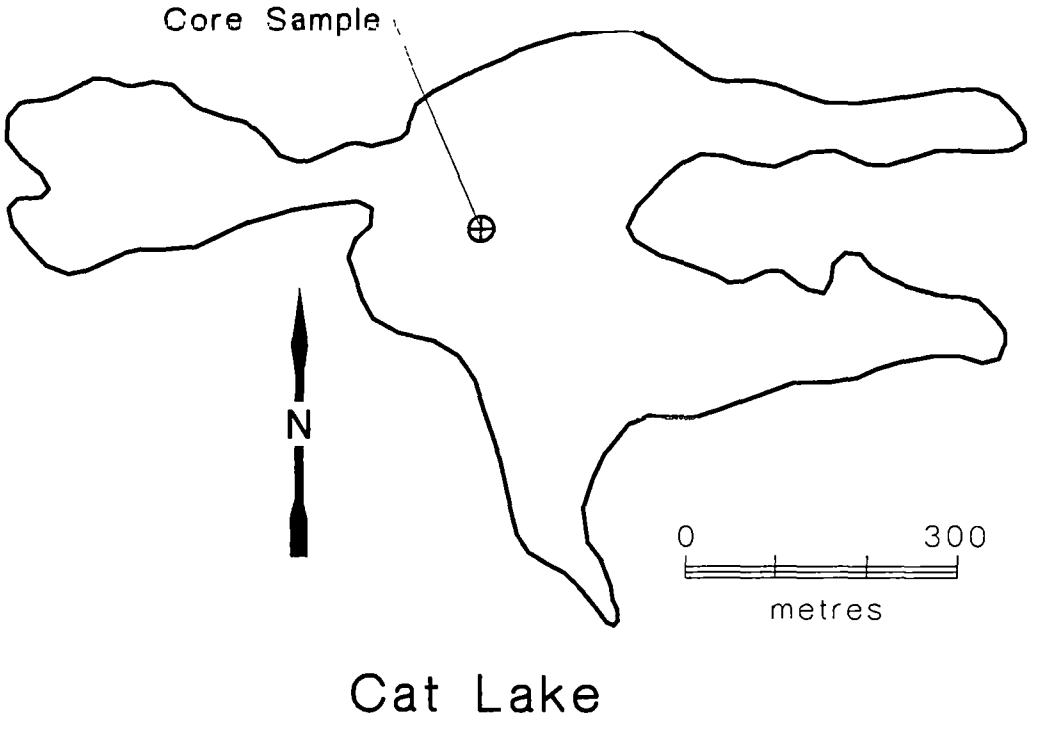

Figure 7: Location of the core sample site within Cat Lake.

Core sediment extended from the surface to 71 cm, although below 34 cm dissolution excluded the identification of any diatom species. Subsamples were taken at 2 cm intervals from 0 to 34 cm for diatom analysis. An uncorrected radiocarbon age of 8170 ± 220 (ANU-8266) at 35 - 42 cm (the lacustrine /till transition) was determined.

A sediment core from Ace Lake was collected in 1995 by Dr. Andrew McMinn of the Institute of Antarctic and Southern Ocean Studies, University of Tasmania. An impact corer was used to collect the core through a 1.7 m thick ice cover from the deepest part of the lake (Figure 8).

Subsamples were taken at 5 mm intervals from 0 to 20 cm and at 5 cm intervals from 20 to 200 cm for diatom analysis. Radiocarbon dating of selected bulk sediment from this core (0, 100 and 200 cm respectively) were carried out at the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, New Zealand. Uncorrected radiocarbon ages of 984 ± 67 (NZA-6854), 6472 ± 90 (NZA-6855) and 13020 ± 150 (NZA-6864) for 0, 100 and 200 cm respectively were determined. Lead-210 sediment accumulation rates for the top 30 cm of another core taken fron Ace Lake in 1995 were determined by Dr. Henk Heijnis of the Environmental Radiochemistry Laboratory, Australian Nuclear Science and Technology Organisation. These Lead-210 analyses are included in Appendix 5.

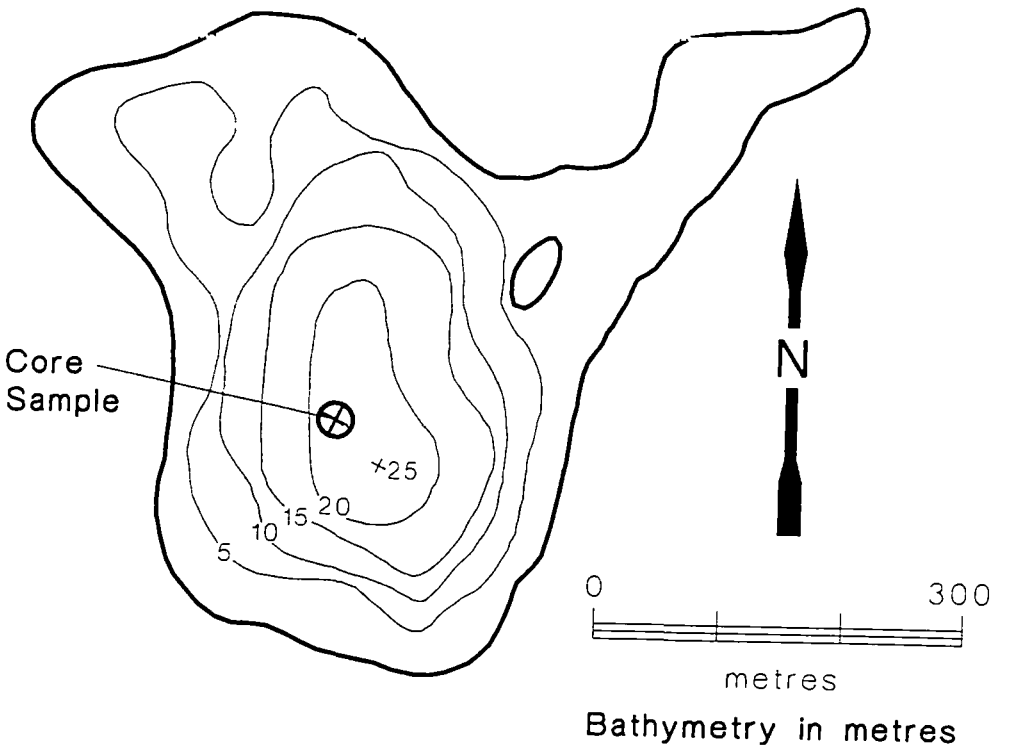

Figure 8: Location of the core sample site within Ace Lake.

Core subsamples for diatom analyses were prepared and treated in the same way as the surface sediment samples (Section 3.1.2). A single count of 400 valves per core segment was made with the exception of Cat Lake in which dissolution was prevalent. In this case, a minimum of 100 valves were counted and all recognisable valve fragments larger than half a valve or with identifiable central areas were counted as a single valve. Core diatom species are therefore expressed as relative abundances of the total number of valves counted.

As the focus of the research herein is the diatom changes throughout each core sampled no attempt was made to log lithology, grain size, etc, for any of the cores.

3.2 Data analysis

3.2.1 Development of the Transfer Function

i. Training Data Set

Canonical correspondence analysis (CCA), a direct gradient ordination technique (ter Braak, 1986), was used to explore the relationships between diatom distributions and

abundances and measured environmental variables and to determine which environmental variables directly accounted for variations observed in the diatom data. All environmental variables had skewed distributions and were log transformed ($\log_{10}(x+1)$) prior to all statistical analyses. All ordinations were performed using CANOCO version 3.12 (ter Braak, 1988, 1990). In each CCA, rare species were downweighted and sample scores were scaled to be weighted averages of species scores.

Following preliminary CCAs, 2 of the 11 measured environmental variables were removed. Nitrate was removed because concentrations were below the detection limit in 27 of the 33 lakes sampled. Phosphate was also removed as large variation in the concentrations analysed (Table 3) caused each lake in turn to have high influence (>5x leverage) in the dataset. The removal of each "outlier" sample constantly substituted the next lake sample with the highest phosphate as an outlier and so on for each lake sample. A preliminary CCA including phosphate revealed that this variable did not significantly influence the variation in the diatom data. Phosphate was subsequently removed from all other numerical analyses. A final preliminary CCA using the remaining 9 environmental variables revealed no outlier samples. Therefore, all lakes remained in all following analyses.

The environmental variables remaining in the dataset were sorted into active and passive variables. Passive variables have high variance inflation factors (VIFs). A high VIF (>20) occurs when a variable is almost perfectly correlated with other variables and does not contribute additional information to the ordination (ter Braak, 1988). Four such multiple collinear environmental variables (Cl, Na, Mg & Ca) were identified to be correlated with salinity.

Prior to forward selection, the active environmental variables remaining in the analysis were salinity, silicate, potassium, sulphate and alkalinity. The relative contribution of these environmental variables to the ordination axes was evaluated by the intra-set correlations (the correlation coefficients between the environmental variables and the ordination axes (ter Braak, 1986)).

Forward selection was used to identify the variables that contributed significantly ($P<0.05$) to the explanation of the variation in the species data in the ordination of the active variables. The independence of each of the forward selected variables was identified by using each variable separately in a constrained CCA. Canonical coefficients and their t-values indicate the importance of each variable's contribution to the fit of the species data. The ratio of the first constrained eigenvalue to the second unconstrained eigenvalue indicates the relative explanatory strength of the individual variable (Dixit *et al.*, 1991). Unrestricted Monte Carlo permutation tests (99 permutations) were used to evaluate the significance of these ratios.

CALIBRATE (Juggins & ter Braak, 1992) was used for the graphical interpretation of the CCA output.

ii. Weighted Averaging Regression and Calibration

Weighted averaging regression and calibration (both with and without tolerance downweighting) were applied to the 33 lakes and the 47 selected diatom taxa in the training set, to generate a transfer function for inferring past lakewater salinity from fossil diatom assemblages.

All statistical analyses were carried out using log-transformed ($\log_{10}(x)$) salinities. Outliers were identified as those samples having a residual greater than the standard deviation of the environmental variable in the training dataset (Jones & Juggins, 1995). All but one sample residual in the training dataset (Watts Lake 0.73) was less than 0.68, the standard deviation of the log-transformed salinity data. Nevertheless, all samples were retained and included in all numerical analyses with due care paid to interpretation of Watts Lake values.

The training dataset was analysed using both simple weighted averaging (WA) and weighted averaging with tolerance downweighting (WA(tol)). Simple weighted averaging takes into account a species optima for a given variable. Weighted averaging with tolerance downweighting also takes into account species tolerances by downweighting each species by its variance for the environmental variable in question (Bennion, 1994). The selection of the most statistically appropriate model for application to a sediment core's fossil diatom assemblage is based on a number of error prediction criterions which are discussed below (section 3.2.4).

3.2.2 Development of the Analogue Matching Method

Analog Matching was also applied to the sediment cores as an alternative method for estimating palaeosalinity from fossil diatom assemblages. Modern analog matching also determines which of the fossil samples have "no" or "poor" analog situations.

M.A.T. (Modern Analog Technique) version 1.1 (Juggins, 1996) was used to analyse the training dataset to determine the cut-off value of the squared chord distance dissimilarity, defining a "good" analog. The fifth percentile of the squared-chord distance values calculated among all modern diatom samples is adopted as a threshold indicator of a "good" analogue while the second percentile is adopted for a "close" analogue (Bartlein & Whitlock, 1993). When these values are exceeded, the reconstructed variable is considered to be less reliable.

Palaeosalinity was then estimated from the fossil diatom assemblages from each sediment subsample within each of the sediment cores. Palaeosalinity estimates based on modern analogue matching are means and weighted means of estimates based on the 4 most similar assemblages from the training set (based on the r^2 and RMSE of the number of modern analogues used for a match from 1 to 10).

3.2.3 Application of the Palaeosalinity Reconstruction Methods

The WA classical deshrinked transfer function was applied to fossil diatom assemblages

enumerated from each of the sediment cores collected. Diatom-inferred salinity concentrations ($\log_{10}$ ‰) were then derived from the classical deshrinking regression equation: Final x_i = (Initial x_i - 0.53)/0.61 where x_i is the inferred value of the environmental variable x for the sample i. These values were back transformed to give estimated epilimnetic palaeosalinity (‰) for each core section.

WA regression and calibration (both with and without tolerance downweighting) were performed using CALIBRATE version 0.54 and 7.0 (Juggins & ter Braak, 1992). Diatom stratigraphies and palaeosalinity trends for each core were plotted using Tilia/Tilia Graph version 2.0 (Grimm, 1991).

The analogue matching method was applied to the same datasets as the transfer function method. "Good" and "close" analogues were identified using M.A.T. (Modern Analog Technique) version 1.1 (Juggins, 1996). Palaeosalinity was also estimated based on the means and weighted means of the 4 most similar assemblages from the training set. Both analogue matches and palaeosalinity trends determined in M.A.T. were plotted using Tilia/Tilia Graph version 2.0 (Grimm, 1991).

3.2.4 Accuracy of the Palaeosalinity Reconstruction Methods

The accuracy of both the transfer function and the analogue matching palaeosalinity estimates was assessed by determining a) the correlation (r^2) between the measured value of a given water-chemistry variable against the reconstructed value calculated from the surficial sediment data and b) the reliability of the reconstructed environmental estimates as assessed by prediction errors. The root mean square of the error (RMSE) was used as a measure of the predictive ability of the training set (Birks, 1994). Jackknifing was used to derive an unbiased overall RMSE of prediction (RMSEP) for the transfer function training set, with the lower the value of both the RMSE and the RMSEP giving the highest degree of predicability (Birks *et al.*, 1990). The RMSE and r^2 gave a measure of the "apparent" error in the model while the jackknife RMSE gave a more reliable indicator of the true predictive ability of a transfer function (Dixon, 1993).

Analysis of the transfer function dataset with both WA and WA(tol) resulted in the selection of WA for palaeosalinity reconstructions as it gave slightly lower error estimates of the jackknifed RMSE (cf. Table 8).

Following analyses using both classical and inverse deshrinking methods, trends in residuals revealed under and over estimation at either extreme of the salinity gradient for inverse deshrinking. Classical deshrinking had no residual trend thus indicating this deshrinking technique will provide a more reliable estimate of palaeosalinity, particularly at the gradient extremes of salinity (cf. Birks *et al.*, 1990; Jones & Juggins, 1995). In contrast, following analyses using the analogue matching technique, no distinction between the mean and weighted mean estimates of palaeosalinity can be made based on the r^2, RMSE or residual distribution in the data (cf. Table 9). As a result, all analogue matching estimates are given in terms of both methods.

Chapter 4: Results

4.1 Development of the Transfer Function

4.1.1 Training Data Set

Physciochemical analyses for each of the lakes in the training set (Figure 3) are given in Tables 2 and 3.

Table 2

Relevant physico-chemical details for lakes sampled Note "Admin", "LP1", "LP2" and "Pointed" are informal names not approved by the Antarctic Names and Polar Medal Committee. All entries as collated from 1994 information Ekman grab samples are identified (#) with all other lakes sampled by Glew Corer (Glew, 1989). Elevations were recorded by H Brolsma (personal communication 1989) Salinity range and mixing status were determined from salinity profiles recorded at time of water sampling. Lake categories are discussed in the text with categories being fresh (< 3 ‰), hyposaline (3 - 30 ‰), marine (30 - 35 ‰) and hypersaline (> 35 ‰)

Lake Name	Lake Code	Latitude	Longitude	Elevation	Maximum Recorded Depth (m)	Mixing Status	Depth Oxycline (m)	Salinity Range (min - max ‰)	Salinity Range above oxycline (min - max ‰)	Salinity (‰ at 2m)	Lake Category
		(°S)	(°E)	(m)							
Abraxas	AB	68 29 5	78 17	13 11	23	meromictic	17 5	15.4 - 22.9	17 3 - 22 9	15 8	hyposaline
Ace	AC	68 28 4	78 11 1	8 91	25	meromictic	11 - 12	16 2 - 40 4	16 2 - 30.9	16.2	marine*
"Admin"	AD	68 27 2	78 16 5	0 95	6	holomictic ?	—	14 8 - 17.5	—	14.8	hyposaline
Anderson	AN	68 36.0	78 10 0	3 50	21	meromictic	3 - 4	57 2 - 144.1	121 6 - 144 1	62 9	hypersaline
Burch	BU	68 27 3	78 16 0	-0 07	7	meromictic ?	5	135 0 - 167 8	147 2 - 166 5	138	hypersaline
Burton #	BT	68 37 5	78 06 0	0 11	16.2	meromictic	4	41 5 - 42 6	41 5 - 41 8	41 6	hypersaline
Camp #	CA	68 32 5	78 04 5	—	7 4	uncertain	4	15 6 - 18 6	18 2 - 18 6	16.4	hyposaline
Clear	CL	68 39 0	78 00 0	-8.28	60 5	meromictic	30	8 7 - 13 8	8 7 - 12 5	10 7	hyposaline
Collerson	CO	68 35 0	78 11 0	4 99	8 2	holomictic	—	7.7 - 9 3	—	8 6	hyposaline
Ekho #	EK	68 31 0	78 15.5	-1 405	39	meromictic	14	46.1 - 149 1	46 1 - 77 0	52 0	hypersaline
Fletcher	FL	68 27.0	78 16 0	0.36	12	meromictic	7 - 8	65 3 - 100 0	65 3 - 90 7	65 3	hypersaline
Franzmann #	FR	68 29 0	78 14 9	—	8 5	meromictic	3 5	71 2 - 96 0	71 2 - 72 9	71 4	hypersaline
Grace #	GR	68 25 3	78 27 5	—	3	holomictic	—	0 6 - 1.2	—	1 1	fresh
Hand	HA	68 33.2	78 19 0	9 55	29	meromictic ?	uncertain	4 9 - 5.6	uncertain	5 5	hyposaline
Highway	HI	68 27 9	78 11 3	8 30	17 4	holomictic	—	4 7 - 5 1	—	4 7	hyposaline
Johnstone #	JT	68 30.0	78 25 0	—	9.8	meromictic	7.5	155 8 - 167 4	163 9 - 167 4	157	hypersaline
Lichen #	LI	68 28 8	78 26 0	—	26	holomictic	—	0 5 - 0 6	—	0 5	fresh
"LP 1"	LP1	68 28 6	78 16 0	7 51	4 9	meromictic	3	73 9 - 127 4	88 4 - 127 4	74 1	hypersaline
"LP 2"	LP2	68 28 6	78 15 5	7 51	1 8	holomictic	—	132 8 - 170 2	—	140	hypersaline
McCallum	MC	68 38 0	78 01 0	-1 71	32	meromictic	19 - 20	10 1 - 23 9	10 1 - 17 9	14.5	hyposaline
McNeil	MN	68 35 6	78 22 0	27 30	3 8	holomictic?	—	8 4 - 11.1	—	8 8	hyposaline
Oblong #	OB	68 37 5	78 14 2	-2.89	14 8	meromictic	5.5	148 4 - 178 1	171.1 - 178 1	165	hypersaline
Organic #	OR	68 27 5	78 11 5	2 75	7	meromictic	4	138 8 - 177 1	175 0 - 177 1	142	hypersaline
Oval #	OV	68 32.0	78 16 0	-28 44	16	meromictic	11	142 9 - 175 3	142 2 - 174 4	143	hypersaline
Pendant	PE	68 27.7	78 14 5	3 045	18 4	meromictic	9 - 11	13 5 - 36.6	13 5 - 18.1	13 6	hyposaline
"Pointed" #	PO	68 31.5	78 19 75	5 52	5	holomictic	—	5 0 - 5.1	—	5 1	hyposaline
Scale	SC	68 35 0	78 10 0	—	10 6	meromictic	4 - 6	16 3 - 32.4	16 3 - 27 6	16 3	hyposaline
Shield #	SH	68 32 0	78 15 0	-6 915	33	meromictic	17 5	71 3 - 154 1	71 3 - 133 4	77.5	hypersaline
South Angle	SA	68 37 5	77 55 0	-0 385	20	meromictic	4	104 6 - 181 5	104 6 - 162 1	138	hypersaline
Vereteno #	VE	68 31 2	78 24 0	0 96	25	holomictic	—	3 7 - 3 8	—	3.7	hyposaline
Watts	WA	68 36 0	78 11 0	—	29 5	holomictic	—	2 2 - 2.4	—	2.3	fresh
Weddell	WE	68 33.2	78 06 5	—	6	holomictic	—	58 9 - 72 6	—	59 4	hypersaline
Williams	WI	68 29 0	78 09 5	1 165	7	meromictic	5 - 6	46.6 - 134 3	104 05 - 134 3	46 9	hypersaline

Table 3

Water chemistry results of each of the lakes in the training dataset.

Lake Name	Lake Code	Salinity (‰ at 2m)	NO3 (µmol l^{-1})	PO4 (µmol l^{-1})	SiO2 (µmol l^{-1})	Na (mg l^{-1})	K (mg l^{-1})	Mg (mg l^{-1})	Ca (mg l^{-1})	Cl (mg l^{-1})	SO4 (mg l^{-1})	Alkalinity (mg l^{-1} $CaCO_3$)
Abraxas	AB	15.8	<0 10	0 08	36 04	3560	237	690	76	6150	1076	50
Ace	AC	16 2	<0.10	0 19	27.20	4420	404	1170	58	9100	312	110
"Admin"	AD	14.8	<0 10	0.91	186.76	4470	340	740	182	7400	1788	67.5
Anderson	AN	62.9	1 45	0 12	104.27	16890	1150	5490	500	33500	1740	90
Burch	BU	138	<0.10	2.76	134.61	52830	3130	15020	2310	92700	3320	80
Burton	BT	41.6	<0.10	15 00	101.42	13270	1350	2890	570	21850	3620	70
Camp	CA	16 4	<0.10	0.29	99.00	4500	360	1140	115	8200	520	75
Clear	CL	10.7	<0.10	0 26	107 92	2370	148	540	24	4400	458	120
Collerson	CO	8.6	<0.10	0 99	98.97	2600	174	560	16	4600	84	237.5
Ekho	EK	52.0	0.13	0.35	41.74	13210	1940	3360	430	26100	1975	80
Fletcher	FL	65.3	0.42	1.27	91.35	25090	1130	6380	1010	35100	5720	52.5
Franzmann	FR	71.4	15.06	3.36	133.31	23880	1070	6090	1080	35700	6460	92.5
Grace	GR	1.1	<0.10	0.79	3.49	132	7.1	28	8 3	275	17.7	10
Hand	HA	5 5	<0.10	0.08	117.91	880	87	320	13	2200	8.8	67.5
Highway	HI	4.7	<0.10	0.18	22 83	510	43	97	26	940	105	32.5
Johnstone	JT	157	<0.10	0.26	90.70	62610	3820	18000	2750	105300	4010	165
Lichen	LI	0.5	<0 10	0.14	5.00	9 8	1.4	1.6	2.5	18	3.2	12.5
"LP 1"	LP1	74.1	<0.10	0 11	147.89	26590	1180	7870	530	45300	2610	215
"LP 2"	LP2	140	<0.10	0.24	139.54	59380	3290	17400	1950	102500	4130	187 5
McCallum	MC	14.5	<0.10	0.15	84.06	2750	184	540	20	4800	390	162.5
McNeil	MN	8 8	<0.10	0.10	122 65	3050	195	930	50	5850	448	82 5
Oblong	OB	165	<0.10	0.21	113.53	65520	4620	19490	2460	117800	2460	157.5
Organic	OR	142	<0.10	16.00	68.74	67640	4870	20080	3190	116400	4100	197.5
Oval	OV	143	<0.10	0.94	122.07	52830	2900	15020	1730	89700	2250	165
Pendant	PE	13.6	<0 10	0.61	118 54	4250	296	870	178	7400	1320	60
"Pointed"	PO	5 1	<0 10	0.18	54.81	1410	430	460	22	2950	81	107 5
Scale	SC	16.3	<0 10	0.16	79 15	4500	435	1500	22	9200	122	245
Shield	SH	77.5	<0.10	0.19	101.60	23410	1240	6680	790	40300	2750	70
South Angle	SA	138	<0.10	0.45	142.38	49180	2760	14430	1810	89700	2400	160
Vereteno	VE	3.7	<0.10	0.10	17.95	1050	205	270	38	1950	207	40
Watts	WA	2 3	<0 10	0 18	9 68	610	105	215	25	1200	187	42.5
Weddell	WE	59.4	0.11	0.13	153 16	17540	2240	4460	430	33500	3485	130
Williams	WI	46.9	0.95	0.21	49.29	12960	1370	3180	570	25550	1910	65

The relationships between the lakes sampled, the diatom assemblages enumerated and the active environmental variables measured are identified in Figures 9 and 10.

The position of each taxon on the CCA biplot approximates its weighted average optimum relative to other taxa (Wilson *et al.* 1994).

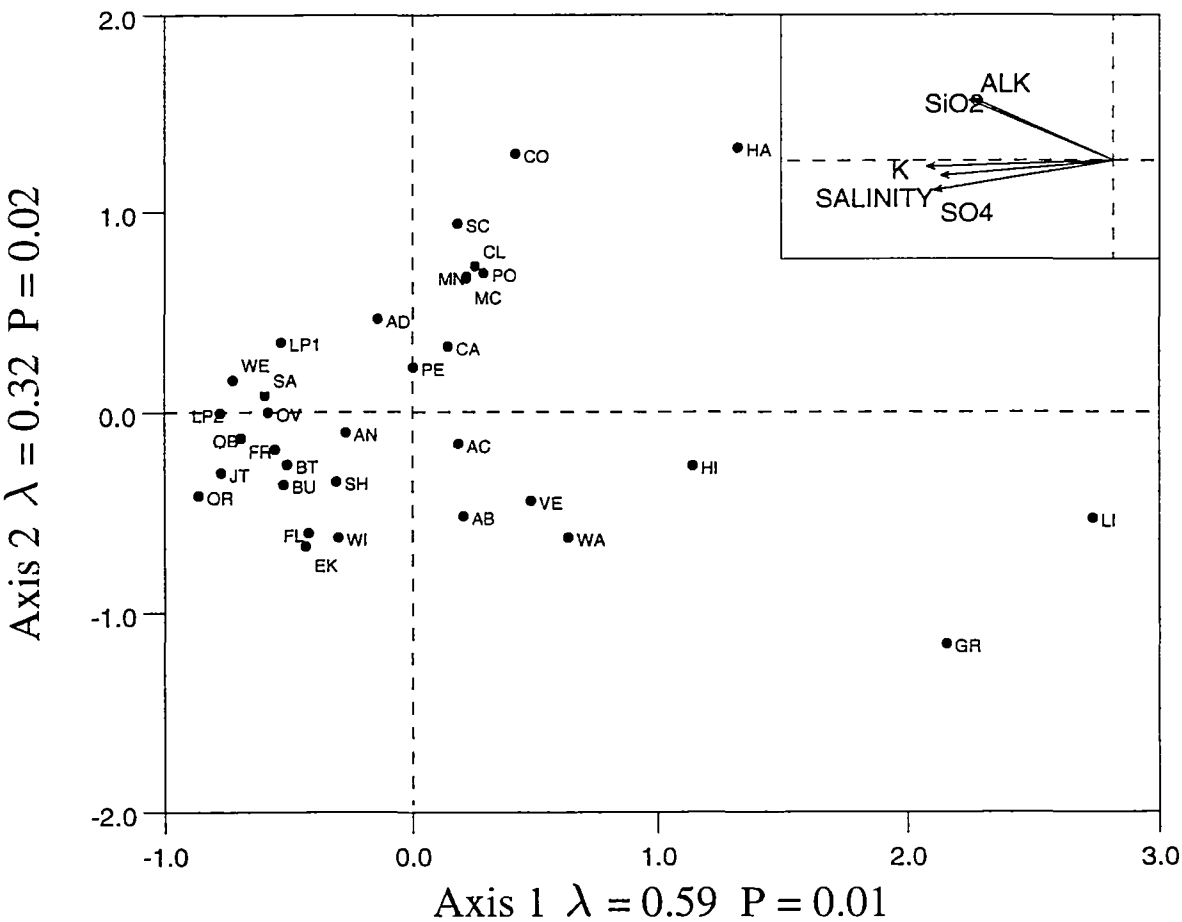

Figure 9: Canonical correspondence analysis ordination biplot showing active environmental variables (inset) and lake sample distributions (circles). Lake codes are listed in Tables 2 and 3.

In a CCA ordination constrained by preliminary CCAs to 5 active environmental variables (salinity, silicate, potassium, sulphate and alkalinity), axes 1 and 2 (eigenvalue 1=0.59, eigenvalue 2=0.32) explain a cumulative total of 19.6% (12.6% and 7.0% respectively) of the variance in the weighted averages of the diatom data. The diatom-environment correlations for axis 1 (0.93) and axis 2 (0.85) are high, indicating a strong relationship between the diatom taxa and the active environmental variables in the ordination. Unrestricted Monte Carlo permutation tests of axis 1 and axis 2 (with axis 1 as covariable) show that both axes are significant ($P<0.05$) (ter Braak, 1990).

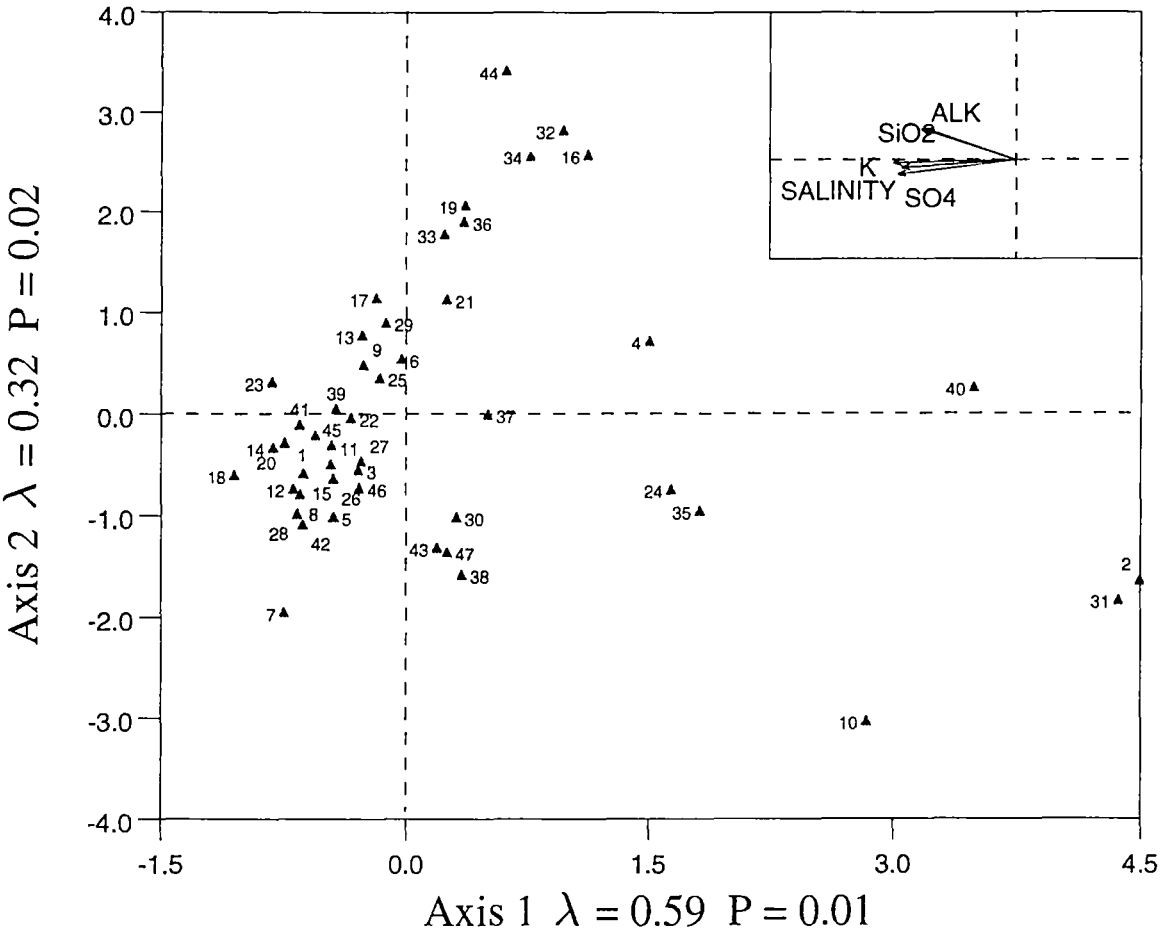

Figure 10: Canonical correspondence analysis ordination biplot showing active environmental variables (inset) and diatom species distributions (triangles). Species reference numbers are listed in Table 4.

The relative contribution of each of the active environmental variables to the ordination axes is evaluated by the intra-set correlations (Table 5) which reflect the correlation between the environmental variables and the ordination axes (Jongman *et al.*, 1987). The first axis corresponds to a gradient in salinity (and correlated ions Na, Mg, Ca and Cl), silicate, potassium, sulphate and alkalinity.. Silicate and alkalinity are also correlated with the second axis.

Forward selection with unrestricted Monte Carlo permutation tests (99 permutations) identified 2 active environmental variables accounting for 60% of the variance explained by the 5 active variables. Salinity (P=0.01) accounted for 38% of the variance explained by the 5 active variables while silicate (P=0.02) accounted for 22%.

Table 4

List of diatom species included in the numerical analyses and reference numbers

Each species is illustrated and discussed in Appendix 2

	Pennales	25	*Navicula* species f
1	*Cocconeis* species a	26	*Fragilariopsis curta*
2	*Achnanthes abundans*	27	*Fragilariopsis cylindrus*
3	*Amphora* species a	28	*Nitzschia lecointei*
4	*Amphora veneta*	29	*Nitzschia permunuta*
5	*Amphora* species b	30	*Nitzschia* species b
6	*Amphora* species c	31	*Stauroforma inermis*
7	*Amphora* species d	32	*Punnularia cymatopleura*
8	*Cocconeis costata*	33	*Punnularia lundii*
9	*Cocconeis fasciolata*	34	*Punnularia microstauron* var. *microstauron*
10	*Cocconeis pinnata*	35	*Punnularia microstauron*
11	*Fragilaria construens* var *venter*	36	*Punnularia quadratera* var a
12	*Fragilaria* species a	37	*Punnularia viridis* Nitzsch
13	*Hantzschia virgata*	38	*Punnularia viridis* var "*constricta*"
14	*Navicula directa*	39	*Stauroneis* species a
15	*Navicula glaciei*	40	*Stauroneis anceps*
16	*Navicula mutica / Navicula muticopsis*	41	*Stauroneis* cf. *saluna*
17	*Navicula tripunctata*	42	*Trachyneis aspera*
18	*Navicula* species a	43	*Tryblionella marginulata*
19	*Navicula seminulum*	44	Genus indetermined species a
20	*Navicula* species b		
21	*Navicula* species d		Centrales
22	*Navicula permunuta*	45	*Chaetoceros* vegetative cells
23	*Navicula* species e	46	*Chaetoceros* resting spores
24	*Navicula* species i	47	*Thalassiosira antarctica*

The remaining active variables did not individually explain any additionally significant proportion of the variance of the diatom weighted averages, although a similarly high portion of the variance was explained when sulphate or potassium was selected instead of salinity and alkalinity was selected instead of silicate.

Table 5

Intra-set correlations of active environmental variables for axes 1 and 2.

Variable	Intra-Set Correlation Axis 1	Intra-set Correlation Axis 2
Salinity	-0.90	-0.13
SiO_2	-0.75	0.54
K	-0.97	-0.05
SO_4	-0.93	-0.26
Alk	-0.72	0.55

Canonical coefficients represent the weight that each environmental variable contributes to the ordination axes, the significance of which can be estimated using approximate t-tests (ter Braak, 1987c). However, when environmental variables are strongly correlated with each other, the canonical coefficients are unstable (ter Braak, 1986). For example, both potassium and sulphate are strongly correlated with salinity (weighted correlation coefficients of 0.94 and 0.87 respectively) and alkalinity is strongly correlated with silicate (weighted correlation coefficient of 0.73). Potassium, sulphate and alkalinity were therefore removed from the dataset to determine the canonical coefficients and t-values of those variables contributing significantly and independently to the ordination axes (Table 6). The canonical coefficients were significant (P = 0.05) for both variables (salinity and silicate) and for both axes.

Table 6

Canonical coefficients and their t-values of the environmental variables selected by forward selection for axes 1 and 2. All t-values are significant (P = 0.05).

Variable	Canonical Coefficient Axis 1	Canonical Coefficient Axis 2	t-value Axis 1	t-value Axis 2
Salinity	-0.56	-0.60	-5.84	-5.83
SiO_2	-0.21	0.71	-2.21	6.91

Due to the strong correlation between potassium and sulphate with salinity and alkalinity with silicate herein, salinity is considered as a proxy for potassium and sulphate as well as all other correlated ions (identified earlier as those variables with VIFs >20). Similarly, silicate is considered as a proxy for alkalinity.

Consequently, the first gradient, from right to left on CCA axis 1 (Figure 9 & 10) corresponds to a gradient in salinity (and correlated variables). Freshwater lakes (e.g. Lichen and Grace) and their constituent diatom assemblages (e.g. *Achnanthes abundans* (2), *Cocconeis pinnata* (10) and *Stauroneis anceps* (40)) are separated from the hypersaline lakes (e.g. Organic, Johnstone and Oblong) and their constituent assemblages (e.g. *Navicula directa* (14) and *Navicula* species a (18) and e (23)). Hyposaline lakes (e.g. Highway, Pointed and Clear) are dominated by *Pinnularia* species (32 - 38) while the marine species (*Fragilariopsis curta* (26), *Fragilariopsis cylindrus* (27), *Nitzschia lecointei* (28), *Navicula glaciei* (15) and *Chaetoceros* vegetative cells and resting spores (45 and 46 respectively)) cluster together close to the origin of the biplot (Figure 10).

The second gradient identified along both CCA axis 1 and CCA axis 2 (Figure 9 &

10), from bottom right to top left, corresponds with silicate concentrations (and correlated variables). Lakes with low silicate (e.g. Lichen, Grace and Watts) are separated from high silicate lakes (e.g. Hand, Admin and LP 1). Taxa plotted bottom right, such as *Achnanthes abundans* (2), *Cocconeis pinnata* (10) and *Stauroneis anceps* (40) are characteristic of lakes with low silicate. Taxa plotted in the top left hand corner of Figure 10 (e.g. *Navicula mutica/muticopsis* (16) and *Navicula seminulum* (19) plus many of the *Pinnularia* species (32 - 38)) are characteristic of lakes with high silicate concentrations. The unidentified genus, Gen. indet species a (44), appears to be indicative of hyposaline, high silicate environments.

Constrained CCA's using salinity and silicate individually were used to estimate the relative importance of each of these variables in explaining the species data (ter Braak, 1988). The ratio of the first constrained eigenvalue to the second unconstrained eigenvalue identifies which variable has the strongest influence on the dataset. Ratios greater than 0.50 suggest that there is a diatom signal for that variable. Values less than 0.50 are less robust and would be of less use in inference models (Dixit *et al.*, 1991). The ratios of 0.85 for salinity and 0.72 for silicate found in this study indicates that both salinity and silicate explain significant amounts ($P<0.05$) of variation in the distribution and abundance of the diatom assemblages. Both variables can therefore be used in inference models although salinity has a greater influence. It is also difficult to quantify the relationship between silicate concentration and climatic change whereas salinity has a clear relationship with changing precipitation and evaporation. As a consequence, salinity would provide a more appropriate climate inference tool.

4.1.2 Weighted Averaging Regression and Calibration

As canonical correspondence analysis revealed that diatom distribution and abundance in the lakes of the Vestfold Hills is strongly and significantly related to salinity, this variable was subsequently chosen as an appropriate environmental variable for a diatom-based transfer function for these lakes.

Weighted averaging regression and calibration was then applied to the full training dataset. Salinity inferences were calculated from the optimum and tolerance of each of the 47 diatom taxa in the 33 surface sediment samples (Table 7). The optima and tolerances of individual diatom taxa are shown in Figure 11. Salinity optima of the diatom taxa range from 0.6 to 122 ‰ with taxa with both narrow and broad salinity tolerances identifiable across the salinity gradient. The continuous distribution of the optima from 0.6 to 122 ‰ shows that there is a good representation of diatom taxa across the entire salinity gradient from low to high salinity (cf. Figure 12). For example, *Achnanthes abundans* and *Stauroneis anceps* have optima below 3 ‰, *Pinnularia* species (*P. microstauron*, *P. cymatopleura* and *P. viridis*) all have optima between 3 and 30 ‰, *Fragilariopsis cylindrus* has an optimum of 33 ‰, and *Navicula glaciei*, *Navicula directa* and *Navicula* species a all have optima above 35 ‰.

Table 7

List of diatom species included in numerical analyses, number of occurrences within the training dataset (N) and the effective number of occurrences (N2-Hill (1973)) upon which optima and tolerance are based, maximum relative abundance (% of total diatoms) and salinity optima and tolerances back-transformed to ‰.

Taxon Name	N	N2	Maximum Relative Abundance (%)	Salinity Optima (‰)	Salinity Tolerance (lower limit - upper limit) (‰)
Pennales					
Achnanthes abundans	5	1 0	64.3	0.6	0.2 - 2.1
Amphora veneta	21	5 2	32.3	6.7	1.5 - 29 2
Amphora species a	12	5 0	2 3	36.8	6.1 - 221.1
Amphora species b	6	3.2	5.3	39 6	17.4 - 90.1
Amphora species c	3	1 1	27 1	15.5	6.8 - 35 1
Amphora species d	2	1 1	2.0	54 5	27.5 - 107.9
Cocconeis costata	15	5.5	4 3	52.2	16.4 - 166 0
Cocconeis fasciolata	12	4.2	4.8	23.6	6.2 - 89.2
Cocconeis pinnata	3	1.8	2.0	1.5	0.5 - 4.7
Cocconeis species a	9	5 9	3.3	39.2	11.5 - 134.1
Fragilaria construens var *venter*	12	4.0	6.9	35 7	13.1 - 97.6
Fragilaria species a	25	7.2	7.5	51.2	17 8 - 147.4
Hantzschia virgata	11	3 6	4.3	38.7	11.5 - 130.8
Navicula directa	28	12.3	59.9	77 5	28 4 - 211 5
Navicula glaciei	13	4.7	16.9	44.8	13 8 - 145.7
Navicula mutica / Navicula muticopsis	25	3.2	23.1	10.6	2.9 - 39.3
Navicula perminuta	15	3.7	7.1	27.1	9.8 - 75.2
Navicula tripunctata	29	9.8	55.4	26.7	7.4 - 96.9
Navicula seminulum	1	1.0	8.5	8.3	2.7 - 26.0
Navicula species a	11	5.3	29.4	122 3	49.5 - 301.8
Navicula species b	24	12 0	29.8	65 2	25 4 - 167.3
Navicula species d	20	6.3	20 6	13.7	8.0 - 23.4
Navicula species e	17	4 3	11.9	82.7	24.7 - 276.2
Navicula species f	3	2 3	2.1	18.0	10.1 - 32 5
Navicula species i	5	1.4	5 3	5.7	1.2 - 27.1
Fragilariopsis curta	16	8 8	2.9	34.2	9.7 - 121.1
Fragilariopsis cylindrus	18	4.1	32.1	33.2	10.2 - 108.1
Nitzschia lecointei	18	5.6	5.5	48.4	19.4 - 120.6
Nitzschia perminuta	20	8.6	4 3	23.9	5.8 - 98.3
Nitzschia species b	5	2.3	3.0	11.2	1.3 - 96.1
Pinnularia cymatopleura	15	4.3	15.9	9.3	5.0 - 17 4
Pinnularia lundii	11	2 3	7.6	13.2	3.7 - 46.8
Pinnularia microstauron var. *microstauron*	5	2.2	8.0	10.8	4.6 - 25.4
Pinnularia microstauron	21	6 2	82 8	3.2	1 2 - 8.7
Pinnularia quadratera var. a	5	1.1	5.8	8.6	2.3 - 31.7
Pinnularia viridis	17	4 5	30.1	13 8	6.2 - 30.6
Pinnularia viridis var. "constricta"	1	1.0	13.6	15.9	5.1 - 49 6
Stauroneis anceps	5	2.1	3.0	1.4	0.2 - 9.7
Stauroneis cf. *salina*	8	4.8	2.3	49.1	20.2 - 119.1
Stauroneis species a	26	12.2	13.5	37 5	13.7 - 102.6
Stauroforma inermis	6	1.3	12 2	0.7	0.1 - 3.1
Trachyneis aspera	6	2.7	2.0	59.9	17 0 - 211.3
Tryblionella marginulata	10	1.6	12.2	17.8	6.8 - 46.4
Genus indetermined species a	7	1 8	64.1	9.2	7.3 - 11.6
Centrales					
Chaetoceros vegetative cells	21	12 8	62.2	44.4	14.5 - 136.4
Chaetoceros resting spores	27	11 3	32 4	33 6	6.7 - 169.7
Thalassiosira antarctica	8	1.7	2.6	18.0	4.5 - 73.1

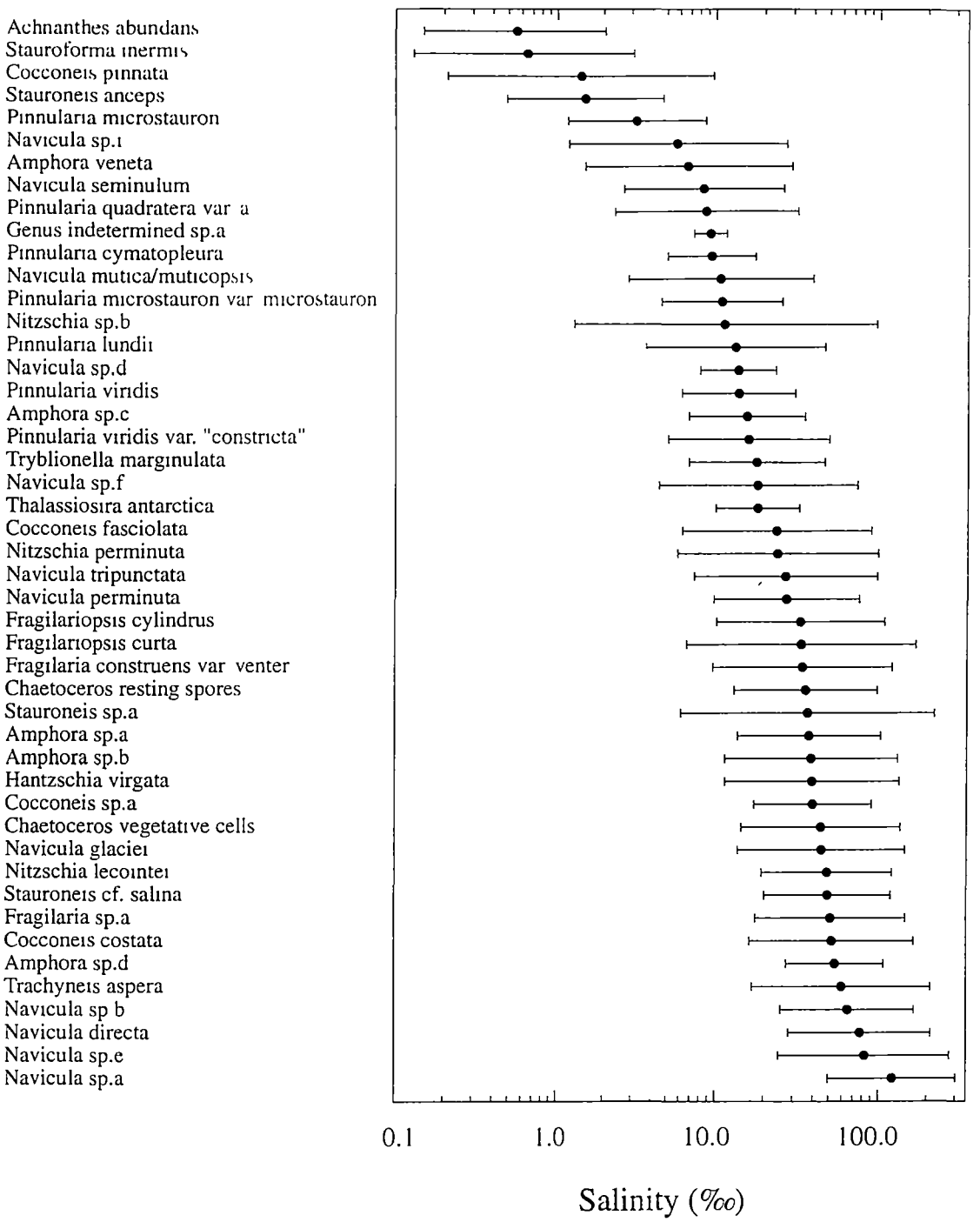

Figure 11: The estimated salinity optima (solid circles) and tolerances (solid lines) of the training dataset diatom species determined by weighted averaging. Species are arranged in order of increasing salinity optima. Logged tolerances were added to and subtracted from the logged optima and all 3 numbers back transformed (included in Table 7).

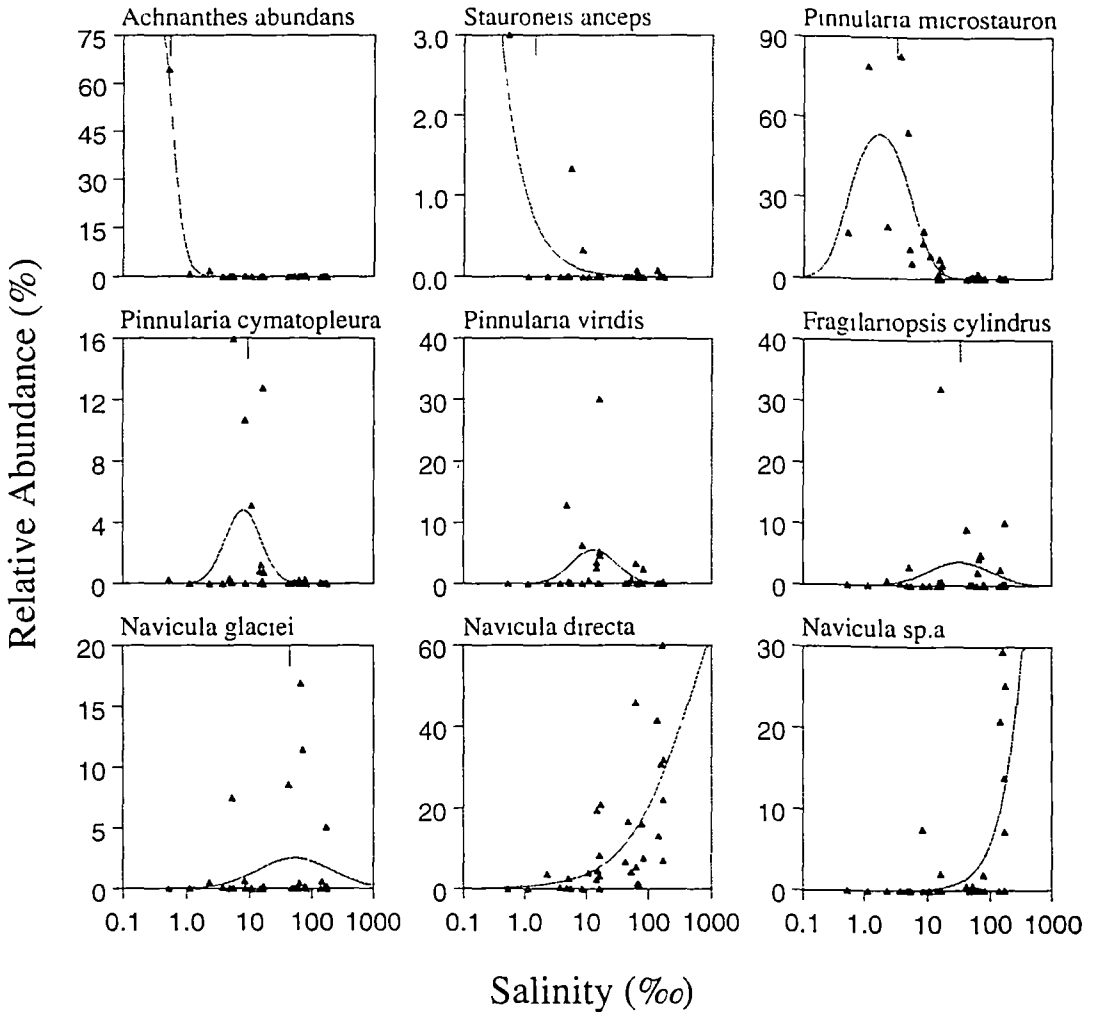

Figure 12: The distribution of selected diatom taxa in the training dataset along a salinity gradient. Gaussian logit curves were fitted to these taxa using CALIBRATE 0.54 (Juggins & ter Braak, 1992). The estimated weighted average salinity optimum of each taxon is marked by a vertical line at the top of each plot.

Pinnularia cymatopleura is an example of a species with a narrow tolerance, only occurring in the hyposaline lakes sampled, while *Navicula directa* has a broad tolerance, occurring in most environments sampled, although in relatively higher abundances in hypersaline environments. The distribution of these few diatom species with salinity show how optima and tolerances can be used in a weighted-averaging model to give certain species an indicator affinity for a particular salinity range. In addition, the relative abundances of these species in sediment cores can also be used to give a qualitative indication of salinity category of the past lake environment.

In developing the transfer function, trends in residuals revealed over estimation at the fresh and under estimation at the hypersaline end of the salinity gradient for inverse deshrinking. Classical deshrinking showed no residual trend, thus indicating this deshrinking technique will provide a more reliable estimate of palaeosalinity, particularly at the extremes of the salinity gradient (cf. Birks *et al.*, 1990; Jones & Juggins, 1995). Classical deshrinking was therefore chosen as the deshrinking method for the transfer function developed herein.

Statistical results for both simple and tolerance downweighted WA show that the predictive ability of the WA and WA(tol) models, in terms of the predicted r^2 and the RMSEP, are comparable (Table 8).

Table 8

Weighted averaging (WA) and weighted averaging with tolerance downweighting (WA(tol)) summary statistics for the classical deshrinked model. The apparent correlation between observed and diatom-inferred salinity (r^2) and the root mean square of the error (observed x_i - inferred x_i) (RMSE) is given as well as the jackknifed correlation (r^2 predicted) and the jackknifed RMSE (RMSEP) which provide a more realistic predictive correlation and error estimate between observed and diatom-inferred salinity. All figures are in $\log_{10}$ units.

Classical Model	r^2	r^2 predicted	RMSE	RMSEP
WA	0.80	0.73	0.33	0.37
WA(tol)	0.85	0.69	0.28	0.38

Simple WA was chosen as it results in slightly higher predicted correlation between measured and diatom-inferred salinity and slightly lower predicted estimates of the error in this model. The strong predicted relationship between observed salinity and diatom-inferred values for this model (both with and without Jackknifing) is illustrated in Figure 13.

The resulting WA classical deshrinked transfer function was applied to fossil diatom assemblages enumerated from each of the sediment cores collected. Diatom-inferred salinity concentrations ($\log_{10}$ ‰) were then derived from the classical deshrinking regression equation: Final x_i = (Initial x_i - 0.53)/0.61 where x_i is the inferred value of the environmental variable x for the sample i. These values were back transformed to give estimated epilimnetic palaeosalinity (‰) for each core (Figures 15,17a,b, 19 and 21).

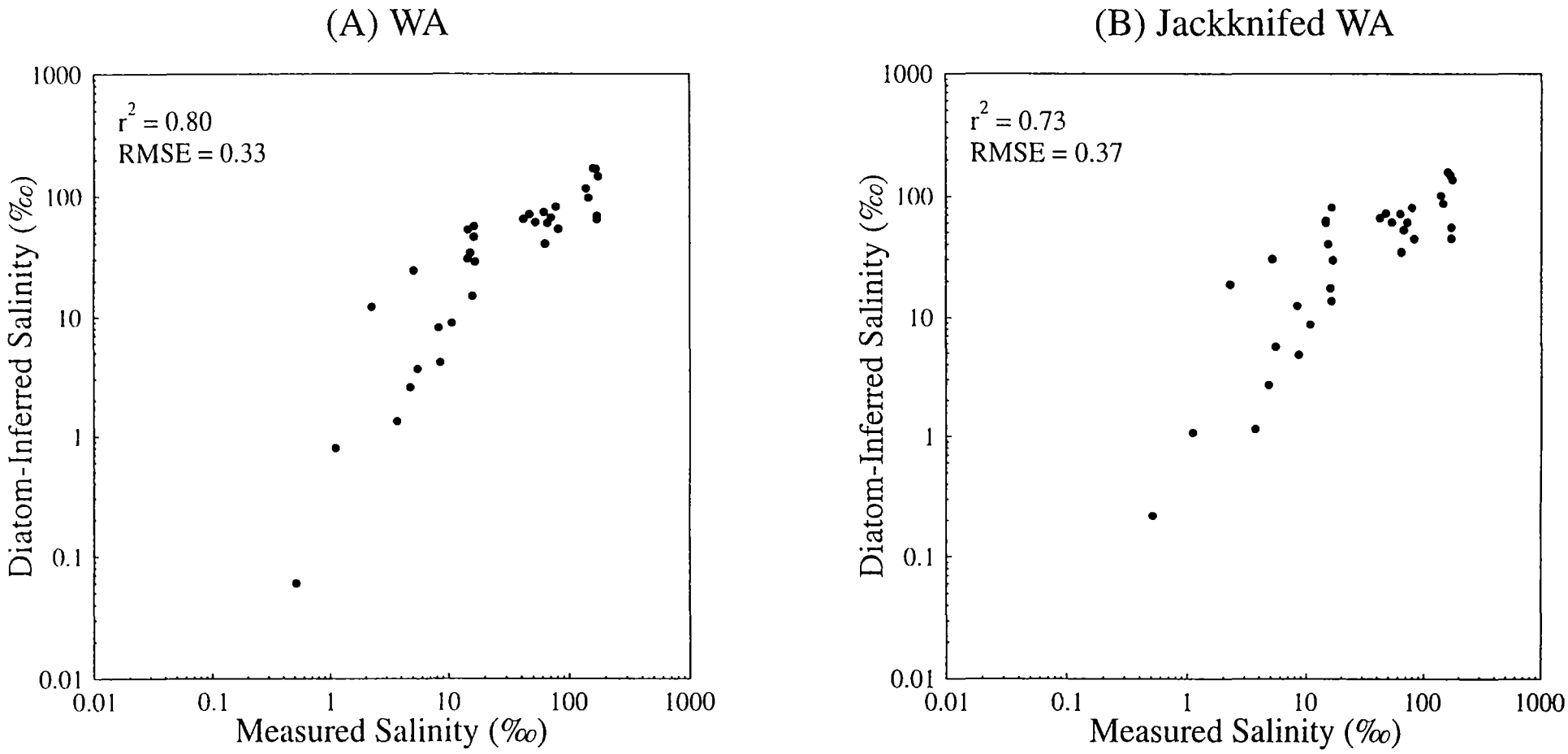

Figure 13: The relationship between measured salinity and diatom-inferred salinity of the training set lakes (33) based on a simple weighted averaging model with (B) and without (A) jackknifing. Jackknifed weighted averaging provides a more realistic view of the predictive ability of the model.

4.2 Development of the Analogue Matching Method

A modern analogue matching technique was also applied to the sediment cores as an alternative method for estimating palaeosalinity from fossil diatom assemblages. In addition to reconstructing the palaeosalinity from the diatom assemblages, modern analogue matching determines which of the fossil samples have "no" or "poor" analogue situations.

Palaeosalinity estimates are given as both means and weighted means of estimates based on the 4 most similar assemblages from the training set (based on the best r^2 and RMSE of the number of modern analogues used for a match from 1 to 10) (Table 9).

Table 9

Mean and Weighted Mean summary statistics for the modern analogue matching method. The apparent correlation between observed and diatom-inferred salinity (r^2) and the root mean square of the error (RMSE) (observed x_i - inferred x_i) is given. All figures are in $\log_{10}$ units.

M.A.T. N closest matches	Mean r^2	Mean RMSE	Weighted Mean r^2	Weighted Mean RMSE
1	0.64	0.44	0.64	0.44
2	0.61	0.43	0.61	0.43
3	0.60	0.44	0.61	0.44
4	0.65	0.41	0.65	0.41
5	0.63	0.43	0.64	0.43
6	0.61	0.43	0.63	0.42
7	0.63	0.43	0.65	0.42
8	0.62	0.44	0.65	0.42
9	0.63	0.44	0.65	0.42
10	0.60	0.45	0.63	0.43

Both the mean and weighted mean based models show the same best relationship between observed salinity and diatom-inferred values ($r^2 = 0.65$) and have the same best error term (RMSE = 0.41) (Figure 14). Both models also have similar trends in residual salinity. As a result no distinction can be made between the two methods and both mean and weighted mean palacosalinity estimates are given for each sediment core (Figure 16, 18, 20 and 22).

Each sediment sample was also evaluated for modern analogue matches. Close and good analogue situations within each sediment core are identified (Figure 16, 18, 20 and 22).

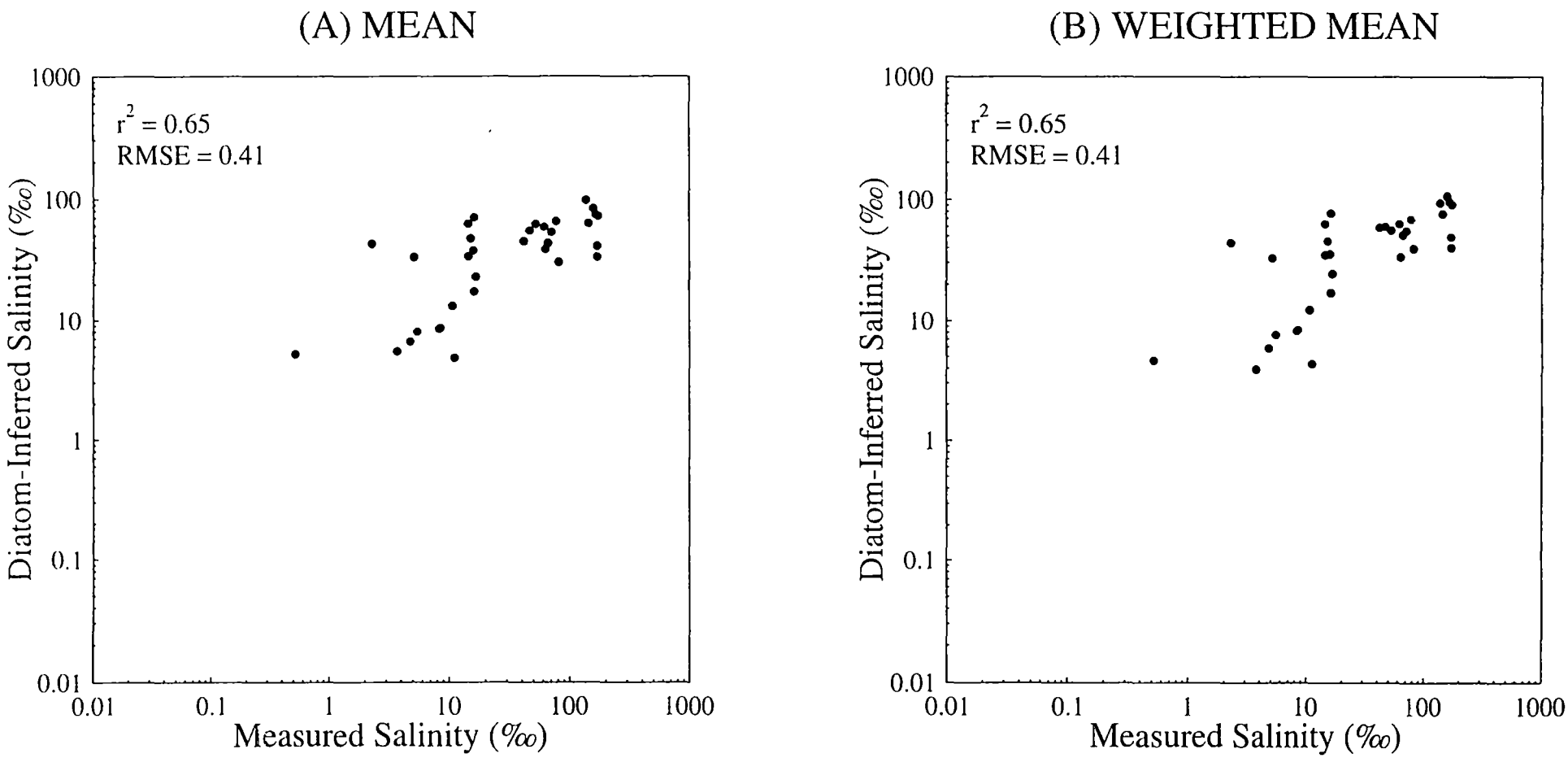

Figure 14: The relationship between measured salinity and diatom-inferred salinity of the training set lakes (33) based on (A) mean and (B) weighted mean modern analogue matching models.

4.3 Application of the Palaeosalinity Reconstruction Methods

Four lake sediment cores are analysed for diatom-salinity changes (Anderson Lake, Ace Lake, Lake McCallum and Cat Lake). Each core has been radiocarbon dated (Table 10) placing the diatom stratigraphy and associated palaeosalinity changes observed (Figures 15-22) into a Holocene chronology.

Table 10

Radiocarbon dates for the sediment cores analysed. Laboratory details are given in the individual lake core method sections (3.1.3).

Core Depth (cm)	Anderson Lake	Ace Lake	Lake McCallum	Cat Lake
0		984 ± 67		
22 - 29 (25.5)			4690 ± 170	
35 - 42 (38.5)				8170 ± 220
40	6730 ± 200			
72 - 78 (75)			9620 ± 110	
100		6472 ± 90		
104	7110 ± 270			
111	8450 ± 210			
102 - 124 (113)			12850 ± 360	
200		13020 ± 150		

4.3.1 Anderson Lake

Anderson Lake is a ~ 0.12 km^2 meromictic hypersaline lake situated on Mule Peninsula (Figure 4), the southernmost of the three Vestfold Hills peninsulas, at a current (February 1997) elevation of 3.33 m a.s.l. Current (i.e. 1994) mixolimnion salinities range from 57 to 75 ‰ while monimolimnion salinities range from 102 to 144 ‰. The mixolimnion freezes seasonally to ~ 1.8 m depth and the salty ice tends not to thaw completely (Pickard *et al.*, 1986). Water temperatures can be as high as 11°C below the ~ 3-4 m oxycline. Surveys by Seppelt *et al.* (1988) revealed no mosses or algae, and a low abundance of lichens, in the Anderson Lake basin. Therefore, negligible amounts of allochthonous organic matter are being deposited in the lake at present, indicating that organic material preserved in the sediments is from *in situ* biological production (Lewis, 1994).

Thirty-seven of the 47 taxa occurring within the training dataset were observed in the Anderson Lake core. Three zones can be identified on the basis of a change in the composition of the diatom assemblage with an associated change in the reconstructed salinity category:

Zone 1 (109.75 - 102 cm): The diatom-inferred salinity values in this zone are below 35 ‰. The base of the core is almost completely dominated by *Pinnularia microstauron*. This hyposaline - freshwater taxon has an estimated optimum of 3.2 ‰. Below 102 cm this species accounts for 9 - 73 % of the total diatoms enumerated.

Zone 2 (102 - 36 cm): The diatom-inferred salinity values in this zone fluctuate between 46 and 63 ‰. Between 36 and 102 cm *Fragilariopsis cylindrus*, and *Chaetoceros* cells dominate, reaching abundances of up to 28 and 68 % respectively. These marine diatoms have estimated optima of 33 and 44 ‰ respectively. *Pinnularia microstauron* was not found in this section of the core.

Zone 3 (36 cm - 0 cm): The diatom-inferred salinity values in this zone are above 50 ‰. From 36 cm to the top of the core *Navicula directa* is abundant (ranging from 5 - 40 %). This zone is also dominated by the hypersaline species *Navicula* species e and *Navicula* species a. All 3 species have high estimated salinity optima (78, 83 and 122 ‰, respectively). *Fragilariopsis cylindrus* and*Chaetoceros* vegetative cells still occur in this core section but decline in abundance from a mean abundance of 4.4 and 37.4 % respectively in Zone 2 to a mean abundance of 0.51 and 7.07 % respectively.

An interesting observation in the very top section of this zone (0 - 3 cm) is the rapid increase in abundance of *Chaetoceros* vegetative cells and the re-appearance of *Pinnularia microstauron*. In this 3 cm sub-zone *Pinnularia microstauron* and *Chaetoceros* vegetative cell abundance rises from 1.0 to 4.5 % and 4.8 to 52.2 % of the total diatoms counted respectively. Over the same sample range *Navicula directa* declines in abundance from 35.0 to 5.3 %.

The diatom stratigraphy and transfer function diatom-inferred salinity reconstruction of Anderson Lake is shown in Figure 15. Analogue matching palaeosalinity reconstruction is shown in Figure 16. Fossil analogues with modern samples in the training set are also identified in Figure 16.

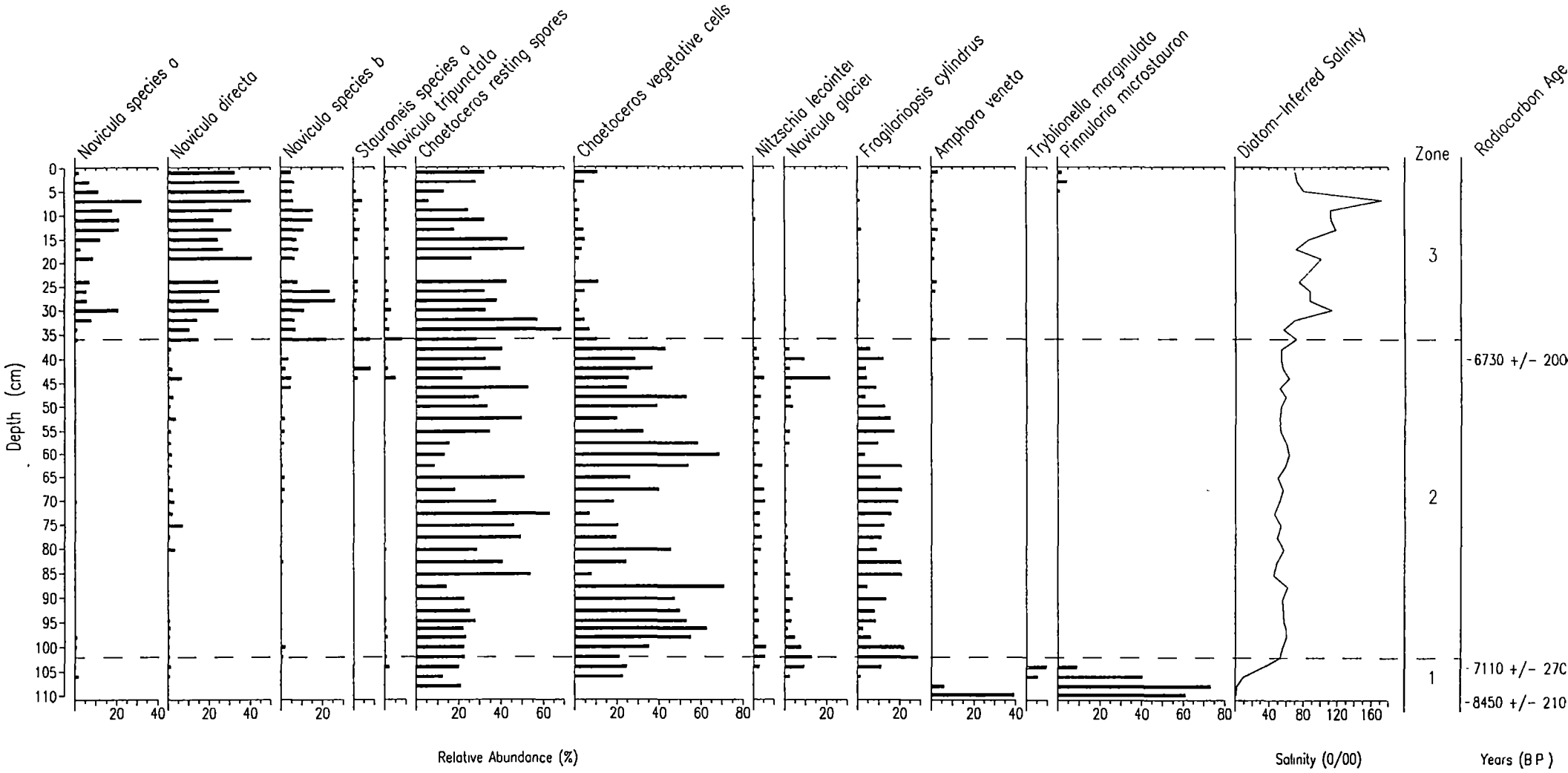

Figure 15: Diatom stratigraphy and transfer function diatom-inferred salinity for Anderson Lake. Relative abundances of the major (>5%) diatom taxa throughout the sediment core are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

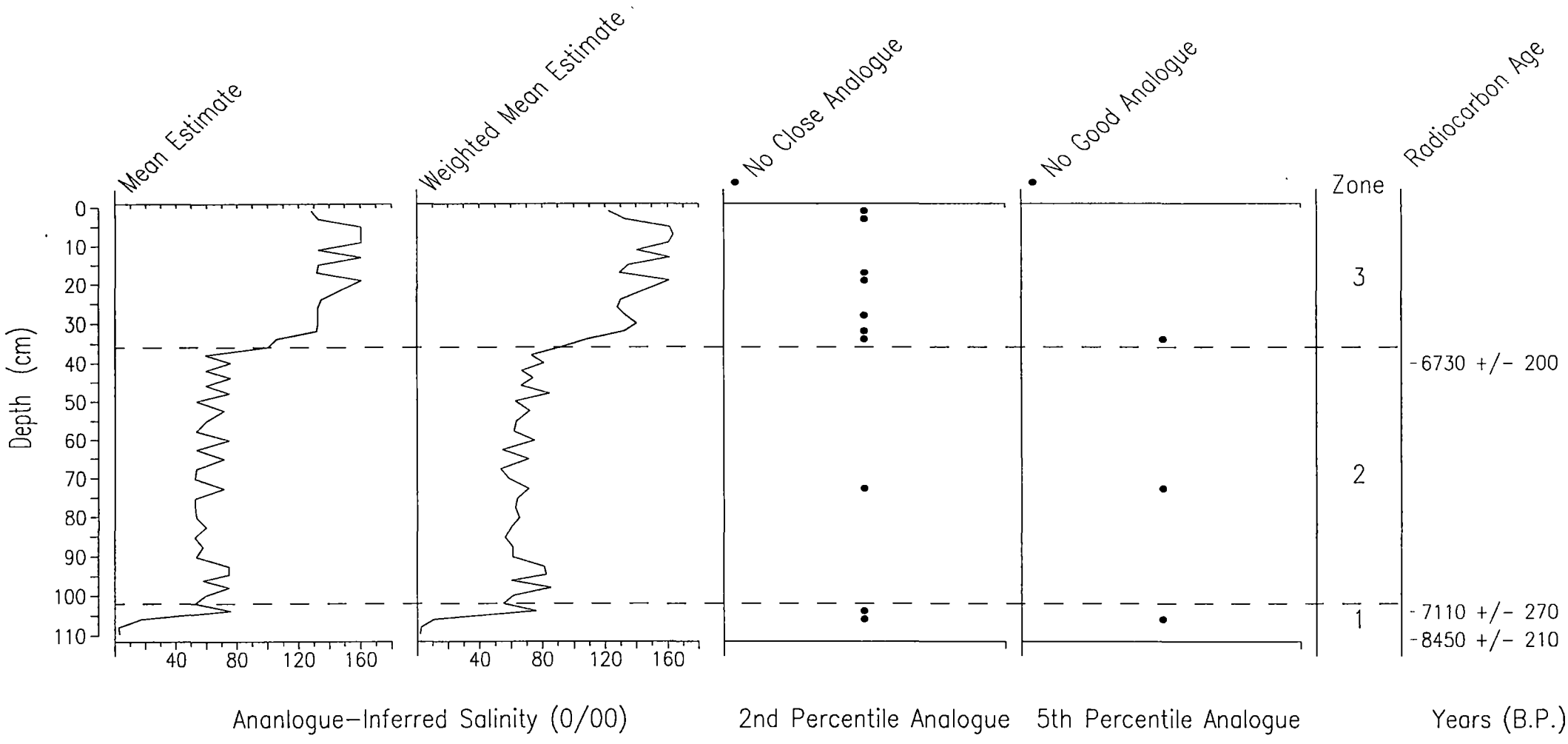

Figure 16: Modern analogue-inferred salinity for Anderson Lake. Both mean and weighted mean salinity estimates are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

Modern analogue matched palaeosalinity estimates show broadly similar trends to transfer function estimated palaeosalinity for Anderson Lake. The fossil assemblages within this core are comparable with those assemblages within the training set. Good analogues can be found for all but 3 fossil assemblages and close analogues can be found for all but 10 fossil assemblages.

Zone	No. of Fossil Samples	Mean Salinity Range Estimated (‰)	Weighted Mean Salinity Range Estimated (‰)	Number of Close/Good Analogues
1	17	2.60 - 76	1.81 - 76	10/16
2	29	53 - 76	54 - 85	28/28
3	4	53 - 160	54 - 163	2/3

Three radiocarbon dates supplied for this core are shown in Table 10. Consequently, diatom stratigraphy and the palaeosalinity estimates in Figure 15 and 16 coupled with radiocarbon dating of the core sediment enables the Holocene environmental history of Anderson Lake to be reconstructed as follows:

Zone	Type of Lake Inferred	Salinity Range Estimated (‰)	Radiocarbon Age (^{14}C yr B.P.)
1	fresh-hyposaline	1.16 - 32	~ 8000 - 7000
2	marine inlet	46 - 63	~ 7000 - 6000
3	saline	57 - 172	~ 6000 -present

4.3.2 Ace Lake

Ace Lake is a ~ 0.18 km^2 meromictic lake situated on Long Peninsula (Figure 4), the northernmost of the three Vestfold Hills peninsulas, at a current (February 1997) elevation of 8.73 m a.s.l. (J. Gibson, *pers. comm.*, 1997). Current (i.e. 1994) mixolimnion salinities range from 16 to 30 ‰ while monimolimnion salinities range from 31 to 40 ‰. Water temperatures are currently as high as 7 °C below the ~ 8 m oxycline. Surveys by Seppelt *et al.* (1988) revealed no mosses and a low abundance of sublithic algae and lichens in the Ace Lake basin.

Forty of the 47 taxa occurring within the training dataset were observed in the Ace Lake core. Diatom stratigraphy (Figure 17a,b) of this core sediment also revealed 3 distinct changes in species dominance and diatom-inferred salinity:

Zone 1 (175 - 135 cm): The diatom-inferred salinity values in this zone are below 15 ‰. The base of the core is almost completely dominated by *Amphora veneta, Pinnularia microstauron* and *Stauroforma inermis*. These hyposaline - freshwater taxa have salinity optima of 6.7, 3.2 and 0.7 ‰ respectively. Within this zone these species occur at maximum abundances of 85.25, 40 and 38 % respectively.

Zone 2 (135 - 30 cm): The diatom-inferred salinity values in this zone fluctuate between 40 and 67 ‰. Between 135 and 30 cm the dominant species from zone 1 disappear and are replaced by the marine and saline taxa *Chaetoceros* (vegetative cells and resting spores), *Fragilariopsis cylindrus, Navicula glaciei* and *Nitzschia lecointei*. These taxa are common in both marine and sea-ice ecosystems in Antarctica. With salinity optima ranging from 33 to 48 ‰, these species reach maximum abundances of 71, 15, 28.75, 19.75 and 18.75 % respectively.

This zone can be subdivided on the basis of the disappearance of *Chaetoceros* vegetative cells and resting spores and *Navicula glaciei*. Zone 2a (135 - 70 cm) is dominated by these planktonic and sea-ice taxons. Zone 2b (70 - 30 cm) is based on the disappearance of these taxons and the appearance of some of the Zone 3 species.

Zone 3 (30 - 0 cm): The diatom-inferred salinity values in this zone are above 45 ‰. From 30 cm to the top of the core *Navicula* species b, *Fragilaria* species a and *Stauroneis* species a become markedly abundant. These hypersaline species (salinity optima of 65, 51 and 37.5 ‰ respectively) reach maximum abundances of 86, 60.75 and 18.25 % respectively. *Fragilariopsis cylindrus* and *Chaetoceros* vegetative cells and spores still occur in this core section but are accompanied by many saline lake species of moderate abundances (between 10 and 20 %) such as *Cocconeis* species a, *Amphora* species b, *Fragilaria construens* var. *venter* and Navicula *directa* (Figure 17a,b).

Again, an interesting observation in this zone (and Zone 2b) is the re-appearance, although very slight, of the fresh water taxa *Pinnularia microstauron, Stauroforma inermis* and *Amphora veneta*.

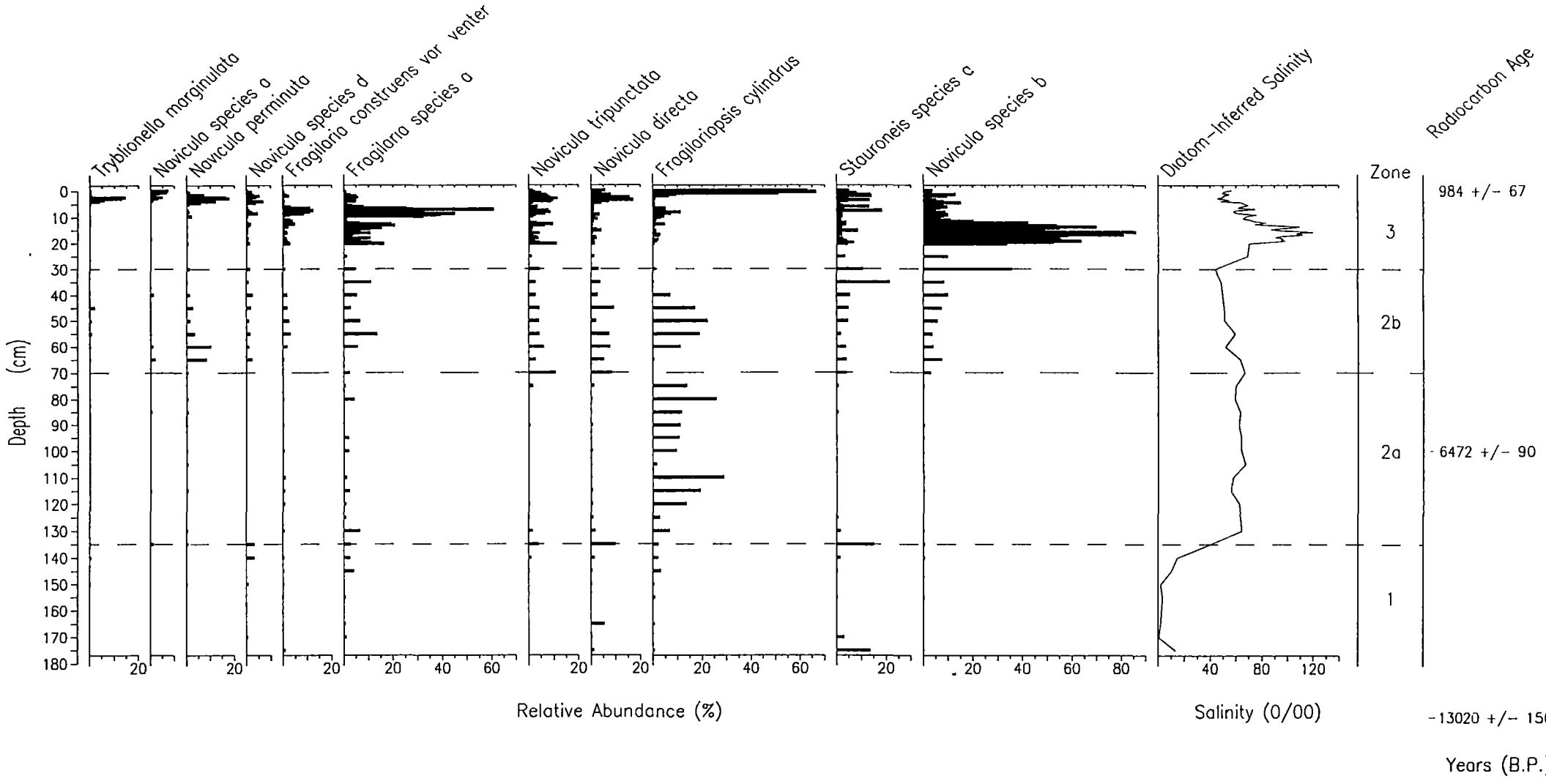

Figure 17a: Diatom stratigraphy and transfer function diatom-inferred salinity for Ace Lake. Relative abundances of the major (>5%) diatom taxa throughout the sediment core are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

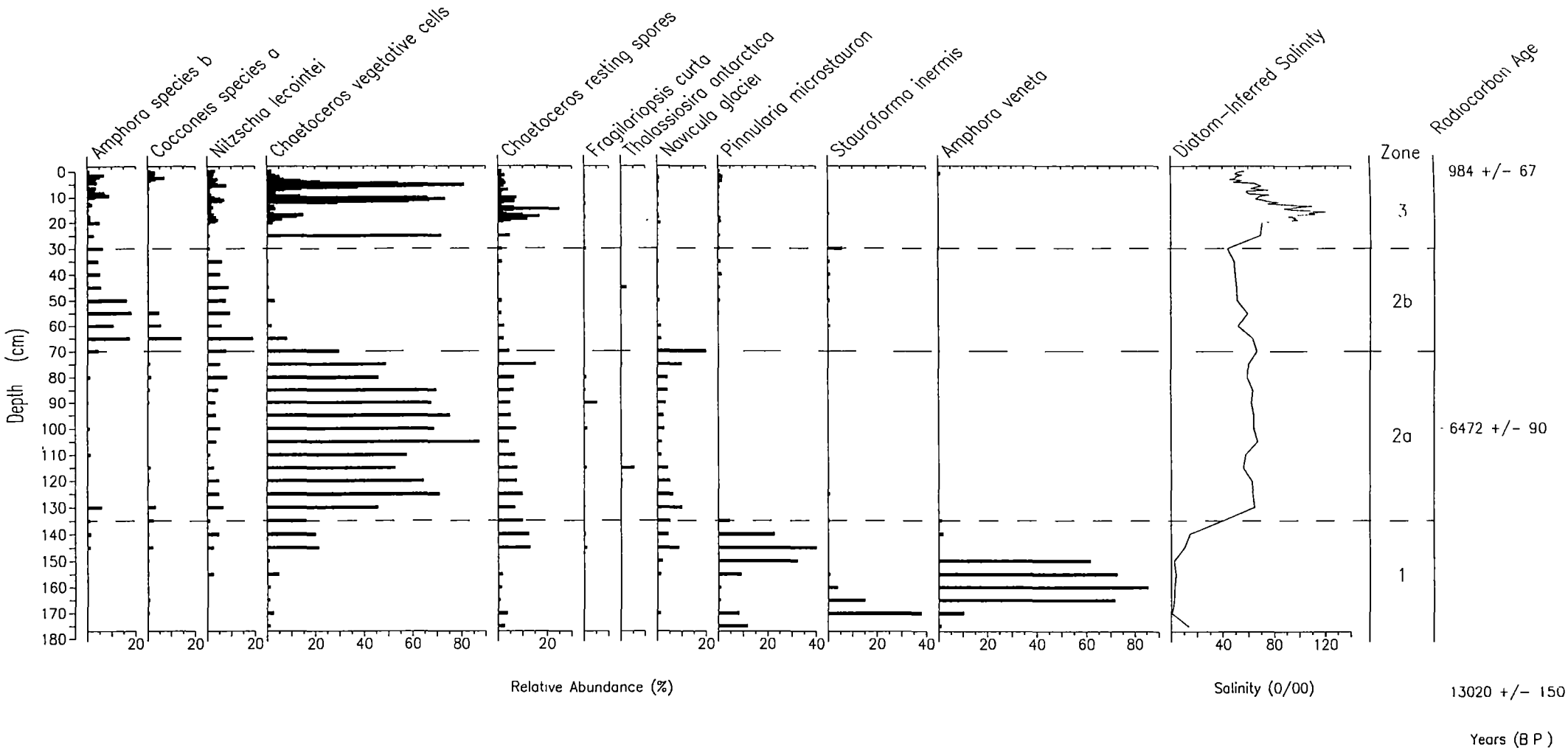

Figure 17b: Diatom stratigraphy and transfer function diatom-inferred salinity for Ace Lake. Relative abundances of the major (>5%) diatom taxa throughout the sediment core are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

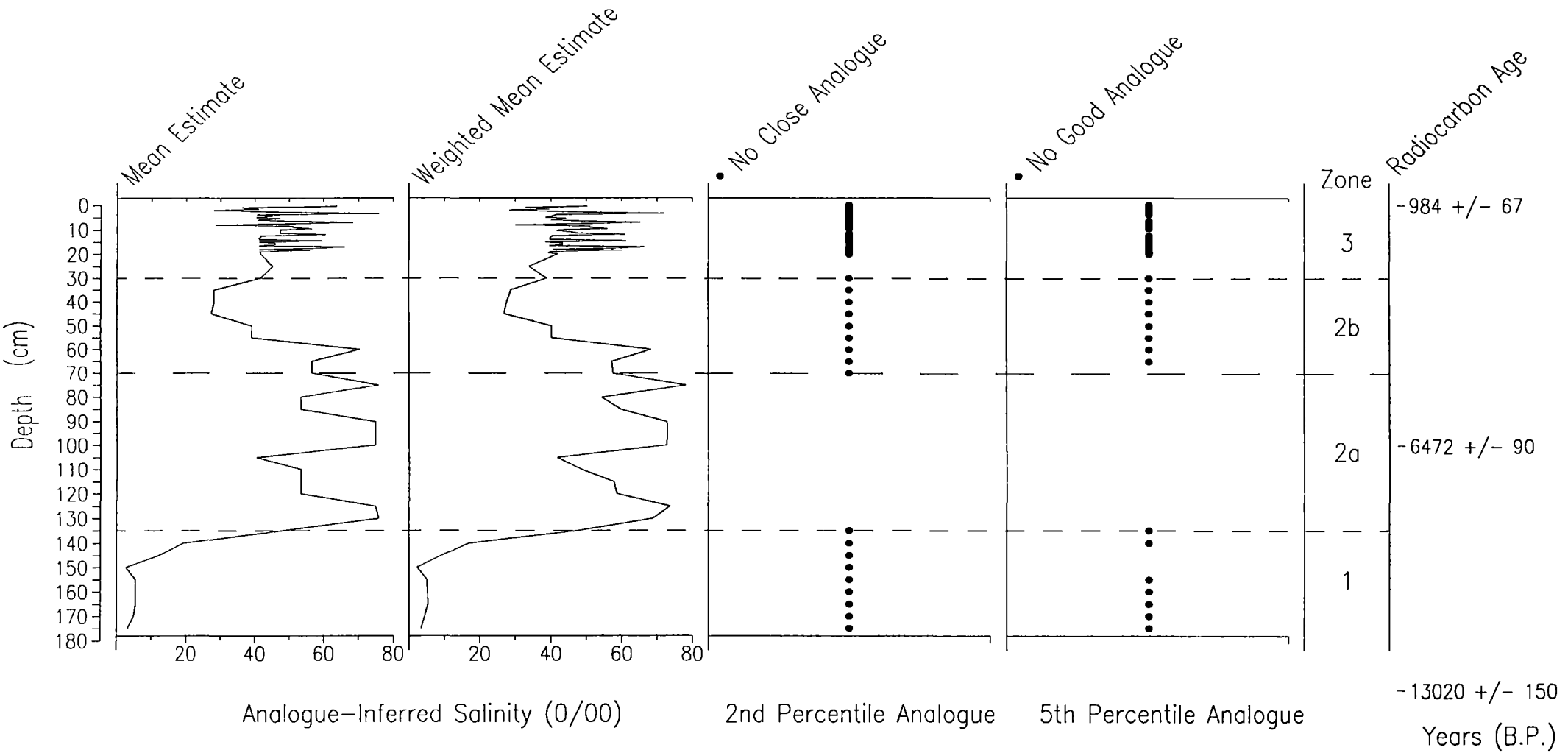

Figure 18: Modern analogue-inferred salinity for Ace Lake. Both mean and weighted mean salinity estimates are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

Modern analogue matched palaeosalinity estimates (Figure 18) show broadly similar trends to transfer function estimated palaeosalinity for Ace Lake (Figure 17a,b) although Zone 2 salinity is higher than Zone 3 salinity estimates. The fossil assemblages within this core are not comparable with those assemblages within the training set. The majority of fossil assemblages have no close or good analogues. Good analogues can be found for only 26 of the 72 fossil assemblages sampled and close analogues can be found for only 17 of these.

Zone	No. of Fossil Samples	Mean Salinity Range Estimated (‰)	Weighted Mean Salinity Range Estimated (‰)	Number of Close/Good Analogues
1	42	2.69 - 19	2.22 - 17	5/11
2	21	27 - 76	27 - 74	12/13
3	9	41 - 76	28 - 72	0/2

Three radiocarbon dates supplied for this core (Table 10) provide a Holocene chronology for the diatom changes throughout this core.

Consequently, diatom stratigraphy coupled with radiocarbon dating of the core sediment enables the Holocene environmental history of Ace Lake to be reconstructed as follows:

Zone	Type of Lake Inferred	Salinity Range Estimated (‰)	Radiocarbon Age (^{14}C yr B.P.)
1	fresh-hyposaline	0.44 - 14	~ 11400 - 8800
2	marine inlet	40 - 67	~ 8800 -2600
3	saline	46 - 112	~ 2600 - 984

A known radiocarbon reservoir effect of between 850 and 1300 ^{14}C years has been identified in the Vestfold Hills (Bird *et al.*, 1991). As a radiocarbon date of 984 was determined for the Ace Lake core this value was interpreted as the radiocarbon reservoir for this lake and it was subsequently subtracted from all 3 uncorrected radiocarbon dates (Table 10) for Ace Lake in order to show a more realistic radiocarbon chronology of the diatom and associated salinity change zones within this core. In addition, Lead-210 sediment accumulation rates have been determined for a similar core taken from Ace Lake in 1995. Full Lead-210 dating results for this core are given in Appendix 5. The constant rate of supply (CRS) sediment accumulation rate of 0.2 mm/yr for the top 20 cm of this core enables a more accurate dating to be inferred for the saline lake sediments in Zone 3. Using the CRS sediment accumulation rate for the 1995 Ace Lake core, Zone 3 is estimated to represent 1500 years of sediment deposition. Consequently, a more realistic dating of the zones within this lake would be:

Zone	Type of Lake Inferred	Salinity Range Estimated (‰)	Corrected * Radiocarbon Age (^{14}C yr B.P.)	^{210}Pb Age (yr B.P.)
1	fresh-hyposaline	0.44 - 14	~ 10400 - 7800	
2	marine inlet	40 - 67	~ 7800 - 1650	
3	saline	46 - 112	~ 1650 - 0	1500 -present

* Corrected Radiocarbon Ages calculated by subtracting 984 from each Uncorrected Radiocarbon Age.

4.3.3 Lake McCallum

Lake McCallum is a ~ 0.11 km^2 meromictic hyposaline lake situated on Mule Peninsula (Figure 4), the southernmost of the three Vestfold Hills peninsulas, at a current (February 1997) elevation of -2.75 m a.s.l. (J. Gibson *pers. comm.*, 1997). Current (i.e. 1994) mixolimnion salinities range from 10 to 18 ‰ while monimolimnion salinities range from 18 to 24 ‰. Water temperatures are currently as high as 7°C below the ~ 20 m oxycline. Thirty-four of the 47 taxa occurring within the training dataset were observed in the Lake McCallum core. Diatom stratigraphy of the core sediment again reveals two distinct salinity based zones with associated changes in species dominance:

Zone 1: (75 - 55 cm) Algal sedimentation begins at 75 cm within this 124 cm long core. The diatom-inferred salinity values in this zone are below 3 ‰. *Pinnularia microstauron* and *Amphora veneta* completely dominate this section of the core. These hyposaline - freshwater taxa have salinity optima of 3.2 and 6.7 ‰ respectively. Within this freshwater zone these species occur at maximum abundances of 87.75 and 21 % respectively.

Zone 2: (55 - 0 cm) The diatom-inferred salinity values in this zone are > 3 ‰. However, this hyposaline zone can be subdivided into two, based on the species changes from hyposaline taxa to marine and hypersaline lake taxa therein. Zone 2a (55 - 25 cm) diatom-inferred salinity values are between 5 and 10 ‰. This zone is characterised by the marked reduction in abundance of the fresher taxa *Pinnularia microstauron* and *Amphora veneta* and the appearance of the hyposaline taxa *Pinnularia cymatopleura* and *Pinnularia viridis* (salinity optima of 9.3 and 13.8 ‰ respectively).

Pinnularia microstauron and *Amphora veneta* have maximum abundances of 37.75 and 9.50 % respectively while *Pinnularia cymatopleura* and *Pinnularia viridis* have a maximum abundance of 15 and 3 % respectively in this zone. More saline lake species*Stauroneis* species a and *Chaetoceros* (vegetative cells and resting spores) with salinity optima of 37.5 and 33.6 ‰ respectively also appear within this zone.

The diatom-inferred salinity values in Zone 2b (25 - 0 cm)are between 20 and 30 ‰. The saline lake species appearing in zone 2a become more abundant in this zone while the freshwater species *Pinnularia microstauron* and *Amphora veneta* decline in abundance to maximum abundances of 8 and 3 % respectively. *Chaetoceros* vegetative cells and *Stauroneis* species a increase in abundance to a maximum abundance of 23 % each in this zone.

Modern analogue matched palaeosalinity estimates (Figure 20) show broadly similar trends to transfer function estimated palaeosalinity (Figure 19) for Lake McCallum. The freshwater fossil assemblages within this core are comparable with those assemblages within the training set while the saline lake fossil assemblages are not comparable with those assemblages within the training set. Close analogues can be found for all freshwater assemblages but only 1 for the saline lake assemblage zone.

Zone	No. of Fossil Samples	Mean Salinity Range Estimated (‰)	Weighted Mean Salinity Range Estimated (‰)	Number of Close/Good Analogues
1	12	2.60 - 2.60	1.48 - 2.24	1/6
2	4	5.10 - 44	5.69 - 29	4/4

Three bulk radiocarbon dates supplied for this core (Table 10) again provide a Holocene chronology for the diatom changes throughout this core.

Consequently, diatom stratigraphy coupled with radiocarbon dating of the core sediment enables the Holocene environmental history of Lake McCallum to be reconstructed as follows:

Zone	Type of Lake Inferred	Salinity Range Estimated (‰)	Radiocarbon Age (^{14}C yr B.P.)
1	freshwater	0.79 - 1.86	~ 9620 - 7628
2	hyposaline	5.00 - 26	~ 7628 - present

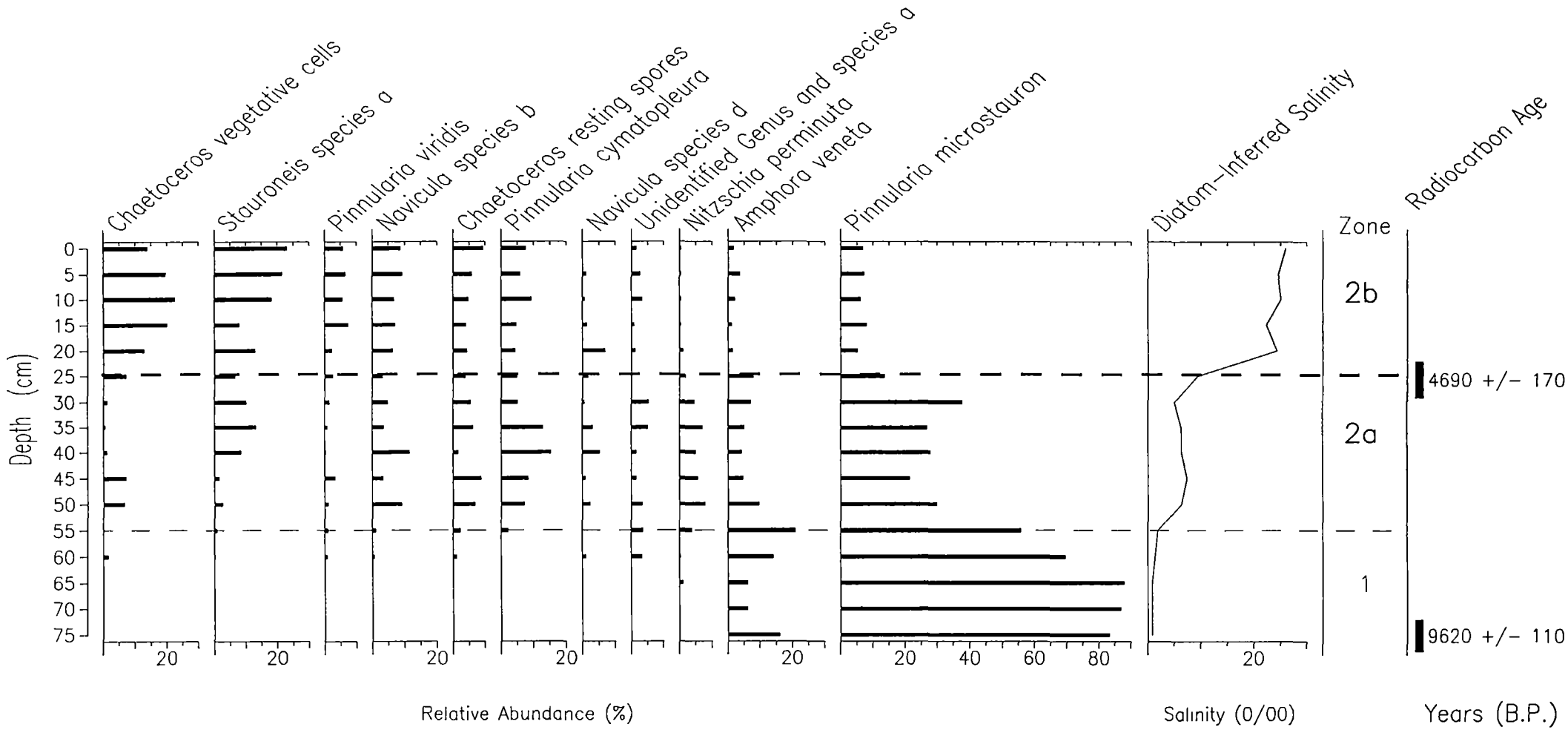

Figure 19: Diatom stratigraphy and transfer function diatom-inferred salinity for Lake M^{c}Callum. Relative abundances of the major (>5%) diatom taxa throughout the sediment core are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

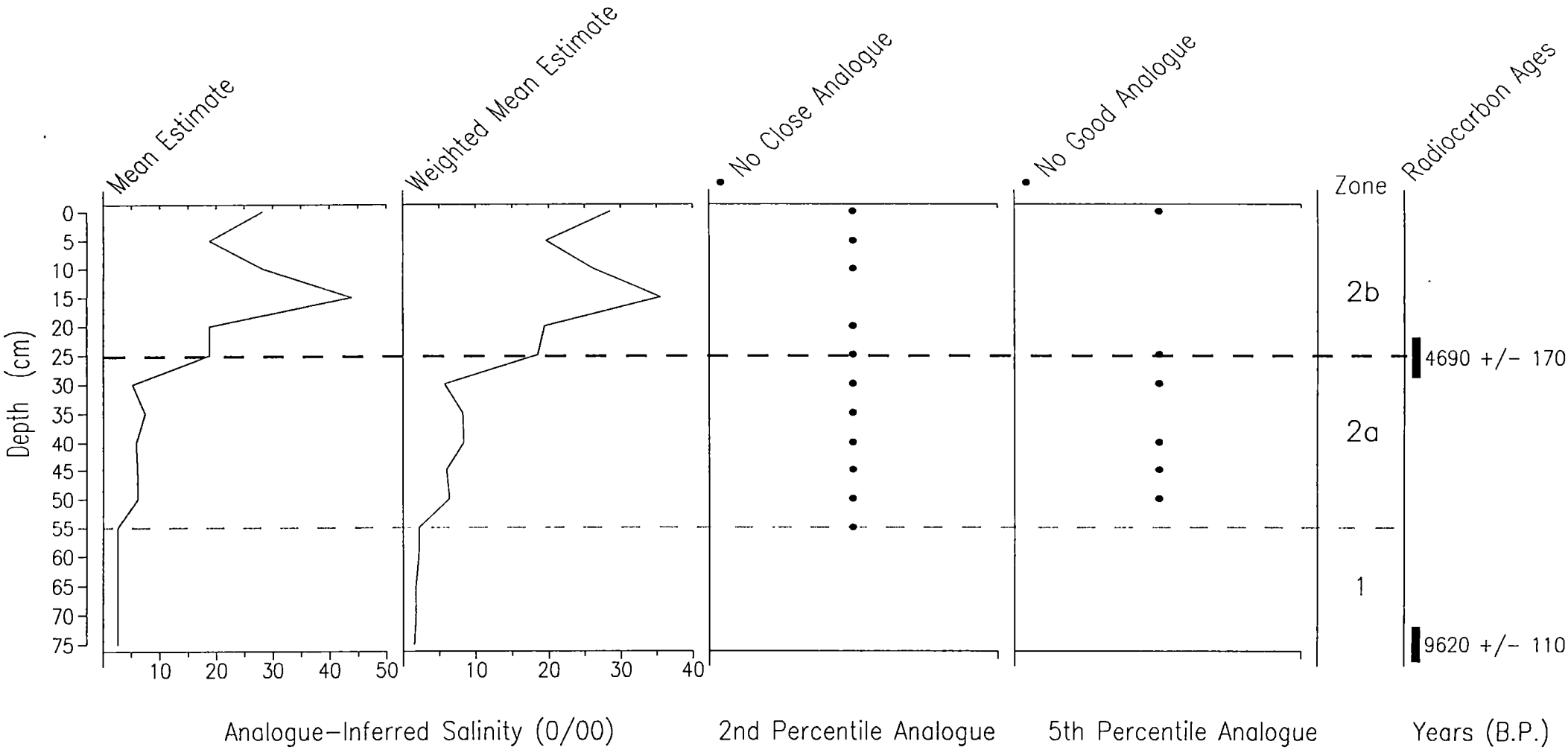

Figure 20: Modern analogue-inferred salinity for Lake M^{c}Callum. Both mean and weighted mean salinity estimates are included. Diatom-based salinity zones and radiocarbon ages of selected sediment sections are also shown.

4.3.4 Cat Lake

Cat Lake is a ~ 0.26 km^2 holomictic freshwater lake situated on Broad Peninsula (Figure 4), the central Vestfold Hills peninsula. There is currently no elevation data available for this lake. Current (i.e. 1997) salinities range from 1.84 to 1.97 ‰.

Only 3 of the 47 taxa occurring within the training dataset were observed in the Cat Lake core: *Hantzschia virgata*, *Amphora veneta* and *Pinnularia microstaruon.* Of these taxa only *Pinnularia microstauron* and *Amphora veneta* (both fresh-hyposaline taxa with salinity optima of 3.2 and 6.7 ‰ respectively) occur in abundances ≥ 2%. Diatom stratigraphy of this lake core is therefore based on the distribution and abundance of these two taxa (reaching maximum abundances of 89 and 72.75 % respectively) revealing freshwater lake sediment throughout the diatom bearing core section (0 - 34 cm) of this core (Figure 21). Slight cyclical changes in the dominance of *Pinnularia microstauron* and *Amphora veneta* are identifiable within this core (Figure 21) but these changes amount to < 2 ‰ (the error component of the transfer function that produced the palaeosalinity reconstruction). As such, no further comment can be made concerning these apparent cycles of changing dominance in response to slight changes in salinity cycles in this freshwater lake core.

Modern analogue matched palaeosalinity estimates (Figure 22) show broadly similar trends to transfer function estimated palaeosalinity (Figure 21) for Cat Lake although all estimates are higher. The fossil assemblages within this core are comparable with those assemblages within the training set. Good analogues can be found for all but 1 fossil assemblage and close analogues can be found for all but 3 fossil assemblages.

Zone (cm)	No. of Fossil Samples	Mean Salinity Range Estimated (‰)	Weighted Mean Salinity Range Estimated (‰)	Number of Close/Good Analogues
0 -34	18	2.60 - 3.24	1.51 - 2.39	15/17

The radiocarbon ages of this lake core (Table 10) enables an estimate to be made of the diatom bearing sediments age.

Zone	Type of Lake Inferred	Salinity Range Estimated (‰)	Radiocarbon Age (^{14}C yr B.P.)
0 - 34 cm	freshwater	0.77 - 1.80	~ 7215 - present

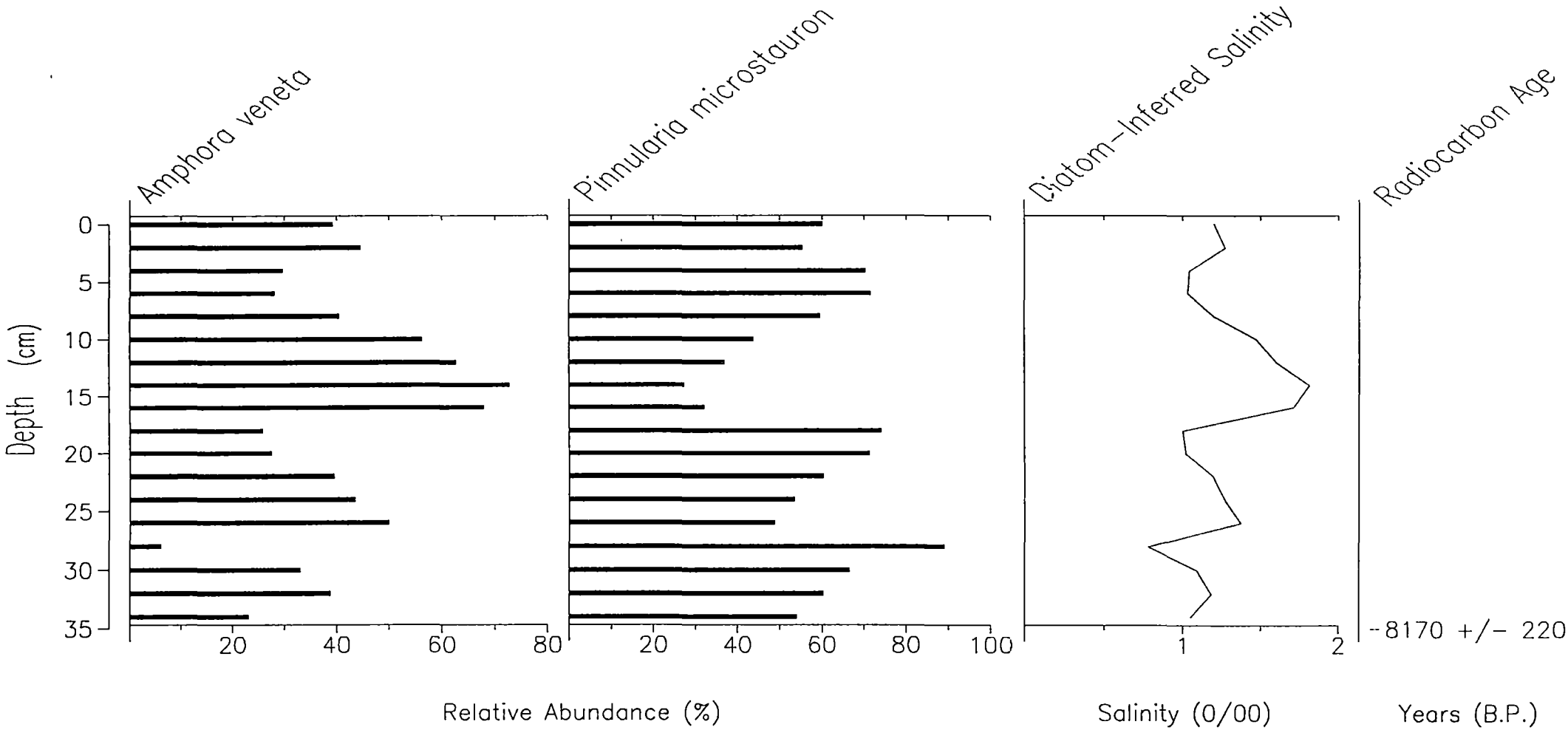

Figure 21: Diatom stratigraphy and transfer function diatom-inferred salinity for Cat Lake. Relative abundances of the major (>5%) diatom taxa throughout the sediment core are included. Radiocarbon ages of selected sediment sections are also shown.

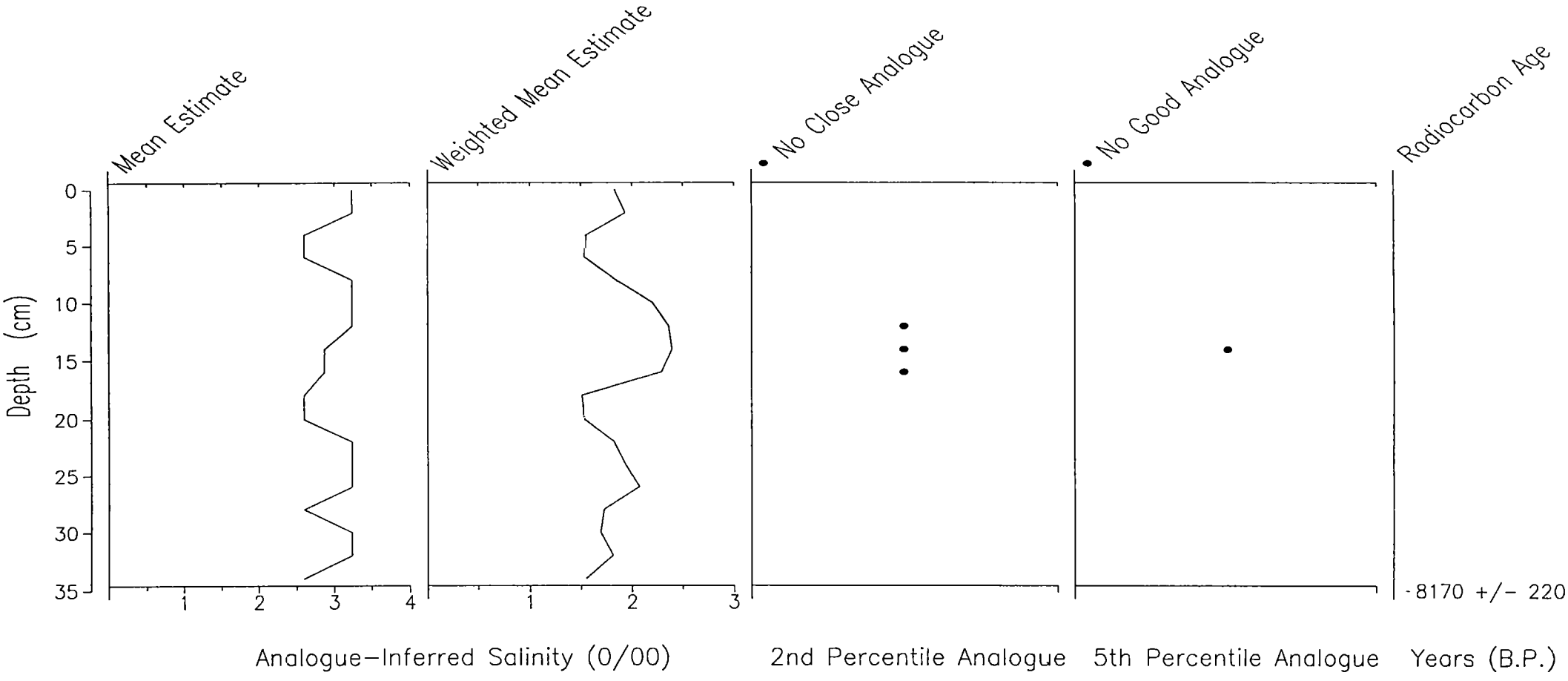

Figure 22: Modern analogue-inferred salinity for Cat Lake. Both mean and weighted mean salinity estimates are included. Radiocarbon ages of selected sediment sections are also shown.

4.4 Comparison of the Palaeosalinity Reconstruction Methods

Individual lake sediment core palaeosalinity estimate comparisons between transfer function estimated salinity and analogue estimated salinity for each zone within each lake sediment core provide a means of assessing the palaeosalinity estimate performance of both the transfer function and the analogue matching techniques.

Anderson Lake

Zone	Transfer Function W.A. Salinity Range Estimated (‰)	M.A.T. Mean Salinity Range Estimated (‰)	M.A.T. Weighted Mean Salinity Range Estimated (‰)
1	1.16 - 32	2.60 - 76	1.81 - 76
2	46 - 63	53 - 76	54 - 85
3	57 - 172	53 - 60	54 - 163

Ace Lake

Zone	Transfer Function W.A. Salinity Range Estimated (‰)	M.A.T. Mean Salinity Range Estimated (‰)	M.A.T. Weighted Mean Salinity Range Estimated (‰)
1	0.44 - 14	2.69 - 19	2.22 - 17
2	40 - 67	27 - 76	27 - 74
3	46 - 112	41 - 76	28 - 72

Lake McCallum

Zone	Transfer Function W.A. Salinity Range Estimated (‰)	M.A.T. Mean Salinity Range Estimated (‰)	M.A.T. Weighted Mean Salinity Range Estimated (‰)
1	0.79 - 1.86	2.60 - 2.60	1.48 - 2.24
2	5.00 - 26	5.10 - 44	5.69 - 29

Cat Lake

Zone	Transfer Function W.A. Salinity Range Estimated (‰)	M.A.T. Mean Salinity Range Estimated (‰)	M.A.T. Weighted Mean Salinity Range Estimated (‰)
All	0.77 - 1.80	2.60 - 3.24	1.51 - 2.39

Palaeosalinity reconstructions from the transfer function and modern analogue matching techniques are broadly similar. In general, the trends identified by the transfer function approaches are mirrored by the modern analogue approach. However, as the reconstructions generated by the analogue technique are unable to extrapolate beyond the salinities in the training dataset, palaeosalinity estimates are not as high in the hypersaline lake sediment estimates as the transfer function technique estimates but interestingly are higher in the freshwater - hyposaline lake sediments. Based on these palaeosalinity estimate comparisons, the correlation between observed and diatom-inferred salinity and the error components of each method (Table 11), the transfer function approach is considered to be the more accurate palaeosalinity estimation technique for Antarctic lakes from the training set used herein.

Table 11

A comparison of the transfer function and modern analogue matching models used to estimate palaeosalinity from fossil diatom assemblages in each sediment core. The apparent correlation between observed and diatom-inferred salinity (r^2) and the root mean square of the error (observed x_i - inferred x_i) (RMSE) is given for both models. All figures given are in $\log_{10}$ units.

Palaeosalinity Reconstruction Technique	r^2	RMSE
Weighted-Averaging Transfer Function	0.80	0.33
Modern Analog Matching	0.65	0.41

Chapter 5: Discussion

5.1 Development of the Transfer Function

5.1.1 Training Dataset

As the ice sheet retreated from the Vestfold Hills at the end of the last ice age, melt water and sea water filled the pre-existing low areas to form the lakes which are present today. The current water level and chemistry of each lake is a result of a limited number of factors: meteorological input (direct and from catchment area snow melt), and loss through evaporation and sublimation (Gibson *et al.*, 1995).

i. Water Chemistry in Lakes of the Vestfold Hills

The lakes sampled for the training dataset represent a particularly wide range of lakewater salinity environments from the Vestfold Hills, with surface sediment samples from these lakes providing diatom communities from fresh (0.5 ‰) to hypersaline (165 ‰) habitats. Sodium is the dominant cation and chloride is the dominant anion in each of the lakes sampled (Table 3). The composition of the major ionic components of these lakes is similar to that of seawater (cf. Torii *et al.*, 1988) with compositions obtained by various degrees of evaporation-concentration and/or freeze-concentration (Matsubaya *et al.*, 1979). Nutrient concentrations vary within the lakes sampled. Silicate ranges from 3.5-187 $\mu mol\ l^{-1}$. Phosphate is generally low between undetectable and 3.4 $\mu mol\ l^{-1}$ except for two lakes which receive occasional marine incursions in which phosphate is 15 and 16 $\mu mol\ l^{-1}$ (Burton Lake and Organic Lake respectively). Nitrate was mostly undetectable in the water samples taken from the lakes surface waters (<0.10 $\mu mol\ l^{-1}$), again excluding a lake which receives marine incursion occasionally and has a nitrate concentration of 15 $\mu mol\ l^{-1}$ (Franzmann Lake). The nutrient levels of the lakes sampled herein are as low, and lower, than those reported for other lakes from the Vestfold Hills by Laybourn-Parry & Marchant (1992) and Perriss & Laybourn-Parry (1997) and fit with Torii *et al.*'s (1988) descriptions of nutrient characteristics in coastal Antarctic saline lakes. However, the manner in which nutrient concentrations effect Antarctic saline lake diatom distribution is not yet clear and this remains a significant question to be answered.

ii. Diatoms in the Lakes of the Vestfold Hills

A mixture of cosmopolitan species and endemic species characterise the diatom flora of the lakes of the Vestfold Hills. Cosmopolitan species include many of the hyposaline *Pinnularia* species, for example *P. microstauron*, *P. lundii* and *P. viridis* , while *Stauroneis* species a (possibly a form of *Tropodoneis laevissima* (cf. Wasell 1993)) is possibly endemic to Antarctic lake habitats. The diatom assemblages identified in this study have similar genera components to those found in Antarctic Peninsula maritime

lakes (cf. Jones *et al.,* 1993, Wasell & Håkansson, 1992) with similar genera represented e.g. *Achnanthes*, *Navicula* and *Pinnularia* and several species are common to both areas, namely *Fragilaria construens* var.*venter*, *Navicula seminulum*, *Pinnularia microstauron* (Jones *et al.*, 1993), *Achnanthes abundans*, *Stauroneis anceps* and*Trachyneis aspera* (Wasell & Håkansson, 1992). However, this study is unique in that it focuses on a much larger salinity gradient than maritime Antarctic studies have to date (cf. Jones *et al.*, 1993) and therefore encompasses a larger saline lake diatom flora than has been encountered in maritime regions.

Throughout the lakes sampled, pennate diatoms are far more abundant than centric diatoms. There is also a noticeable dominance of benthic species. This pattern is echoed in the freshwater lakes of the maritime Antarctic (Jones *et al.,* 1993) and the Canadian Arctic (Smol, 1988). The abundance of benthic taxa in such habitats is thought to be related to ice cover duration, i.e. many planktonic diatoms lack the morphological and physiological characteristics such as high buoyancy capacity or ability to form resting stages that would enable them to survive prolonged periods of ice cover (Smol, 1983; Priddle *et al.*, 1986; Jones *et al.,* 1993). The benthic genera *Navicula* and *Pinnularia* were ubiquitous and dominant in most of the Vestfold lake sediments. However, the marine centric genus *Chaetoceros* did contribute markedly to the flora of some of the marine and hypersaline lakes. The occurrence of this planktonic genus in these lakes of the Vestfold Hills is possibly due to their marine origin.

iii. Diatom Response to Water Chemistry Gradients

Diatom distribution and abundance in the lakes of the Vestfold Hills is clearly related to measured chemical gradients (Figures 9 & 10). The choice of canonical correspondence analysis for the training dataset lakes was due to its capacity to show directly the relation between the environmental variables and the ordination axes. The positions of the lakes and species along the axes are readily interpretable in terms of environmental gradients.

Among the lake water characteristics measured, salinity and silicate account for a significant amount of the explained variation in the species dataset. These variables reflect similar gradients in potassium or sulphate, and alkalinity respectively.

Salinity has a major role in determining the diatom composition of the Vestfold Hills saline lakes, as by its attendant effects on thermal conditions (Gibson *et al.*, 1989) and ice cover (Simmons *et al.*, 1993), it places more than simply osmotic stress upon the biota of these lakes. An increase in salinity will increase osmotic strength, depress the freezing point, reduce the ice cover, increase ice opacity and produce a progressively more severe environment (Wright & Burton, 1981). Therefore, a clear distinction occurs between the freshwater and saline lake diatom assemblages (Figure 10). Freshwater lake assemblages are dominated by the freshwater taxa *Achnanthes*

abundans, *Cocconeis pinnata* and *Stauroneis anceps*. As salinity increases along a gradient from freshwater to hyposaline to marine and then hypersaline, there is a subsequent change in assemblage domination from the freshwater taxa to *Pinnularia* species, then *Fragilariopsis*, *Nitzschia* and *Chaetoceros* species and finally to *Navicula* species (particularly *Navicula directa*, *Navicula* species a and *Navicula* species e) in the most saline lake habitats. This trend identifies species characteristic of a particular salinity category which can then be used to make significant contributions to inference models for reconstructing the palaeosalinity of these Antarctic lakes.

A constrained CCA eigenvalue ratio of 0.85 for salinity suggests that salinity inference models would in fact be viable and informative tools for the Vestfold Hills region and as lake salinity (and ionic composition) reflects effective local precipitation (i.e. precipitation plus runoff minus evaporation), the relationship between salinity and diatom distribution and abundance identified here allows fossil diatom assemblages to be indicators of past precipitation/evaporation gradients in the Vestfold Hills.

Silicate was identified as another significant (P=0.02) variable accounting for the observed diatom distribution in the lakes of the Vestfold Hills (Figure 10). Silicate concentrations within the lakes sampled range from 3.5 – 187 μmol l^{-1}. Low silicate levels (<10 μmol l^{-1}) are found in the freshwater lakes sampled while higher values (> 68 μmol l^{-1}) are found in the markedly hypersaline (> 100 ‰) lakes sampled. The lower values of silicate in freshwater lakes demonstrate the greater diversity and therefore the greater importance (in terms of production within the system) of diatoms in these lakes. The high silicate levels throughout the remaining saline lakes reflects the lower diversity and therefore the lesser requirement for silicate of the diatoms in these systems.

The influence of silicate on the diatom assemblage is a result of the requirement of diatoms for silica as a major part of the cell wall. Various authors have quantified the amount of silica in diatom cells. According to Lewin & Guillard (1963) and Golterman (1975) the usual range for silica is between 4 – 50 % and 5 – 60 % of the dry weight respectively, though ranges of 10 – 72 % and 39 – 79 % are quoted by Schmid *et al.* (1981) and Sicko-Goad *et al.* (1984). In many instances silicate availability also controls the growth rate of diatom assemblages (Kilham 1975). Sommer (1986) predicted that at low silicate concentrations small, lightly silicified diatoms (planktonic) would out-compete larger, more heavily silicified taxa. In the present study, however, heavily silicified diatoms such as *Achnanthes abundans*, *Cocconeis pinnata* and *Stauroneis anceps* are only found in lakes with a low silicate concentration while smaller lightly silicified species such as *Fragilariopsis cylindrus* and *Berkeleya adeliensis* are present in lakes with much higher concentrations of silicate. This apparent conflict with Sommer's prediction is most likely due to the almost exclusive dominance of benthic taxa in the Vestfold Hills diatom flora which are able to obtain additional silicates from their substrates (cf. Douglas & Smol, 1995).

As silica solubility is a function of pH (Lewin, 1961) (hence the strong correlation of silicate with alkalinity), the acidity of the preservational environment will have an influence on the type of diatoms preserved in the sediments of each lake basin. Consequently, the preservation of diatoms in the meromictic lakes of the Vestfold Hills was generally good due both to their low pH and the absence of a benthic fauna and consequent lack of sediment disturbance by bioturbation (McMinn, 1995).

As silica solubility is influenced by so many factors (e.g. pH, availability of silicates in both the water column and the sediment, growth rates of individual diatoms, etc.) it is difficult to make difinitive statements about the types of diatom communities found along the silicate gradient. For example, smaller, more lightly silicified diatoms may be well preserved in the higher silicate lakes than the heavility silicified diatoms due to their faster growth rates enabling them to deplete the silicate stocks quickly in addittion to the preservational quality of these waters. Many variables must be taken into account making the silicate influence on diatoms in these Antarctic ecosystems, at this stage, extremely difficult to quantify.

Of the water chemistry variables identified to have a significant influence on the distribution and abundance of the diatom assemblages in the lakes of the Vestfold Hills (salinity and silicate), silicate (P=0.02) concentration has less influence than salinity (P=0.01). Furthermore, it is difficult to quantify the relationship between silicate concentration and climatic change. Therefore, salinity, which has a clear relationship with changing precipitation and evaporation, is chosen as the environmental variable most informative for the development of a diatom-based transfer function in the Vestfold Hills lake district.

5.1.2 Weighted Averaging Regression and Calibration

Weighted averaging regression and calibration takes the diatom-salinity relationship identified by canonical correspondence analysis one step further and derives a quantitative transfer function from the training dataset. Weighted averaging regression and calibration does this by deriving a salinity inference relationship from the optimum of each of the 47 diatom taxa in the 33 surface sediment samples (Table 7, Figure 11). The continuous distribution of salinity optima of diatom species within the training set from 0.6 to 122 ‰ (Figure 11) shows that there are good indicators across the salinity gradient measured and that prediction should be equally as good across this range (Juggins *et al.*, 1994). Outside these limits the transfer function may be less accurate and it is possible that, as a result of the lack of very fresh sites in the dataset (< 0.5 ‰) and the abundance of hypersaline lakes (>30 ‰) in the dataset, the salinity optima of some taxa (e.g. *Cocconeis costata*) is overestimated. Nevertheless, once salinity optima are established from the training set, they are used to infer palaeosalinity from fossil diatom assemblages by assuming that species responses to salinity have remained unchanged, and therefore their salinity optima have remained unchanged, through time (see Appendix 1 for a list of the assumptions involved in transfer function applications).

5.2 Development of the Analogue Matching Method

Modern analogue matching provides an alternative method to the transfer function approach of estimating palaeosalinity from fossil diatom assemblages. A simultaneous matching of modern analogue situations also provides an objective way of determining whether fossil assemblages are representative of modern assemblage situations within the training set.

The analogue approach might be considered to be advantageous because it is less statistical and involves straight comparison of individual taxa, although this could also be done subjectively (Bartlein & Whitlock, 1993). In contrast to the transfer function approach, the analogue based approach does not involve the construction of a generalised relationship between diatoms and water chemistry, and therefore reconstructions derived using the analogue approach may depend overmuch on the nature of the particular assemblages in the analogue set (Bartlein & Whitlock, 1993). While providing an alternative approach to palaeosalinity estimation from fossil diatoms, the modern analogue matching method is not as appropriate for inferring realistic palaeosalinity estimates from a limited training set as the transfer function appears to be (cf. Table 11). This may be due to the fact that the reconstructions generated by the analogue approach are limited to values present in the modern dataset (or weighted means of them) with the consequence that the analogue approach is unable to extrapolate when applied to fossil diatom assemblages (Bartlein & Whitlock, 1993) further showing the requirement for a very large training dataset for use with this approach.

Consequently, while analogue matching is a useful tool, the problems associated with limited numbers of lake types (as in this training set) brings about the situation where many no or poor analog situations arise. These no or poor analogue situations may be influenced by poor training set selection rather than actual no or poor analogue situations within a lake province. Bartlien & Whitlock (1993) therefore advise that as the transfer function approach has the intrinsic merit of being statistically optimal when the assumptions underlying the approach are not violated and is based on a formal statistical model, this approach is preferable whenever uncertainties arise in a reconstructed value.

The lack of numerous lakes of each salinity category within the training set herein results in a much stronger relationship and a lower error estimate between observed and diatom-inferred salinity for the transfer function approach than the modern analogue matching approach (Table 11). Consequently, the best estimates of palaeosalinity can be reconstructed within the Vestfold Hills using the weighted averaging transfer function and further discussions will be restricted to the application and palaeoclimatic implications of these.

5.3 Application of the Transfer Function

Figures 15, 17a,b, 19 and 21 show the Holocene diatom stratigraphy for Anderson Lake, Ace Lake, Lake McCallum and Cat Lake, with transfer function developed diatom-based reconstructed lakewater salinity. Each of the cores from currently saline lakes (Anderson Lake, Ace Lake and Lake McCallum) reveals distinct salinity changes while the core taken from the currently fresh lake (Cat Lake) has remained fresh throughout. Individual core assemblage changes and associated transfer function palaeosalinity estimates are discussed below.

5.3.1 Anderson Lake

Application of the transfer function to the fossil diatom assemblages of Anderson Lake suggests that previous transitions from a freshwater lake to a marine inlet to a saline lake occurred (Figure 15). Salinities have fluctuated between ~ 1.2 and ~ 170 ‰ with the highest salinity recorded in the late Holocene (~ 1200 ^{14}C uncorrected yr B.P.). Three uncorrected radiocarbon dated zones have been interpreted from Anderson Lake as follows:

Zone 1 [~ 8500 - 7000 ^{14}C yr B.P.]: fresh - hyposaline lake
Zone 2 [~ 7000 - 6000 ^{14}C yr B.P.]: marine inlet
Zone 3 [~ 6000 ^{14}C yr B.P. - present]: saline lake

At the beginning of the Holocene (10 000 yr B.P.), the ice sheet was in rapid retreat, the land was rising in isostatic uplift and sea level was rising rapidly (Pickard *et al.*, 1986). Isostatic uplift of the bedrock on Mule Peninsula eventually exposed Anderson basin (~ 8500 yr B.P.), following which, a freshwater lake existed, dominated by benthic diatoms with low salinity optima. A modern analogue of the Holocene freshwater lake can be demonstrated by Lake Vereteno (situated close to the continental ice sheet with fresh-hyposaline epilimnion salinity of 3.7 ‰). Relative sea-level rise after this period (~ 7000 yr B.P.) led to marine inundation of the lake and marine inlet sediments were deposited for approximately 1000 years. The abundance of *Chaetoceros* cells, a planktonic taxa, in this zone indicates flushing with seawater. The higher sediment accumulation rate seen in Zone 2 compared to the freshwater sediments and saline lake sediments in Zone 1 and 3 respectively is the result of higher productivity in a marine environment primarily due to the constant replenishment of nutrients to these systems. A modern analogue of the Holocene marine inlet can be demonstrated by Burton Lake (a lagoon with a shallow connection to the sea which is subject to small tidal fluctuations (Pickard *et al.*, 1986)), Lake Fletcher (a lake which is occasionally influenced by marine tidal influx during summer (Eslake *et al.*, 1991)), and Franzmann Lake (a lake with occasional considerable interchange of water

between the lake and Long Fjord (Gibson, 1994)). These lakes all receive various degrees of sea water input, and with current epilimnion salinities of 42, 65 and 71 ‰ respectively, demonstrate how a marine inlet can gradually become a saline lake upon continued cut-off from a marine influence and possibly the type of marine inlet that Anderson Lake may have been.

Initial changes in the lakes basin thus far have been attributed to glacial retreat, meltwater inputs and isostatic uplift with relative sea-level changes. These processes have masked climatic cycles. However, within the last ~ 6000 years sea level stabilised, isostatic rebound continued and the isolated marine basin developed a negative water balance i.e. evaporation greater than precipitation. The resulting concentration of dissolved salts led to the current saline lake state of the basin, dominated by benthic diatoms with high salinity optima. The range of salinities estimated within this ~ 6000 year zone may demonstrate cyclical changes in response to changing precipitation/evaporation regimes. Many saline lakes within the Vestfold Hills are analogues for the various stages of Anderson Lake throughout this time period. For example, Oblong, South Angle and Williams Lakes are all meromictic hypersaline lakes with respectively decreasing epilimnetic salinities of 165, 138 and 47‰.

Consequently, based solely on diatom-inferred salinity changes, it can be suggested that Anderson Lake was once a freshwater lake which underwent a transitional marine inlet phase upon relative sea level changes with isostatic movement of the Vestfold Hills to become the saline lake it is at present.

5.3.2 Ace Lake

Despite the differences in present-day salinity of Anderson Lake and Ace Lake the two show broadly similar salinity histories. The Holocene diatom stratigraphy of Ace Lake also shows evidence of a transition from a freshwater to marine to saline environment (Figure 17a,b). Salinities have fluctuated between ~ 0.4 and ~ 112 ‰ with the highest salinity recorded ~ 700 years ago. Three zones (dated by both corrected radiocarbon and ^{210}Pb chronologies) have been interpreted as follows:

Zone 1 [~ 10 500 - 7850 ^{14}C yr B.P.]: fresh - hyposaline lake
Zone 2 [~ 7850 - 1650 ^{14}C yr B.P.]: marine inlet
Zone 3 [~ 1650 ^{14}C yr B.P./ 1500 ^{210}Pb yr B.P. - present]: saline lake

As with the history of Anderson Lake, isostatic uplift of the bedrock at the beginning of the Holocene exposed Ace basin, following which, a freshwater lake existed, dominated by benthic diatoms with low salinity optima. Relative sea-level rise on Long Peninsula after this period (~ 7850 yr B.P.) led to marine inundation of the lake and marine inlet sediments were deposited for ~ 6000 years. Again, the

abundance of *Chaetoceros* cells in this zone indicates flushing with seawater. After these glacial, isostatic and relative sea-level influences sea level stabilised, isostatic rebound continued and the isolated marine basin developed a negative water balance i.e. evaporation greater than precipitation. The resulting concentration of dissolved salts led to the current saline lake state of the basin, dominated by benthic diatoms with high salinity optima.

Consequently, based solely on diatom-inferred salinity changes, it can be suggested that, as with the history of Anderson Lake, Ace Lake was once a freshwater lake which underwent a transitional marine inlet phase upon relative sea level changes with isostatic movement of the Vestfold Hills to become the saline lake it is at present.

While broad changes in salinity can be seen, it is the very high resolution salinity fluctuations in zone 3 of this core that provides the most exciting possibilities for palaeoclimate correlations. Diatom-inferred salinity within this section of the core provides a unique record of fine scale fluctuations.

5.3.3 Lake McCallum

Diatom stratigraphy of Lake McCallum reveals a distinct change from an initial freshwater lake to a hyposaline lake (Figure 19). Two uncorrected radiocarbon dated zones have been interpreted as follows:

Zone 1 [~ 9600 - 5500 ^{14}C yr B.P.]: freshwater lake
Zone 2 [~ 5500 ^{14}C yr B.P. - present]: hyposaline lake

Again, at the beginning of the Holocene, the ice sheet was in rapid retreat, the land was rising and sea level was rising rapidly (Pickard *et al.*, 1986). Isostatic uplift of the bedrock on Mule Peninsula eventually exposed Lake McCallum (~ 9600 yr B.P.), following which, a freshwater lake existed, dominated by benthic diatoms with low salinity optima. With continual concentration since the formation of this lake a hyposaline lake evolved and is continuing to become more saline.

Lake McCallum did not become inundated with sea water upon isostasis and relative sea level change as can be seen in both Anderson Lake and Ace Lake as the sill height (14 m a.s.l.) around this lake basin was too high (cf. Figure 24). Anderson Lake and Ace Lake both have sill heights ~ 8.5 m a.s.l. Lakes within the Vestfold Hills with sill heights less than ~ 8.5 m above present sea level all have this marine incursion stage whereas lakes with sill heights above 9 m show purely lacustrine histories (Bird, 1993).

5.3.4 Cat Lake

Cat Lake is situated on the middle Peninsula of the Vestfold Hills (Broad Peninsula) closer to the ice sheet than the other 3 lakes (Figure 4). This lakes salinity history has recorded a steady and continual freshwater state for ~ 8000 years (Figure 21). This is not surprising as it is close to the ice sheet receiving direct meltwater (no evidence of groundwater movement has been found in the catchment) and has a sill height of 40 m a.s.l. There is no diatom evidence at this site for periods of climatically-induced higher salinity or lower lake levels (while subtle changes in dominance are occurring between *Pinnularia microstauron* and *Amphora veneta* (Figure 21) the salinity change associated is < 2 ‰ making it difficult to interpret these changes further in light of the RMSE of 0.37 $\log_{10}$ salinity units involved in estimating the palaeosalinity in all lake sediment cores).

The lack of salinity change recorded in this lake demonstrates the superiority of the saline lakes as sensitive recorders of climatic changes in this region. Other researchers have recorded similar results i.e. closed-basin saline lakes are powerful palaeohydrologic and palaeoclimatic recorders whereas in contrast, freshwater lakes are unlikely to contain as clear an archive of past climate, because water chemistry in these basins does not change sufficiently to leave a palaeosalinity record (Fritz, 1990).

5.4 Limitations of the Transfer Function

Interpretation of the palaeosalinity reconstructions herein must take into account the possibility that the fossil diatom assemblages are not direct counterparts of the floral communities from which they were derived with dissolution, breakage and complications from sediment mixing amongst the possible sources of error (Wasell, 1993). However, breakage and sediment mixing are minimised in Antarctic meromictic lakes (although this is not the general case for meromictic lakes), making Antarctic meromictic systems ideal environments for the deposition of diatom frustules. A large proportion (~5%) of the worlds meromictic lakes are found in this one small area (Gallagher *et al.*, 1989) and at least 19 of the 33 lakes chosen for the training set herein are meromictic.

Interpretation herein must also take into account the taxonomic and ecological uncertainties surrounding several of the taxa, the extreme environmental conditions, and the possibility that a few frustules may be derived from sea-spray, birds and terrestrial habitats (Wasell, 1993). Nevertheless, sediment composition at any depth below the sediment surface generally reflects the diatom communities living in the lake at the time of deposition (Lebo *et al.*, 1994).

Also, the absence of a species from the sediment of a lake does not preclude the possibility of its presence in the water column as sampling of sediments cannot ensure every diatom occurring in the lake is included. However, sediment sampling gives a more representative selection of the flora of a lake than spasmodic, infrequent water

sampling does, particularly as blooming diatoms are seasonal and may be missed in the latter sampling method. Sediment sampling is representative of all but the most lightly silicified algae.

As the diatoms in the calibration set are almost exclusively benthic (excluding the planktonic vegetative *Chaetoceros* cells), some of the error in estimating epilimnetic salinity may be related to the conditions experienced by the benthic assemblages (cf. Douglas & Smol, 1995; Jones & Juggins, 1995). However, despite the lack of planktonic species, it has been shown to be both possible and statistically reasonable to use benthic diatom assemblages to reconstruct water column (epilimnetic) salinity reliably. Similarly, Jones & Juggins (1995) have demonstrated that benthic diatom assemblages in maritime Antarctic freshwater lakes can be used to reliably reconstruct epilimnetic chlorophyll-a concentrations and therefore provide reconstructions of lake trophic status for that region.

Another possible source of error in the transfer function is the characterisation of each lake sample by a single summer epilimnion value. A single midsummer salinity measurement from a single year may not adequately characterise the range of lakewater salinities represented by an integrated surface sediment sample (Fritz *et al.*, 1993). However, Cumming and Smol (1993) recommend that if only one water chemistry sample is to be taken, as if most often the case with logistically difficult Antarctic lake provinces, that water samples be collected over a relatively short time period (as in this study) as a large seasonal variability can also bias results.

Coupled with the complication of the representativeness of a single water sample of the lake environment is the small size of our training dataset. Most other diatom-based salinity inference models make use of similar salinity gradients using much larger numbers of lakes (e.g. Fritz, 1990; Fritz *et al.*, 1991, 1993; Cumming & Smol, 1993; Wilson *et al.*, 1994, 1996) than are included here. Thirty-three lakes is not an ideal number for a training dataset sample from a region of over 300 lakes but climate, access and resource constraints precluded further lake samples from being collected and therefore included.

Weighted averaging regression and calibration is based upon the salinity optima estimated for the training set species. The high salinity optima estimated by the weighted averaging model for the marine species occurring within the lakes of the Vestfold Hills may be due to the dominance of saline lakes in the training dataset, and thus optima in general may be somewhat skewed towards the high salinity end of the gradient. This could lead to unrealistically high salinities in some cases. The solution to this problem is the deliberate addition of lakes from currently poorly-represented salinity types to the present training set e.g. freshwater lakes and marine inlets. The addition of such samples would improve the estimates of species optima and therefore the palaeosalinity predictive ability of the transfer function.

Finally, a common concern connected with the transfer function approach is that ecological taxa may change significantly over time, such that interpretations of past conditions based on ecological data obtained from studies of modern assemblages may be biased and incorrect (Charles *et al.*, 1994) thereby nullifying the major assumption of the technique. Charles *et al.* (1994) discuss this concern, concluding that firstly, similar taxa occur together today that occurred together millions of years ago in the same types of environments; secondly, many taxa have geographic distributions spanning one or more continents, yet exhibit similar ecological characteristics throughout their range and thirdly; a low selection pressure forcing genetic adaptation as a result of the size, ease of dispersion to a new habitat and the number of taxa that can coexist in many habitats suggests that the total amount of change in most communities is small enough that it does not preclude their use in inferring palaeoecological change over the relatively short time period discussed in the present study.

Despite these possible limitations, it has been shown here that a simple weighted averaging technique can be used to reconstruct statistically reasonable estimates of epilimnetic salinity from sedimentary diatom assemblages in the saline lakes of the Vestold Hills. Furthermore, there are remarkably strong signals of Holocene salinity fluctuation within the saline lake cores analysed from this region.

5.5 Holocene Lake Histories in the Vestfold Hills

The palaeosalinity reconstructions of each of the lake cores analysed herein are compared in Figure 23 and Figure 24 presents a schematic representation (adapted from Bird (1993)) of the way in which each of these lakes recorded their respective salinity histories.

Errors in radiocarbon dating methods may be misleading when trying to compare the timing of diatom-inferred changes throughout the sediment cores sampled. The use of standard ^{14}C dates in the Antarctic is problematic as a result of the "reservoir effect". This effect is caused by ^{14}C depleted CO_2 being released into the lake system by glacial melt water and/or by the slow equilibrium of the local carbon reservoir with atmospheric CO_2. Therefore, marine organisms and the sediments they produce will obtain an apparent age which is older than the actual age (Kaland *et al.*, 1984). Bird *et al.* (1991) report that the majority of reported ^{14}C ages in the Vestfold Hills for living lacustrine and marine organisms are about 850 – 1300 yr. B. P. Squyres *et al.* (1991) report a reservoir effect on surficial Lake Hoare sediments of at least 1900 years showing that this effect is not confined to the Vestfold Hills.

When comparing radiocarbon based chronologies for lake sediments (cf. Figure 23) it is important to use corrected ages wherever possible. In this case, radiocarbon ages for Ace Lake are corrected as it is known that surficial sediments give a radiocarbon age of 984 ^{14}C years (Table 10). Lake McCallum and Cat Lake are entirely lacustrine with no prior marine influences and therefore their radiocarbon ages are under little, if any, reservoir effect influence (Melles *et al.*, 1994).

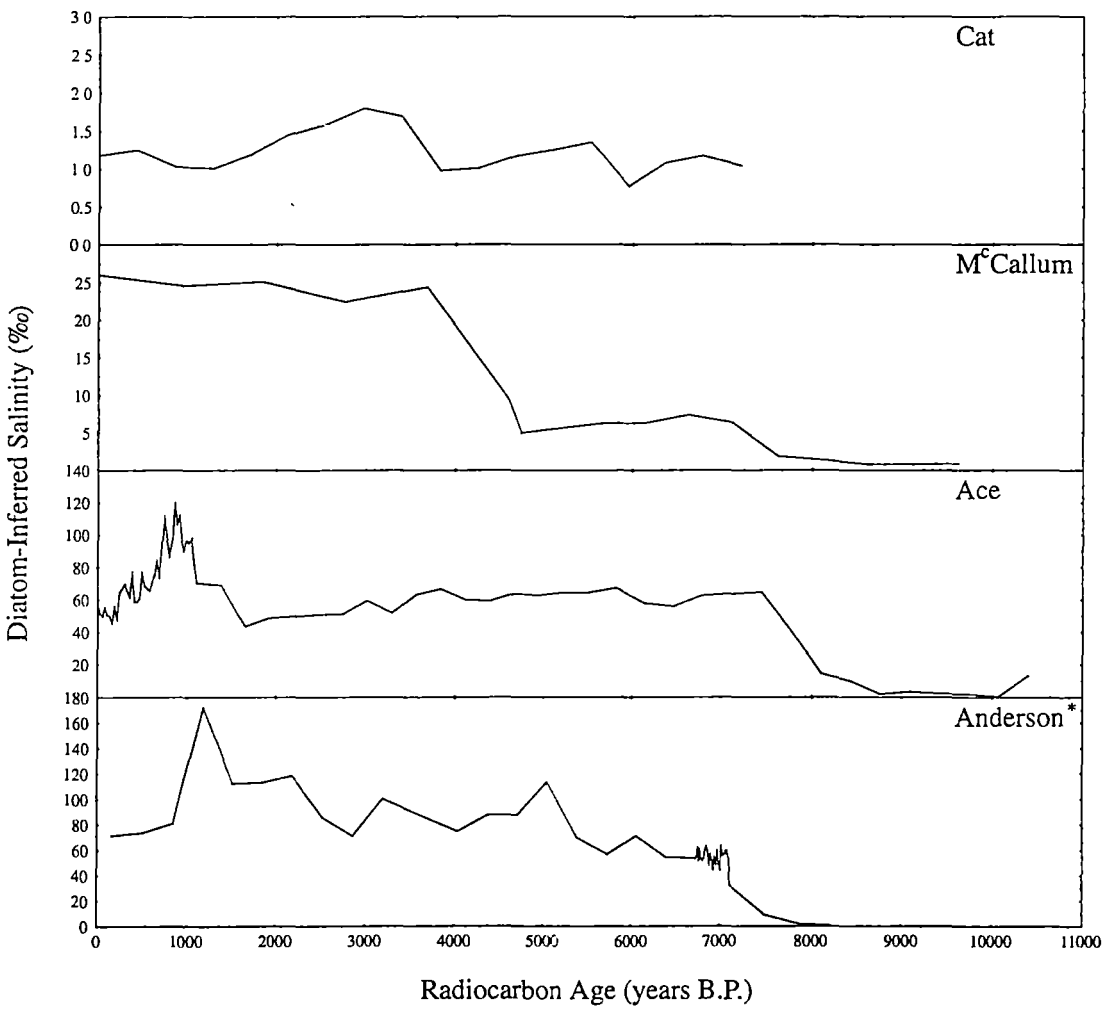

Figure 23: Diatom-inferred Holocene salinity histories for Anderson Lake, Ace Lake, Lake McCallum and Cat Lake. Radiocarbon ages for Lake McCallum and Cat Lake are free of reservoir effects, radiocarbon age estimates for Ace Lake are corrected for using the known reservoir effect in this lake basin and only the radiocarbon age estimate of Anderson Lake (*) is based on an uncorrected radiocarbon age determination.

Consequently, only radiocarbon ages of Anderson Lake are uncorrected. The radiocarbon ages used for Anderson Lake were calculated from dates determined at 40, 104 and 111 cm respectively (Table 10). It was assumed that a constant sediment accumulation rate applies to the 40 to 0 cm sediment section (which encompasses a change from marine sedimentation to closed basin saline lake sedimentation). As a result, the ages of the salinity history changes within Anderson Lake should be interpreted with caution, particularly as there would be a reservoir effect (of the order of ~ 850 – 1300 years (Bird *et al.*, 1991)) associated with these sediments.

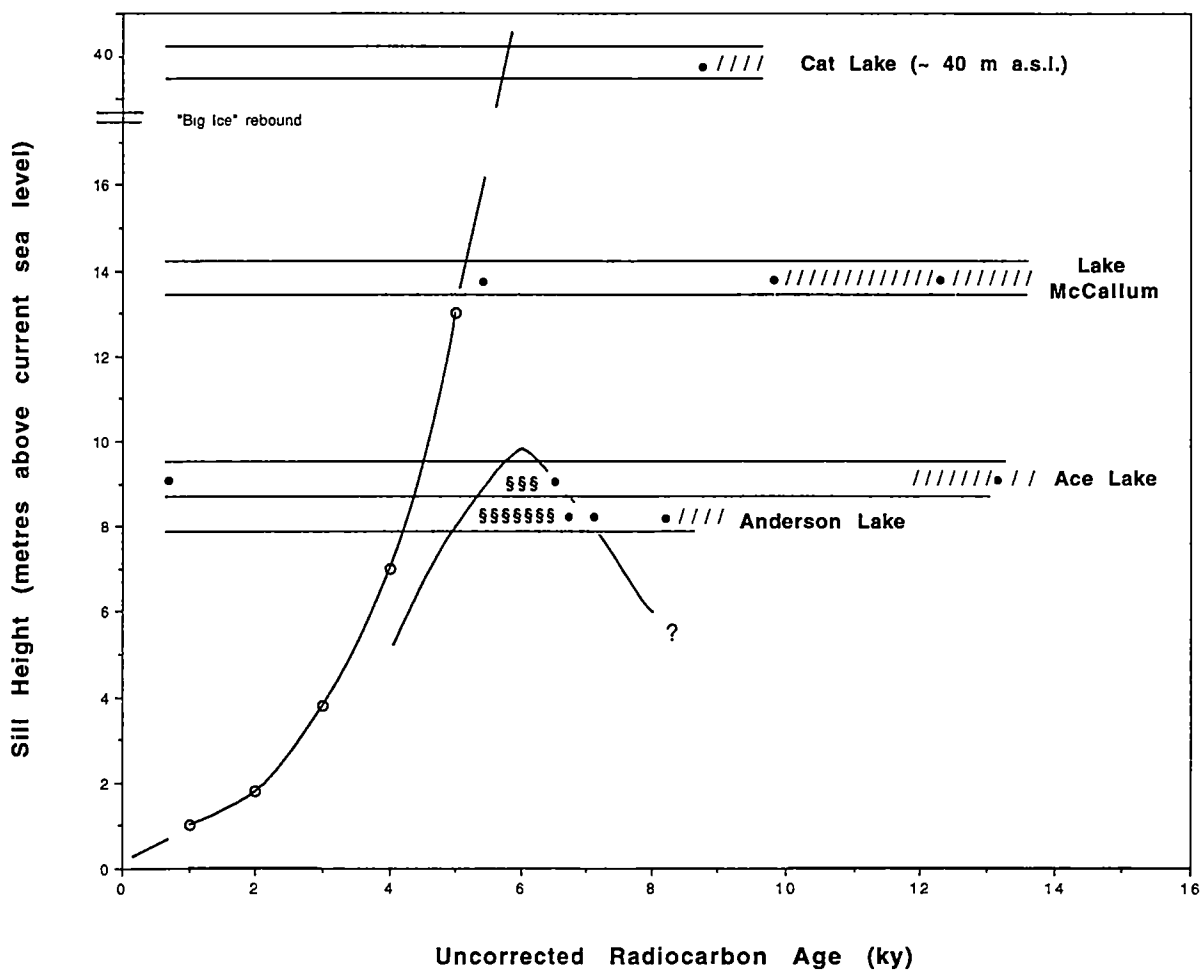

Figure 24: Holocene sea level change (relative to its present position) in the Vestfold Hills adapted from Bird (1993). The carbon-dated stratigraphy for each lake basin is plotted at the height of its former connection to the sea. Bullets (•) show radiocarbon dates, slashes (/) represent glacial till and bare areas represent lacustrine sediment. Intervals of marine sedimentation are represented by §. Relative sea level in the Hills is defined by these intervals, which must lie beneath the sea-level curve as shown. Although not well constrained before 7000 years B.P., sea level cannot have stood above ~8 m at any time between ~ 12, 000 and 7 000 B.P. (Bird, 1993). The "Big Ice" rebound curve shows sea-level change predicted for removal of a thick last-glacial icecap, melting in phase with the ice sheets of the northern hemisphere (Bird, 1993).

Irrespective of these possible dating inaccuracies, ^{14}C ages obtained from the cores analysed for this study can be used to infer the broad Holocene salinity history of each lake as recorded by the diatom assemblages making it possible to discuss the history of these lakes in terms of the evolution of the lake basin, climatic influences after isolation of the lake basin and the resulting salinity changes therein.

5.6 Palaeoclimate Reconstruction Capabilities of the Transfer Function

Ultimately, salinity reconstructions are most useful when they can be interpreted in terms of a climate change in a lake's basin.

During dry intervals, lakewater levels in closed basins drop and the concentration of dissolved salts generally increases while, during wetter intervals, lake levels rise and the lakewater salinity levels often decrease. In polar deserts, warm periods tend to be related to rising lake levels and decreasing salinity while cold periods are related to decreasing lake levels and therefore, more saline lake systems (Wharton *et al.*, 1992). These changes are recorded by diatoms in the lakes sediment, allowing the reconstruction of a lakes salinity history to possibly be interpreted in terms of long-term climatic change.

The saline lake sediment cores analysed herein provide this opportunity. Anderson Lake, Ace Lake and Lake McCallum all have identifiable trends in salinity. Anderson Lake and Lake McCallum however, have coarse sediment sample periods (approximately 2 and 5 cm intervals respectively - representative of approximately 300 and 900 year intervals respectively). Ace Lake has a much finer scale of sediment sampling (every 5 mm for the top 20 cm - representative of approximately 25 year intervals).

Consequently, Ace Lake, and in particular the closed-basin saline lake sediment deposited in Zone 3, provides a high enough resolution record of salinity fluctuation that meaningful climate inferences can be made. Palaeoclimatic analysis of the salinity fluctuations within these sediments is discussed in Chapter 6.

Chapter 6: Implications

6.0 Prologue

Extreme cold and aridity characterise the Antarctic environment and profoundly influence the limnological properties of lakes and streams throughout the south polar region (Vincent, 1987). Most continental aquatic life is restricted to the coastal fringes where temperatures are above freezing for only a few days or weeks of each year and total annual precipitation, falling as snow, is between 100 and 150 nm of water equivalent (Weller *et al.*, 1987). Consequently, low temperatures and precipitation have a significant influence on coastal Antarctic lake ecosystems.

The hydrologic budgets of many lakes are intricately tied to climate, and significant fluctuations in lake levels are often correlated with periods of climatic change (Laird *et al.*, 1996). Closed lakes in arid and semi-arid regions of the world are known to respond particularly rapidly to climate-driven hydrological change, with fluctuations in the balance between precipitation and evaporation resulting in both changes in lake level and the concentration or dilution of dissolved salts (Last & Slezak, 1988; Fritz *et al.*, 1991; Gasse *et al.*, 1995). In turn, the fluctuations in lakewater salinity are recorded in a variety of palaeolimnological indicators, including the composition of the diatom community (Juggins *et al.*, 1994).

Now that the relationship between salinity and diatom distribution and abundance has been established for the saline lakes of the Vestfold Hills (herein) the reconstruction of past fluctuations in salinity can be used to infer past fluctuations in lake level which can in turn provide a tool for predicting future hydrologic responses to climatic change (Fritz, 1990).

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*This chapter was significantly contributed to by Jason L. Roberts (Department of Civil and Mechanical Engineering, University of Tasmania GPO Box 252-65, Hobart, Tasmania, Australia, 7001). Discussions with John A. E. Gibson (Australian Antarctic Division, Channel Highway, Kingston, Tasmania, Australia, 7050) also played a major role in the development of the ideas presented here.

6.1 Ace Lake: An Example of Palaeoclimate Reconstruction

Ace Lake is a closed saline lake basin located at 68° 28'S, 78° 11'E, on a narrow section of Long Peninsula (Figure 4). It is only 150 m from the nearest sea and approximately 10 km from the edge of the ice cap (Hand & Burton, 1981). It has a maximum depth of 24.7 m (Franzmann *et al.*, 1991) and a current surface area of 0.18 km^2 (Figure 8). The catchment (0.5 km^2) consists of low hills on which little snow accumulates due to exposure to the prevailing direction of strong winds (Hand & Burton, 1981). Ice covers all but the most saline of the Vestfold Hills' lakes for about 8 - 12 months of each year and precludes wind-induced turbulent mixing over the winter, when strong winds are most frequent (Ferris *et al.*, 1991). Ice cover on Ace Lake lasts for 10 - 12 months each year up to thicknesses of 2 m (Burch, 1988). Current (i.e. 1992) mixolimnion salinities range from 16 to 30 ‰ while monimolimnion salinities range from 31 to 40 ‰ (Figure 25).

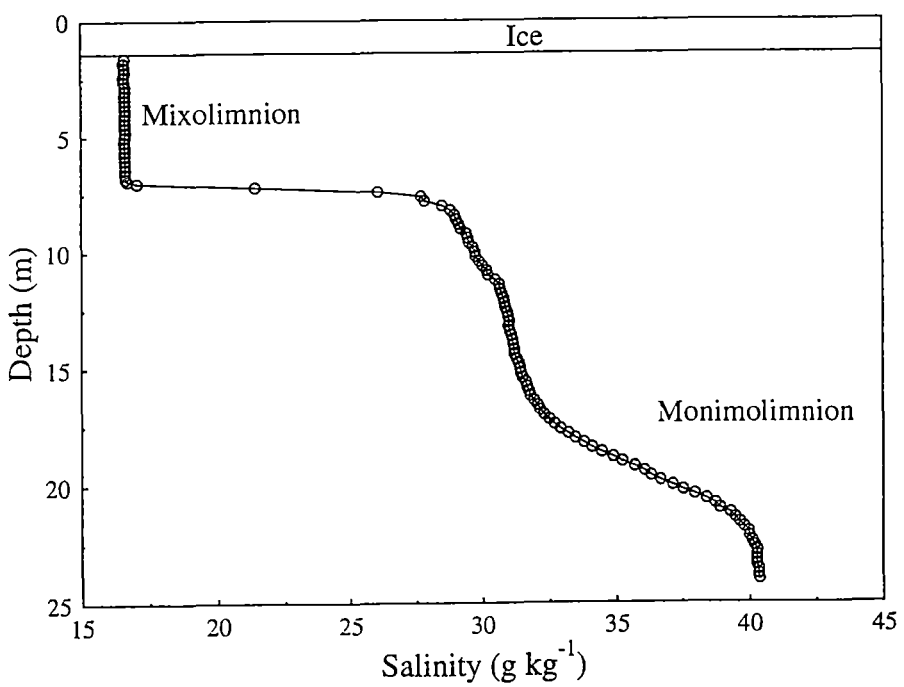

Figure 25: A salinity profile of Ace Lake recorded on 20 November 1992.

The water level in the lakes of the Vestfold Hills is determined by the balance between melt-water inflow from nearby snow banks and water loss by ablation (when ice covered) and evaporation (Gibson & Burton, 1996). Most of the snow banks in the Vestfold Hills are small, building up in the lee of low hills during winter and melting completely during the summer (Gibson & Burton, 1996). Therefore, for the lakes of the Vestfold Hills, including Ace Lake, water balance is a function of local precipitation, ablation and evaporation (Gibson & Burton, 1996).

The saline lake sediment deposited within Ace Lake (the top 30 cm of the impact core-Figure 17a,b) contains a particularly high resolution record of the salinity fluctuations in this lake basin which, coupled with present day salinity and water level measurements and precipitation estimates (below), enables the reconstruction of water level and effective net precipitation fluctuation for this sub-section of the core.

6.2 Current Water Loss Mechanisms for Ace Lake

Direct measurement of precipitation in Antarctica is fraught with difficulty (Streten, 1986; Bromwich, 1990) particularly eliminating the wind blown component which accounts for as much as a third of the precipitation in past estimates (Rusin, 1958). Therefore, the current precipitation rate for the catchment of Ace Lake is determined from theoretical estimates of lakewater loss mechanisms: evaporation, sublimation and heat transfers.

Evaporation was calculated using the Colburn analogy which relates mass transfer to the more extensively studied and understood skin friction (Chapman, 1984). This gives an average mass transfer coefficient analogous to a drag coefficient approximating the area of Ace Lake as a square of the same surface area. Ace Lake is ice covered for approximately 11 months of each year (cf. Burch, 1988). Therefore, known environmental data for temperature and wind speed (Russell-Head & Simmonds, 1993) and relative humidity (Bureau of Meteorology, unpublished data) at nearby Davis Station (Figure 2) were averaged for the warmest month of every year in the period 1981 - 1989 and water loss through evaporation was subsequently calculated at 1.26 kg day^{-1}. Therefore, a total water loss through evaporation in Ace Lake is determined to be 38 mm yr^{-1}.

Sublimation was calculated in a similar manner to evaporation making allowance for the depression in saturated vapour pressure of water over ice compared with vapour over liquid water (at -11°C the saturated vapour pressure over ice is 90% of that over liquid water - Gray, 1982). Again, using known environmental data for temperature and wind speed (Russell-Head & Simmonds, 1993) and relative humidity (Bureau of Meteorology, unpublished data) at nearby Davis Station (Figure 2) for the 11 coldest months of every year in the period 1981 - 1989, the resulting water loss was calculated to be 0.47 kg day^{-1} or a total of 156 mm yr^{-1} for the period of ice cover.

The heat input into Ace Lake from the surrounding rocks was calculated using a two dimensional finite difference scheme modelling an 8 x 8 m cross section of rock immediately neighbouring the lake. Boundary conditions made allowance for solar radiation input and re-radiation back to atmosphere as well as convective heat loss to the atmosphere from the rock surface. The vertical boundary opposite the lake was assumed to be sufficiently far from the influence of the lake for a one dimensional heat transfer solution to be valid. The finite difference solution to the resulting conductive heat transfer problem would supply enough energy to evaporate 34 mm yr^{-1} of ice.

The energy input due to the absorption of solar radiation was calculated to be 221 W m^{-2} based on a total solar energy flux of 3527 MJ m^{-2} yr^{-1} for Davis station (Streten, 1986) and an average of 4 hr sunlight day^{-1}. Re-radiation of heat to the atmosphere was calculated to be approximately 130 W m^{-2} and the convective heat loss from the lake surface was 77 W m^{-2}. Conductive heat transfer due to the vertical temperature gradient within the lake was approximately 0.5 W m^{-2}. The resulting gain in energy of 13 W m^{-2} potentially results in an evaporation of 24 mm yr^{-1} of ice.

The estimates of each of the water loss mechanisms above provides an upper bound estimate of total water loss in Ace Lake of 252 ± 45 mm yr^{-1}. Geothermal heat flux, although insignificant, was included in this calculation. However, a loss in ice cover due to physical abrasion by wind borne grit was not included as no data for the calculation of this factor were available.

6.3 Current Precipitation estimate of Ace Lake

As no other loss mechanisms are calculated the difference between the calculated water loss and input due to precipitation must manifest itself as a change in lake level. The water level in Ace Lake was monitored between 1985 and 1989 resulting in a measured average increase in lake level of 60 mm yr^{-1}. A net water balance for the catchment for this period indicates a precipitation rate of 64 mm yr^{-1} was required to account for this increase. This estimate compares well with a rare measurement of annual precipitation at nearby Davis Station of 69 mm in 1961 (Commonwealth Bureau of Meteorology, 1961). The theoretical estimate of precipitation herein assumes 100% efficiency of precipitation transport from the catchment to the lake. The real value would be less but this would not effect the relative changes of precipitation recorded in the sediments.

Having established the current precipitation rate for known water level changes in Ace Lake, a baseline against which to compare long term changes of these parameters has been established.

6.4 Palaeolake Water Level Estimates from Palaeosalinity Estimates

Closed lake basins fluctuate in both water level and water chemistry in response to seasonal, inter-annual or longer term climatic fluctuations enabling past lake-level and water chemistry fluctuations to be recorded in the lake sediment (Gasse *et al.*, 1995; Guiot *et al.*, 1993). Thus reconstruction of past water balances are possible from palaeolimnological indicators (Juggins *et al.*, 1994). It has been shown herein that Antarctic lake diatoms are strongly and significantly correlated with epilimnetic (=mixolimnion) salinity. Therefore, from the diatom-salinity transfer function established for the saline lakes of the Vestfold Hills, palaeosalinity fluctuations can be used to make inferences about past water levels of the lake basin.

The top 30 cm of the sediment core* taken from Ace Lake (equivalent to 1500 ^{210}Pb years and 1650 corrected ^{14}C years) was identified as closed-basin saline lake deposited sediment (Figure 17a,b). Diatom-inferred salinity fluctuations within this period are reconstructed in Figure 26.

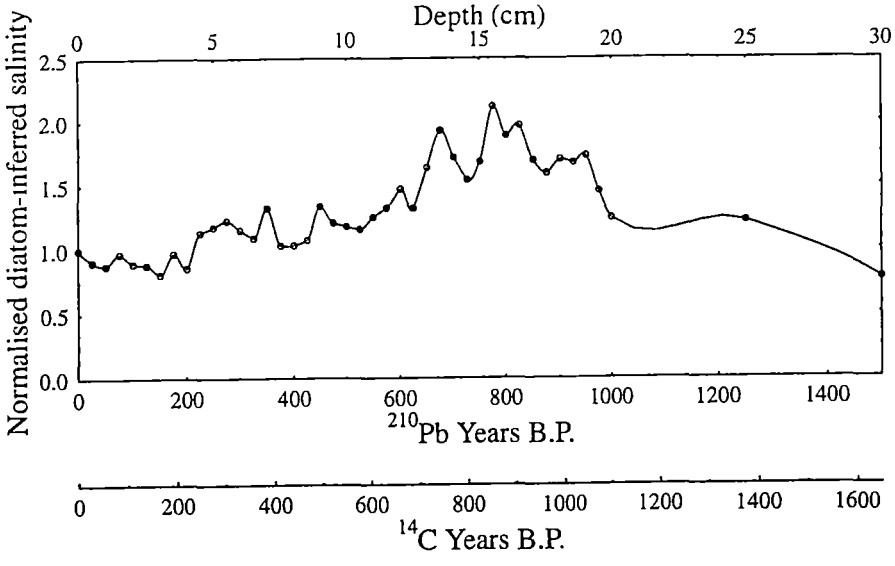

Figure 26: Normalised diatom-inferred salinity estimates for the top 30 cm of the Ace Lake sediment core. Each diatom-inferred salinity value has been normalised by the current predicted salinity to relate all predicted salinity values to current mixolimnion values.

An increasing salinity trend is apparent from ~ 1500 years B.P. to a salinity maximum at 775 ^{210}Pb years B.P. / 850 ^{14}C years B.P., after which a declining trend to ~ 200 years B.P. is indicated. In the last two centuries salinity appears to have stabilised.

The lake structure is very stable (Figure 25) so that the mixolimnion will behave as a separate lake until the salinity gradient at the halocline disappears. It is therefore assumed that the total salt content of the mixolimnion is constant and therefore the change in mixolimnion water depth is inversely proportional to the change in salinity, enabling water levels to be determined from palaeosalinity estimates over the last 675 ^{210}Pb years / 750 ^{14}C years (Figure 27). Water levels estimated before this can not be calculated with confidence as at this time the salt concentration of the mixolimnion became equal to that of the monimolimnion thereby destroying the lake structure.

* It is possible that the top of this core does not represent the most recent sediments. Some loss of material during the coring process is always a possibility.

As a result, lake water level reconstructions prior to ~ 700 years B. P. are no longer reliable.

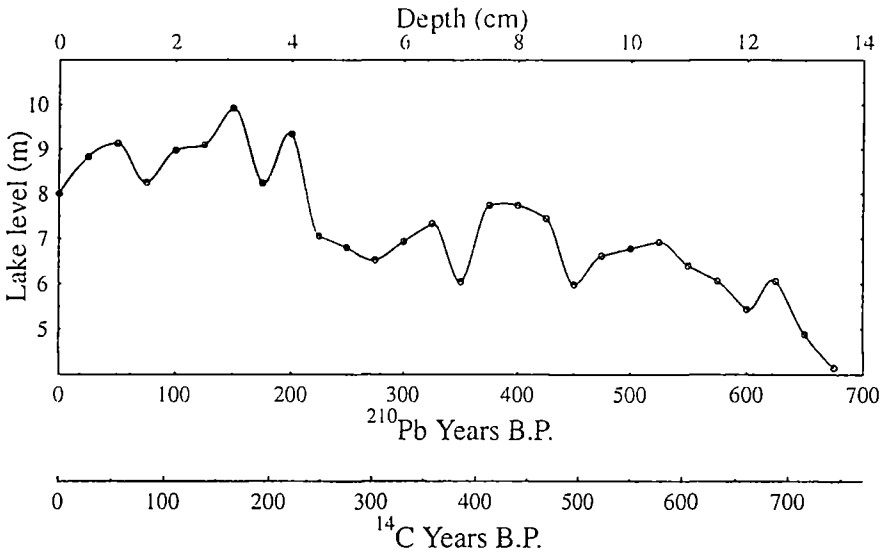

Figure 27: Water level estimates reconstructed from diatom-inferred salinity fluctuations for the previous ~ 700 years.

6.5 Palaeolake Precipitation Estimates

Water levels of the lakes of the Vestfold Hills are a function of local precipitation, sublimation and evaporation (Gibson & Burton, 1996). Hindcasting of changes in the precipitation rate is therefore possible (assuming constant rates of sublimation and evaporation) from the changes in water level inferred from the palaeosalinity signal (Figure 28).

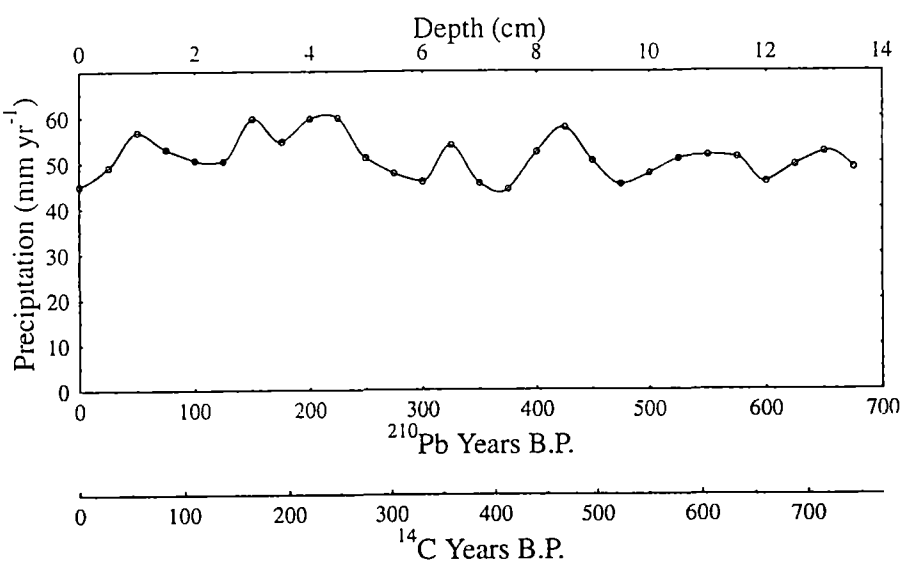

Figure 28: Precipitation estimates reconstructed from water level estimates and current water loss calculations for the previous ~ 700 years.

Although the water budget has increased in the last ~ 700 years, a long term precipitation increase is not apparent (Figure 28). Precipitation is relatively stable throughout the past ~ 700 years with no significant trends evident throughout this time period.

6.6 Discussion

Lake sediments such as those described here contain an excellent record of past climatic fluctuations. The strong relationship between diatom assemblage composition and lakewater salinity demonstrated for the Vestfold Hills reveals that sedimentary diatoms provide an excellent tool for reconstructing past changes in salinity and therefore water level in Antarctic saline lake environments. These changes in water level can then be used as proxies for relative water input and effective precipitation in the lake basin.

Diatom stratigraphy of Ace Lake demonstrates how this can be achieved. Diatom stratigraphy of Ace Lake reveals distinct changes in species dominance throughout the 175 cm core sample length (Chapter 4, Figure 17a,b). Diatom-based palaeosalinity zones indicate that Ace Lake has undergone 3 distinct stages in its history, namely a freshwater stage, a marine inlet stage and finally, a saline lake stage. Within this latter stage of the lakes development salinity has fluctuated, markedly at some times. The marked salinity fluctuations in the most recent sediments are indicative of changes in the lakes water level and subsequent precipitation rates in the basin throughout this time period.

From current estimates of precipitation in the catchment of Ace Lake and current salinity/water level relationships, palaeoclimatic inferences can be made within the last ~700 years worth of sediment. Although fluctuations in salinity, water level and precipitation are apparent within these sediments, long term precipitation trends are not. It would appear that natural fluctuations are marked and that as yet there is no identifiable increase in precipitation as would be expected with anthropogenically influenced warming in such a region (cf. Kattenberg *et al.*, 1996).

Current global climate models suggest that greenhouse gas emissions resulting from human activities will enhance the natural greenhouse effect and result in additional warming of the earth's surface (Houghton *et al.*, 1990; Adamson & Adamson, 1992). An increase of about 0.3°C per decade is predicted, resulting in a likely increase in global mean temperature of about 1°C by 2025 and 3°C before the end of next century (Adamson & Adamson, 1992). If this is correct, warming will be more rapid than any experienced over the past 10, 000 years (Adamson & Adamson, 1992) and coupled with this warming would be an increase in precipitation in coastal Antarctic regions (Kattenberg *et al.*, 1996). The reconstruction of water level and precipitation over the past ~ 700 years in Ace Lake based on lakewater salinity fluctuations inferred from fossil diatom assemblages shows that there has been no significant change in precipitation in this lakes basin over this period.

Verification of this precipitation trend from other Antarctic lakes in the area is difficult as, to date, few records of comparable resolution exist. However, measurements of snow accumulation in ice cores from Law Dome, East Antarctica (Morgan, 1985) show a cool period around 200 years ago with temperatures then increasing during the nineteenth and twentieth centuries. It would appear that the maximum precipitation in Ace Lake (Figure 28) is recorded during a cool event in East Antarctica, suggestive of a cool moist period at ~ 200 years B.P. Low temperatures between 500 and 150 years ago in the Northern Hemisphere are associated with the cool moist "Little Ice Age" (Fritz *et al.*, 1994). It is possible that precipitation estimates herein suggest a Little Ice Age event occurred in the Antarctic, although not of as great a magnitude as that in the Northern Hemisphere. The Vestfold Hills would then hold an intermediate position between the Dry Valleys (76°30' - 78°30' S, 160° - 164° E), where no Little Ice Age has been detected and the Sub-Antarctic Islands, where it is clearly discernible (Clapperton & Sugden, 1988).

The palaeolimnological water level and precipitation inferences for Ace Lake shown here shows the manner in which a high resolution salinity signal can provide an indication of the natural variability of the precipitation fluctuation. A significant increase in precipitation is not apparent in Ace Lake which implies that climatic processes acting on this coastal Antarctic lake basin have not yet been significantly influenced by anthropogenic processes. This local precipitation model can now be applied to several saline lake cores from the Vestfold Hills in order to develop a regional precipitation model for this coastal Antarctic region.

Chapter 7: Conclusions

7.1 Summary of Research

The specific objectives of this thesis were to use fossil diatom assemblages to quantify palaeo-lakewater variables in Antarctic lakes by:

1) exploring relationships between recent diatom assemblages and limnological environmental parameters;

2) determining which lake characteristics are most strongly related to the composition of surface sediment diatom assemblages;

3) modelling the response of the variables identified in 2) to allow these parameters to be calculated from the relative percentage of diatom species in palaeolake samples; and

4) extending this correlation to fossil sediment samples allowing palaeoenvironmental parameters to be estimated.

These objectives have been successfully researched with the relationship between recent diatom assemblages and limnological variables allowing the determination of salinity as the strongest variable effecting diatom distribution and abundance in the lakes of the Vestfold Hills. This relationship was modelled successfully allowing the first palaeosalinity reconstructions for the Vestfold Hills. These reconstructions have defined the timing and extent of significant Holocene salinity fluctuations within the sediment cores analysed. Furthermore, these methods have defined recent (~ 700 years) precipitation trends in one of these cores, demonstrating the significance of this research.

7. 2 Implications of Research

Current environmental problems, like acid rain and global warming, have increased interest in fossil species assemblages as indicators of the palaeo-environment and thus, in quantitative methods for reconstructing environmental variables from species assemblage data (ter Braak & Juggins, 1993). The salinity inference model developed here can now be used to infer past climatic conditions and most notably palaeoprecipitation changes (Chapter 6), as reflected in lakewater salinity changes, based on the diatom assemblages in sediment cores from appropriate closed-basin lakes in the Vestfold Hills.

7.3 Recommendations for Future Research

Palaeolimnology has seen some important developments over the last 15 years (reviewed by Smol, 1990, 1992; Anderson, 1993; Charles & Smol, 1994 and Moser *et al.*, 1996). However, for palaeolimnological records to be of maximum resolution some improvements in techniques can be made.

The existing training dataset is adequate for reconstructing salinities in the range 0.5 to 165 ‰, but there are too few freshwater lakes in the present training set to be confident of fresher gradient end reconstructions and there may be a tendency of an over estimation of salinity optima's because of the dominance of the markedly saline lakes in this dataset. The key to improving the current transfer function further is the addition of more lake samples with particular emphasis given to freshwater lakes.

Also, an initial dataset of 33 lakes is sufficient to generate a transfer function for salinity reconstruction but a much larger (e.g. 150 +) data set is required for secondary gradient responses to be identified (cf. Gasse *et al.* 1983; Juggins *et al.* 1994). Experimental studies have suggested that major anions and cation concentrations can affect the diatom communities (Tilman *et al.*, 1990). Many more training set lakes are required to assess the significance of possible correlations between cation and anion concentrations and diatom community structure.

Enlargement and imporvement of the training database by amalgamation of existing data sets is also another possibility, although difficult as few comparative training sets exist to date from the Antarctic.

Silica microfossil dissolution is recognised as a problem in the marine context where it can lead to erroneous palaeoecological interpretations (e.g. Shemesh *et al.*, 1989) and where quantification of biogenic silica dissolution has been attempted (e.g. Pichon *et al.*, 1992). Differential dissolution within a fossil diatom assemblage has the potential to reduce greatly the accuracy of transfer functions designed to provide quantitative estimates of water chemistry (Gasse 1987; Fritz *et al.*, 1991). If diatom-based palaeoenvironmental reconstruction in saline lakes is to reach its full potential, the causes and implications of assemblage modification by dissolution must be made more thoroughly understood, with particular attention paid to the role of the ionic composition and concentration (Barker *et al.*, 1994) in saline lake provinces.

Another area not sufficiently known about is the possible nutrient influence on saline lake diatom distribution and abundance. The manner in which nutrient concentrations and/or ratios effect Antarctic saline lake diatoms is not clear and remains another significant question to be answered.

And finally, underlying all diatom-based research is the need for an accurate and precise taxonomy.

Postscript

The saline lakes of the Vestfold Hills offer unique environments in which to integrate research into past, present and future climate change, particularly as they exhibit special characteristics that make them excellent climate recorders e.g. abundance of closed saline and meromictic lakes, etc. I therefore concur with DASET (1992) that " as a monitoring site of change Antarctica is unsurpassed but not yet fully utilised."

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Appendix 1: Choosing the Most Appropriate Statistical Technique

Assumptions of a Transfer Function

If the distributional patterns of diatoms in the modern lake are to be used to infer past environmental parameters from fossil assemblages then certain assumptions must be made about the concordance between the modern and ancient lake systems (Juggins, 1988).

The general assumptions of a transfer function approach have been discussed by Imbrie & Kipp (1971), Imbrie & Webb (1981), Birks & Gordon (1985), Juggins (1988), Birks *et al.* (1990) and Charles & Smol (1994).

Assumptions defining the transfer function developed herein are:

1) That modern (surface sediment) diatom assemblages are systematically related to the physical and chemical environment from which they were sampled.

2) That fossil (core) diatom assemblages are related to the physical and chemical environment in which they were deposited.

3) That the present day physical and chemical lake environment is the same as the physical and chemical palaeolake environment.

4) That species responses to their environment have remained constant throughout time.

5) That the relationships between the diatom assemblages and the water chemistry parameters sampled are non-linear.

General Theory of a Transfer Function

The basic method of the transfer function approach is to formalise the relationship between a set of biological responses and environmental variables in terms of a series of transfer functions (Juggins, 1988) i.e.

$$D = T * E$$

where D represents a matrix of biological responses, in this case the proportion of each diatom taxon; E represents an environmental variable matrix and T represents a set of transfer functions that act to transform the diatom data into climatic information.

The entire procedure can be expressed as a two-step process (after Webb & Bryson, 1972; Birks & Gordon, 1985, Juggins, 1988 and Birks, 1994).
First, the responses of modern taxa (D_m) to the contemporary environment (E_m) are modelled. This is a regression problem (ter Braak & Prentice, 1988). In this regression step the aim is to calculate the transfer functions that transform the diatom data into environmental estimates (T) from the modern training set:

$D_m = T * E_m$

Then assuming the climatic response represented by each diatom species has remained constant throughout time, T can be used to interpret fossil biological data in terms of environmental data. This second step uses the modelled responses from the first step (T) to infer past environmental conditions (E_f) from the fossil diatom assemblage (D_f). This is a calibration problem (ter Braak & Prentice, 1988):

$E_f = T^{-1} * D_f$

T can be solved using multivariate statistical procedures.

Multivariate Statistics

Multivariate statistical techniques serve to summarise massive, complex, multidimensional data sets by reducing dimensionality and extracting major directions of variations (Shi, 1993). The major statistical techniques available for the analysis of multivariate ecological data sets include REGRESSION - a technique used to model the relation between a particular species and environmental variables, and to detect whether a species can be an indicator for a particular environmental variable; ORDINATION - a technique used to summarise data on communities of species, and CALIBRATION - a technique used to infer about the environment from (indicator) species (Jongman *et al.* 1987). But before a statistical technique can be chosen to apply to an ecological data set the type of response model it represents must be determined. The way in which a species responds to an environmental variable is termed its response model. Response models are assumed to be either linear or non-linear.

Linear response models

Linear response models assume that a species responds to an environmental gradient in a linear way i.e. a graph representing the manner in which they vary with each other will be a straight line. If the straight line passes through the origin (x,y = 0,0) the variables are directly proportional and the equation of the line is y=bx where b is the gradient or slope (ratio of vertical distance to horizontal distance) of the line (Uvarov & Isaacs, 1986). In the more general case (Figure A1-1), the line does not pass through the origin and the equation of the linear relationship becomes y = a + bx with a the intercept of the line on the y-axis and b the slope of the line, or regression coefficient (ter Braak & Prentice, 1988). In this way the abundance of a taxon (y) at a given environmental value (x) can be determined.

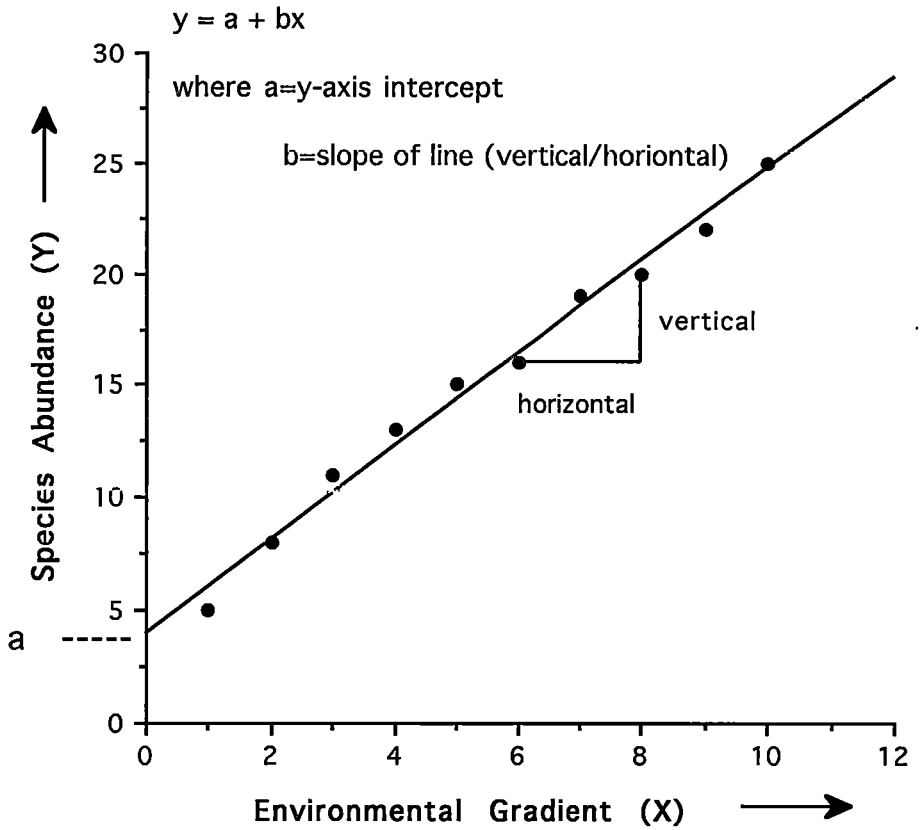


Figure A1-1: Response model used in fitting a straight line to data points (•) by least squares regression.

A range of techniques which assume an underlying linear response model have been developed and used to develop transfer functions. These include Imbrie & Kipp's (1971) determination of ocean palaeotemperature using factor analysis, Imbrie & Webb's (1981) estimation of Quaternary palaeotemperatures from pollen using multiple regression of individual species, Flower's (1986) determination of lake water pH from diatoms using multiple regression of groups of species and Webb & Bryson's (1972) estimation of Quaternary palaeotemperatures from pollen using canonical correlation analysis.

Species abundances may seem to change linearly through short sections of environmental gradients, so a linear response model may be a reasonable basis for analysing quantitative abundance data spanning a narrow range of environmental variation (ter Braak & Prentice, 1988). However, over longer environmental gradients species are more likely to exhibit a non-linear response.

Non-linear response models

Data with non-linear structures are common in ecology. They occur whenever the measured variables (species quantities) are nonlinearly dependant on underlying environmental factors (Pielou, 1977). Gause (1930), among others, observed that species typically show unimodal (bell-shaped) response curves with respect to environmental gradients i.e. each species thrives best at a particular value (optimum) and cannot survive when the value is either too low or too high (cf. Shelford's "law" of tolerance (Odum, 1959)(ter Braak & van Dam, 1989).

A unimodal response model for one environmental variable can be obtained by adding a quadratic term (x^2) to the linear model, changing the response curve from a straight line into a parabola (ter Braak & Prentice, 1988). But this quadratic model can predict large negative values, whereas species abundances are always zero or positive (ter Braak & Prentice, 1988). A simple remedy for the problem of negative values is provided by the Gaussian response curve (ter Braak & Prentice, 1988).

Gaussian Response Model

The Gaussian response curve (Austin 1980) is a simple bell-shaped curve in which each species has a maximum abundance at its optimum and abundance declines either side of that optimum. If the relationship between species occurrences and values of a quantitative environmental variable approximate Gaussian responses, then each species' curve can conveniently be summarised by an indicator value (optimum) and an ecological amplitude (tolerance) (Figure A1-2). The range of occurrence of a species can also be seen, in figure A1-2 the species range of occurrence is 4t. Although real ecological response curves are still more complex than implied by Gaussian models, these models are nevertheless useful in developing descriptive techniques for data showing mostly unimodal responses, just as linear models are useful in statistical analysis of data that are only approximately linear (ter Braak & Prentice, 1988).

Gaussian response models have been used to develop diatom-based transfer functions (ter Braak & van Dam, 1989) although with a more limited following due to the computer intensive nature of Gaussian methods. A more complete discussion of Gaussian response models and Gaussian theory and application is available in Gauch *et al.* (1974), Ihm & Groenewoud (1975), Hill & Gauch (1980) and Gauch (1982).

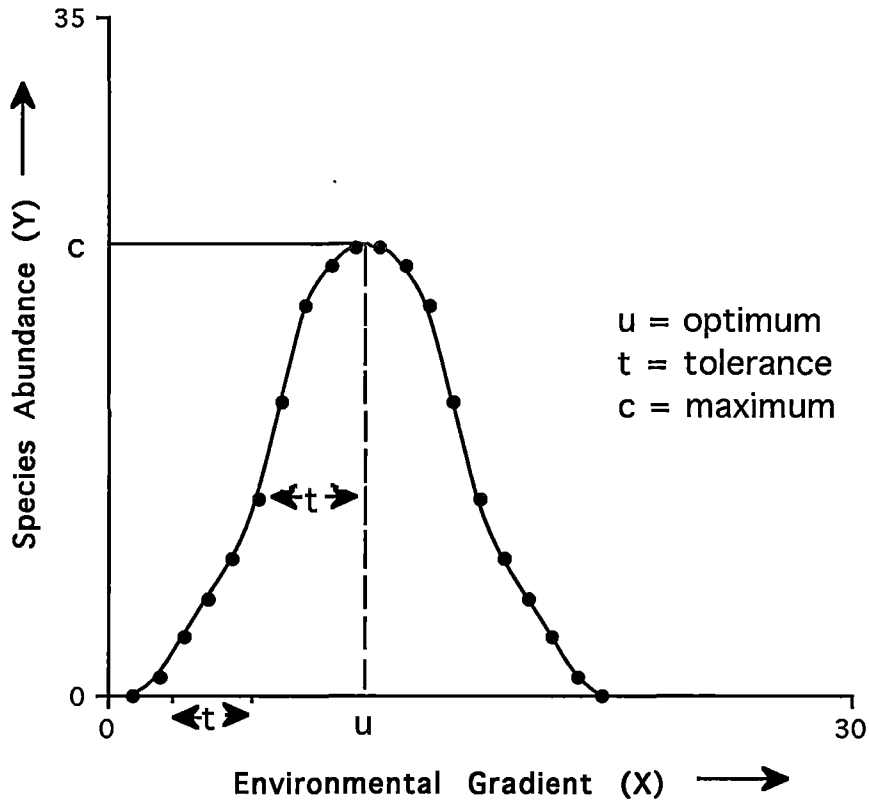


Figure A1-2: Gaussian response curve with its three ecologically important parameters: maximum (c), optimum (u) and tolerance (t).

Weighted Averaging Response Model

Ecologists have developed alternative, heuristic methods that are simpler but have essentially the same aims as the Gaussian models and each method in the Gaussian family has a counterpart in the family of methods based on WA (ter Braak & Prentice, 1988).

When a species shows a unimodal relationship with environmental variables, the species' presences will be concentrated around the peak of this function (ter Braak & Prentice, 1988). One intuitively reasonable estimate of the optimum is therefore the average of the values of the environmental variable over those sites in which the species is present (ter Braak & Prentice, 1988). With abundance data, WA applies weights proportional to species abundance with absences carrying zero weight (ter Braak & Prentice, 1988).

The WA method has advantages over earlier quantitative techniques, as it ignores species absences and does not assume a linear species response over long

environmental gradients. It also avoids the loss of ecological information, as each taxon is assigned an optimum and tolerance value (Birks *et al.*, 1990). Consequently, a weighted-average response model is considered to be ecologically more realistic and a weighted average method statistically more robust and numerically more accurate than other methods (Birks *et al.*, 1990).

Birks *et al.* (1990) and ter Braak & van Dam (1989) compared Gaussian and WA response model based transfer functions for inferring pH. Their findings suggest that while formal Gaussian based techniques are statistically rigorous they are computer intensive. The WA approach is, in comparison, a more practical and computationally straightforward alternative that approximates the Gaussian technique. A more complete discussion of WA theory and application is available in ter Braak & Barendregt (1986), ter Braak & Looman (1986); ter Braak & Prentice (1988); ter Braak & van Dam (1989) and Birks *et al.* (1990).

As weighted averaging methods perform well with noisy, species-rich data that cover a long ecological gradient many recent diatom-based transfer functions are based on a WA model (e.g. Dixit *et al.*, 1991; Hall & Smol, 1992; Christie & Smol, 1993; Fritz *et al.*, 1993; Bennion, 1994; Jones & Juggins, 1995; Pienitz *et al.*, 1995; Reavie *et al.*, 1995; Vyverman & Sabbe, 1995).

Transfer Function Techniques

Reconstruction of lake environments from palaeolimnological diatom assemblages involves two distinct stages. The first stage models the responses of modern diatom abundances to modern environmental parameters, and the second uses the modelled responses to infer environmental variables from diatom assemblages preserved in lake sediments. The first stage involves quantifying the relationship between species' abundance and one or more environmental variables. This can be done using regression or ordination. The second stage is a calibration problem where the relationships quantified in the first stage are used to infer environmental values from fossil diatom assemblages.

PART 1: Model the response of modern diatom assemblages to modern water chemistry parameters

Regression

The goal of regression analysis is to describe a single species' abundance as a function of one or more (multiple regression) environmental variables (ter Braak & Looman, 1987). Regression analysis allows the assessment of which environmental variables contribute most to the species' response and which environmental variables appear to be unimportant as well as the prediction of species responses at sites from observed environmental variables (ter Braak & Looman, 1987).

Linear Regression

If a plot of the abundance (y) of a species against an environmental variable (x) looks linear, or can easily be transformed to linearity, then it is appropriate to fit a straight line by linear regression (ter Braak & Prentice, 1988). The formula $y = a + bx$ describes the linear relation as previously discussed, with a the intercept of the line on the y-axis and b the slope of the line, or regression coefficient (ter Braak & Prentice, 1988). Regression analysis is concerned with solving the values a and b in this equation. Separate regressions can be carried out for each species (ter Braak & Prentice, 1988).

Species experience the effect of more than one environmental variable simultaneously, so more than one variable may be required to account for variation in species abundances (ter Braak & Prentice, 1988). The joint effect of two or more environmental variables on a species can be analysed by multiple regression (ter Braak & Prentice, 1988).

Multiple regression based transfer functions have been developed for inferring water chemistry variables from diatoms in many parts of the world (e.g. Northern New England (Davis & Anderson, 1985); South West Scotland (Flower, 1986); Sweden (Håkansson, 1992) and Canada (Agbeti, 1992).

Non-Linear Regression

Weighted averaging regression assumes that the maximum relative abundances of taxa occur at or near their ecological optima, and the WA inferred value is simply an average of the optima of all taxa that occur in a sample, weighted by their individual relative abundances (Dixit *et al.*, 1993).

The weighted averaging regression idea is simple and ecologically reasonable. Each species is largely confined to a specific interval along an environmental variable (ter Braak, 1985). The value most preferred by a species, its optimum, is estimated by taking the average of the values of the environmental variable in those samples in which the species occurs (for quantitative data, the average is weighted by species abundance) (ter Braak, 1985). A taxon's optimum for a given environmental parameter is therefore the average of all the values for lakes in which the taxon occurs, weighted by the taxon's abundance (Fritz, 1990). Conversely, with known species optima, weighted averaging can be used to estimate the value of an environmental variable in a sample from the species that it contains - WA Calibration (ter Braak, 1985).

WA regression and calibration is a commonly used technique for inferring past nutrient and salinity gradients throughout the world (Hall & Smol, 1992; Bennion, 1994; Cumming & Smol, 1993; Fritz *et al.*, 1993; Wilson *et al.*, 1994) as these variables usually have a wide range in natural limnological environments.

Ordination

Where regression analysis provides a detailed account of the relations between species and their environment, the ordination approach gives a more global picture of the general patterns of the assemblage of species to their environment (ter Braak, 1987c).

Ordination arranges points in a two-dimensional space such that points that are close together correspond to samples that are similar in species composition, and points that are far apart correspond to samples that are dissimilar in species composition (ter Braak, 1987c). Major directions of variation are extracted from the original data by rearranging the data points in a multidimensional space so that the data points are concentrated on the first few, preferably two or three, principal axes that represent the major directions of variation of environments that control the variations of samples or taxa in the data (Orlóci, 1978; Davis, 1986 in Shi, 1993). The outcome of an ordination is a low, usually two- or three- dimensional scatter plot, in which samples or variables are located relative to one another according to their variations on these axes (Shi, 1993). If natural groupings of samples or variables do exist in the original data, they may be revealed in the scatter plot (Shi, 1993).

Two ordination techniques exist for the interpretation of species/environment data sets in terms of gradients of phenomena. In one, indirect gradient analysis, community samples are displayed along axes of variation in composition that can subsequently be interpreted in terms of environmental gradients. In the other, direct gradient analysis, each species' abundance is described as a function of measured environmental variables (ter Braak & Prentice, 1988).

Indirect Gradient Analysis Techniques

Indirect gradient analysis seeks to express variations of samples or taxa on few major axes that are hoped to represent underlying environmental factors (Shi, 1993). The indirect gradient analysis technique is a two-step approach to relate species data to environmental variables (ter Braak & Prentice, 1988). The first step is to summarise the main variation in the species data by ordination (ter Braak, 1986). The second step is to relate the ordination axes to environmental variables - this can be done graphically by calculating correlation coefficients or by multiple regression of the site scores on the environmental variables (ter Braak, 1986).

There are many indirect ordination methods developed in community ecology that all have the primary objective of reducing dimensionality and revealing major directions of data variation. Principal component analysis (PCA), correspondence analysis (CA) also known as reciprocal averaging (RA), and detrended correspondence analysis (DCA) are some examples. These methods are potentially effective in summarising data sets when there are no measured environmental variables available with which to compare community composition.

Direct Gradient Analysis Techniques

Direct gradient analysis constrains the two-step approach into one. Axes in ordination of the species data are constrained to be linear combinations of known environmental variables. In this way community variation can be directly related to environmental variation (ter Braak, 1986). Consequently, in the direct gradient approach, samples or variables are ordinated either graphically or mathematically within an environmental framework in which the ordinated samples or taxa are directly related to environmental gradients (Shi, 1993).

Canonical correspondence analysis (CCA) and detrended canonical correspondence analysis (DCCA) are just two examples of direct gradient analysis ordination techniques. These techniques are particularly effective when known environmental gradients are used to ordinate the species assemblage.

Choices must therefore be made not only based on the type of species response model a dataset represents but the type of environmental dataset being worked with. Measured environmental variables require a direct ordination technique if the aim is to explore their effect on species compositions and distributions. If this information is not known then indirect ordination will allow the major directions of variation within the dataset to be extracted.

Linear Ordination

Linear ordination requires the species response model to be a linear one. An example of this type of technique is principal components analysis (PCA). This technique is a linear indirect gradient analysis technique that may be used effectively as a tool for summarising large, quantitative data sets that are relatively homogeneous in structure (Shi, 1993). PCA is of limited use, however, when a dataset is heterogenous and is also vulnerable to effects of sampling errors and outliers because both virtually lead to increasing data noise and heterogeneity (Shi, 1993). PCA can be relied upon to perform well only if the observed variables (species quantities) have, at least approximately, a linear data structure (Pielou, 1977).

Non-linear Ordination

Methods for Gaussian ordination exist but due to their computational complexity weighted averaging methods have gained wider acceptance as the more useful and less rigid non-linear response model technique. Weighted averaging ordination techniques assume non-linear species responses to environmental variables. An example of a weighted-averaging based ordination technique is
canonical correspondence analysis (CCA). This non-linear direct gradient analysis technique relates community composition to known variation in the environment (ter Braak, 1986). Ordination axes are derived that are linear combinations of

environmental variables and individual species are then related directly to these axes under the assumption of a unimodal species response to the environmental variables (Stevenson *et al.*, 1989). Consequently, CCA satisfies ecologists' desire for a simple, robust method to relate species to environmental variables, if the relationships are assumed to be unimodal (ter Braak, 1987a).

PART 2: Calibrate past water chemistry parameters from fossil diatom assemblages

Calibration

The goal of regression analysis is to express the response of a species as a function of one or more environmental variables. The reverse process: namely how to express values of an environmental variable as a function of species data is termed calibration (ter Braak, 1987b).

There are situations where direct measurement of environmental variables is impractical if not impossible. Repeated measurements of one variable may be too costly or logistically impractical and/or direct environmental measurements may not be possible. One example is the many continental Antarctic lakes which have never been sampled and for which detailed historical records are not available. Palaeolimnological techniques have particular relevance for the inference of past water chemistry variables, lake levels and climate in the Antarctic as there are few other techniques available for the reconstruction of such important factors.

Linear Calibration

Linear calibration or "inverse regression" is simply multiple linear regression of the environmental variable on the species abundances (Brown, 1982): the environmental variable is treated as if it were the response variable and the species abundances, possibly transformed, as predictor variables (ter Braak & Prentice, 1988). The regression coefficients can be estimated from the training set of species abundances and environmental data, the resulting equations being applied directly to infer environmental values from further species abundance data (ter Braak and Prentice, 1988).

Non-Linear Calibration

Weighted averaging calibrations allow estimates to be made of environmental values at sites from species' optima (ter Braak & Prentice, 1988). When species replace one another along the environmental variable of interest, i.e. have unimodal response functions with optima spread out along that variable, then species with optima close to the environmental value of a site will naturally tend to be represented at that site (ter Braak & Prentice, 1988). In fact, weighted average calibration assumes that at a given

value for an environmental variable (e.g. at a given salinity), taxa with optima near that value will be the most abundant (Fritz, 1990). Intuitively, to estimate the environmental value at this site, one can average the optima of the species that are present (ter Braak & Prentice, 1988). This is "simple" weighted averaging calibration (WA). Taxa with a narrow tolerance for an environmental variable can be given greater weight in WA calibration than taxa with a wide tolerance. Tolerances can be used in addition to optima's in calibrations. This is tolerance-downweighted weighted averaging calibration (WA(tol)). The reconstructed value of the environmental variable for a fossil sample is generated from a diatom assemblage by calculating the weighted average of the optima (and tolerances) of the taxa present in that sample (Birks *et al.* 1990).

The WA calibration method differs from "inverse regression" only in the way in which the species optima are estimated, since the linear combination of percentage values used to estimate the environmental values in "inverse regression" is by definition a weighted average of the regression coefficients (ter Braak & Prentice, 1988).

Calibration by weighted averaging is the natural endpoint of a historical development that started with Imbrie & Kipp (1971). To reconstruct past sea-surface temperature from foraminifera, Imbrie & Kipp (1971) considered applying inverse regression to a training data set i.e. regression of temperature on the abundances of the species (ter Braak, 1987a). Due to the multicollinearity of the abundances of many of the species, abundances were reduced to a few axes by principal components analysis (PCA) and temperature was regressed on these axes. The resulting equation was used for temperature reconstruction (ter Braak, 1987a). Roux (1979) produced a better estimate of temperature by replacing PCA with a weighted average method, correspondence analysis (CA) (ter Braak, 1987a).

Weighted averaging calibration is now a commonly used palaeoecological technique. Diatom-based transfer functions for the inference of pH (Gasse & Tekaia, 1983; Birks *et al.*, 1990), nutrients (Hall & Smol, 1992; Bennion, 1994) and salinity (Fritz, 1990; Fritz *et al.*, 1991, 1993, 1994; Cumming & Smol, 1993; Wilson *et al.*, 1994) are all based on weighted averaging calibration.

The choice of one technique over another depends on both the characteristics of the data set to be analysed and the type of output required by the researcher. The following questions should always be asked before a choice is made.

Which Response Model ?

Linear or non-linear?

Where gradients are short, there are sound statistical reasons to use linear methods (ter Braak & Prentice, 1988). But if data has been collected over a sufficient range of environments for species to show unimodal (or more complex) relationships with environmental variables, it is clearly inappropriate to analyse these relationships by standard statistical methods that assume linear relationships such as principal components analysis (ter Braak, 1987a). Therefore, as gradient lengths increase, linear methods become less useful; Gaussian methods become feasible and weighted averaging related techniques become the most effective.

The linear techniques are conceptually the simplest and methods based on linear response models may be suitable for deriving transfer functions covering a short range of environmental variation (Juggins, 1988). However, they have found only limited application in ecology because of the generally non-linear response of species to environmental variables (ter Braak & Prentice, 1988). As a result, palaeolimnological researchers have turned to non-linear weighted averaging methods for more ecologically sound reconstruction techniques. With the development of direct-gradient and unimodal statistical models that are based on weighted averaging computational techniques our ability to make quantitative inferences of lake-water chemistry from diatom assemblages has vastly improved (Hall & Smol, 1992).

Which Technique?

Regression, ordination or calibration?

Whether to use ordination instead of a series of separate regressions depends on whether or not there is any advantage in analysing all the species simultaneously (ter Braak & Prentice, 1988). Regression allows a very detailed account of how each species responds to particular environmental gradients. However, ecological data that are collected over a large range of habitat variation require non-linear models, and building good non-linear models by regression is demanding in time and computation (ter Braak & Prentice, 1988). Ordination has therefore become the more widely used technique for initial data analyses as it allows a more global picture of the assemblages response to environmental gradients than many separate species regressions are able to.

Calibration must be considered if inferences about values of a particular environmental variable from species data are required from existing knowledge of species-environment relations (ter Braak, 1987b).

For a complete look at any ecological data set a combination of all three techniques will provide the most comprehensive detail about species responses to their environment.

Which Method ?

In-direct or direct gradient analysis?

Direct gradient analysis allows the study of part (large or small) of the variation on community composition that can be explained by a particular set of environmental variables (ter Braak & Prentice, 1988). In indirect gradient analysis attention is first focused on the major pattern of variation in community composition; the environmental basis of this pattern is to be established later (ter Braak & Prentice, 1988).

If the relevant environmental data are available, the direct approach - either fitting separate response surfaces by regression for each major species, or analysing the overall patterns of the species-environment relationship by ordination - is likely to be more effective than the traditional indirect approach (ter Braak & Prentice, 1988). If important environmental factors are obvious and have been measured, direct gradient analysis has the advantages of simplicity and ease of interpretation (Gauch, 1982). However, indirect gradient analysis does have the advantage that no prior hypothesis is needed about what environmental variables are relevant (ter Braak & Prentice, 1988) and can be carried out after a direct gradient analysis in order to summarise the community variation that remains after known effects have been removed (ter Braak & Prentice, 1988).

Appendix 2: Numerical Dataset (47 species x 33 lakes).

SPECIES NUMBER	SPECIES INCLUDED IN NUMERICAL ANALYSES	ABRAXAS	ACE
1	Cocconeis species a	0.00	0.00
2	Achnanthes abundans	0.00	0.00
3	Amphora species a	0.00	0.00
4	Amphora veneta	0.33	0.00
5	Amphora species b	0.33	0.00
6	Amphora species c	0.00	0.00
7	Amphora species d	0.00	0.00
8	Cocconeis costata	0.00	0.00
9	Cocconeis fasciolata	0.00	0.00
10	Cocconeis pinnata	0.00	0.00
11	Fragilaria construens var. venter	0.17	0.00
12	Fragilaria species a	0.00	0.00
13	Hantzschia virgata	0.08	0.25
14	Navicula directa	8.25	3.17
15	Navicula glaciei	0.00	0.00
16	Navicula mutica/muticopsis	0.67	0.00
17	Navicula tripunctata	0.50	1.08
18	Navicula species a	0.00	2.08
19	Navicula seminulum	0.00	0.00
20	Navicula species b	0.08	3.83
21	Navicula species d	3.67	1.08
22	Navicula perminuta	0.00	0.00
23	Navicula species e	0.08	0.75
24	Navicula species i	0.00	0.00
25	Navicula species f	1.17	0.00
26	Fragilariopsis curta	0.00	0.08
27	Fragilariopsis cylindrus	0.00	32.08
28	Nitzschia lecointei	0.25	0.67
29	Nitzschia perminuta	0.00	0.17
30	Nitzschia species b	0.00	0.00
31	Stauroforma inermis	0.00	0.00
32	Pinnularia cymatopleura	0.17	0.00
33	Pinnularia lundii	0.00	0.17
34	Pinnularia microstauron var. microstauron	0.00	0.00
35	Pinnularia microstaruon	0.00	0.00
36	Pinnularia quadratera var. a	0.00	0.00
37	Pinnularia viridis	30.08	0.00
38	Pinnularia viridis var. "constricta"	13.58	0.00
39	Stauroneis species a	1.33	1.33
40	Stauroneis anceps	0.00	0.00
41	Stauroneis salina	0.00	0.00
42	Trachyneis aspera	0.00	0.00
43	Tryblionella marginulata	12.17	0.42
44	Genus indetermined species a	0.08	0.00
45	Chaetoceros vegetative cells	0.00	29.75
46	Chaetoceros resting spores	0.00	17.75
47	Thalassiosira antarctica	2.58	0.00

SPECIES NUMBER	ADMIN	ANDERSON	BURCH	BURTON	CAMP
1	0.25	0.00	0.00	1.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.33	0.08	0.83	0.00
4	5.50	9.33	1.08	0.00	0.50
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.17	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.08	0.42	0.83	0.33	0.00
9	0.00	0.00	0.00	0.33	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	1.58	0.00
12	0.25	0.08	0.50	7.50	0.08
13	0.00	0.00	0.00	0.00	0.00
14	4.50	5.25	59.92	6.58	21.00
15	0.00	0.42	0.00	8.58	0.17
16	0.08	0.17	0.58	0.00	0.42
17	3.67	0.75	0.00	0.83	15.17
18	0.00	0.00	13.83	0.58	0.00
19	0.00	0.00	0.00	0.00	0.00
20	29.83	1.17	15.08	0.58	2.67
21	8.08	0.00	0.00	0.08	20.58
22	0.75	0.25	0.00	1.25	0.00
23	2.75	0.50	0.17	0.00	0.00
24	0.00	0.08	0.00	0.00	0.00
25	2.08	0.00	0.00	0.00	0.00
26	1.00	1.25	0.00	2.92	0.00
27	0.50	2.17	0.00	9.25	0.67
28	0.25	0.00	0.00	5.33	0.17
29	0.75	0.67	0.00	0.50	0.00
30	0.25	2.67	0.00	0.00	0.00
31	0.00	0.00	0.00	0.08	0.00
32	1.25	0.25	0.00	0.00	0.75
33	0.08	0.00	0.00	0.00	0.00
34	0.00	0.00	0.00	0.00	0.00
35	7.25	1.83	0.00	0.00	5.00
36	0.00	0.00	0.00	0.08	0.00
37	0.08	0.00	0.00	0.00	4.67
38	0.00	0.00	0.00	0.00	0.00
39	10.00	0.92	4.08	0.50	8.67
40	0.00	0.08	0.00	0.00	0.00
41	0.00	0.17	0.00	0.00	2.25
42	0.00	0.00	0.00	0.00	0.00
43	0.00	0.17	0.00	1.50	0.00
44	0.00	0.00	0.08	0.00	0.00
45	0.17	52.42	0.00	34.42	0.50
46	0.42	14.92	0.25	6.50	0.00
47	0.00	0.00	0.08	0.00	0.00

SPECIES NUMBER	CLEAR	COLLERSON	EKHO	FLETCHER	FRANZMANN
1	0.00	0.00	0.00	1.92	3.25
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.17
4	3.92	0.25	2.00	0.33	0.00
5	0.00	0.00	5.33	4.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	2.00	0.00	0.00
8	0.33	0.00	0.00	0.00	0.25
9	0.42	0.00	0.00	0.08	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	4.67	1.08
12	0.25	0.08	0.33	0.75	0.83
13	0.00	0.00	1.25	0.00	0.00
14	4.00	0.00	4.08	1.33	0.92
15	0.00	0.00	0.00	16.92	11.42
16	2.17	0.08	0.25	0.08	0.00
17	9.25	9.25	4.33	2.00	0.33
18	0.00	0.00	0.58	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.58	0.00	13.92	7.50	6.33
21	2.67	0.42	0.00	0.67	0.00
22	0.00	0.00	0.00	0.42	1.25
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.08	0.42	1.08
27	0.08	0.00	0.17	4.42	5.08
28	0.00	0.00	0.92	5.50	2.42
29	4.08	1.17	0.92	0.50	0.42
30	0.00	0.00	0.00	0.00	0.00
31	0.00	0.00	0.08	0.00	0.00
32	5.08	0.00	0.08	0.00	0.00
33	0.17	0.00	0.50	0.00	0.08
34	0.25	0.00	0.00	0.00	0.00
35	8.33	17.50	0.58	0.00	0.00
36	0.00	0.00	0.00	0.00	0.00
37	0.58	6.33	0.50	0.00	0.00
38	0.00	0.00	0.00	0.00	0.00
39	5.25	0.33	13.50	1.42	0.92
40	0.00	0.00	0.00	0.00	0.00
41	0.00	0.00	0.33	0.17	0.17
42	0.00	0.00	0.00	0.00	0.00
43	0.00	0.00	0.00	0.00	0.08
44	27.58	64.08	0.00	0.00	0.00
45	3.83	0.00	22.50	21.92	53.33
46	2.00	0.50	5.08	20.92	6.75
47	0.00	0.00	0.00	0.00	0.00

SPECIES NUMBER	GRACE	HAND	HIGHWAY	JOHNSTONE	LICHEN
1	0.00	0.00	0.00	0.00	0.00
2	0.67	0.00	0.00	0.08	64.33
3	0.00	0.00	0.58	0.17	0.00
4	14.92	32.33	1.75	0.00	0.25
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.17	0.92	0.00
9	0.00	0.00	0.00	0.58	0.00
10	2.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.42	0.00
12	0.25	0.08	0.17	1.17	0.00
13	0.00	1.00	0.00	0.00	0.00
14	0.00	0.00	0.08	30.75	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	23.08	0.17	0.75	0.08
17	0.17	1.33	18.75	0.25	0.00
18	0.00	0.00	0.00	29.42	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	23.42	0.00
21	0.00	0.08	3.33	0.08	0.00
22	0.00	0.00	0.00	0.08	0.00
23	0.00	0.83	0.00	0.08	0.00
24	0.00	0.00	5.25	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.08	0.00	0.00	0.08	0.00
27	0.00	0.00	0.00	0.33	0.00
28	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00
31	1.75	0.00	0.00	0.08	12.17
32	0.00	15.92	0.33	0.00	0.25
33	0.00	0.92	0.00	0.08	0.00
34	0.00	2.67	0.00	0.00	0.00
35	79.00	5.75	54.42	0.00	16.75
36	0.00	0.00	0.08	0.08	0.00
37	0.00	0.00	12.75	0.00	0.08
38	0.00	0.00	0.00	0.00	0.00
39	0.00	0.00	0.25	0.00	0.00
40	0.00	1.33	0.00	0.00	3.00
41	0.00	0.00	0.00	0.00	0.00
42	0.00	0.00	0.00	0.25	0.00
43	0.00	0.00	0.00	0.00	0.00
44	0.00	0.08	0.00	0.00	0.00
45	0.00	0.00	0.00	0.08	0.00
46	0.00	0.33	0.83	9.08	0.00
47	0.00	0.00	0.08	0.00	0.00

SPECIES NUMBER	LP1	LP2	MCCALLUM	MCNEIL	OBLONG
1	0.00	0.00	0.00	0.00	1.33
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.50	0.83	1.33	0.00
5	0.00	0.00	2.17	0.75	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	4.75	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.92
12	0.00	0.00	0.00	0.00	0.92
13	4.25	0.00	0.00	0.67	0.00
14	7.58	22.08	2.33	0.08	7.00
15	0.00	0.00	0.00	0.58	5.08
16	1.08	0.00	0.25	9.75	0.25
17	38.75	50.00	2.33	13.25	0.25
18	0.00	0.00	0.00	7.58	7.25
19	0.00	0.00	0.00	8.50	0.00
20	26.58	11.08	2.92	0.08	0.58
21	0.67	0.00	0.58	0.25	0.00
22	0.00	0.00	0.08	0.00	0.92
23	1.50	10.50	0.00	0.00	0.17
24	0.00	0.00	0.00	0.17	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.50
27	0.00	0.00	0.00	0.00	10.33
28	0.00	0.08	0.00	0.00	1.50
29	0.08	0.33	0.92	0.00	0.00
30	0.00	0.00	0.00	0.08	0.00
31	0.00	0.00	0.00	0.00	0.08
32	0.00	0.00	0.83	10.67	0.00
33	1.83	0.00	0.00	7.58	0.00
34	0.00	0.00	0.00	0.00	0.08
35	0.00	0.00	1.58	13.17	0.00
36	0.00	0.00	0.00	5.83	0.00
37	2.42	0.33	2.58	0.08	0.00
38	0.00	0.00	0.00	0.00	0.00
39	6.00	1.67	5.75	0.00	0.33
40	0.00	0.00	0.00	0.33	0.00
41	0.00	1.50	0.00	0.00	0.00
42	0.00	0.00	0.00	0.00	0.00
43	0.00	0.00	0.00	0.00	0.08
44	0.00	0.00	0.42	0.00	0.00
45	0.00	0.00	62.17	0.00	34.92
46	0.17	0.00	9.42	0.17	25.92
47	0.00	0.00	0.00	0.00	0.00

SPECIES NUMBER	ORGANIC	OVAL	PENDANT	POINTED	SCALE
1	0.00	0.33	1.75	1.42	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.17	0.08	0.00	0.00	0.00
4	0.00	0.00	0.00	0.33	0.00
5	0.00	0.08	0.00	0.00	0.00
6	0.00	0.00	27.08	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.25	0.00	0.00	0.17	0.00
9	0.08	0.17	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.25	6.92	0.00	0.00
12	0.67	0.42	0.08	0.17	0.00
13	0.00	0.00	0.17	0.00	0.25
14	31.92	13.08	19.50	2.42	0.00
15	0.17	0.58	0.00	7.50	0.00
16	1.33	0.50	0.00	0.00	0.83
17	0.42	0.17	15.00	37.50	55.42
18	25.25	20.83	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	9.33	4.42	0.00	3.25	0.00
21	0.00	0.00	11.42	5.83	9.67
22	0.00	0.08	7.08	0.25	0.00
23	1.08	0.25	3.17	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.33	0.50	0.00	0.92	0.00
27	0.25	2.67	0.00	3.08	0.00
28	0.00	0.42	0.08	0.58	0.00
29	0.17	3.42	0.17	4.33	0.00
30	0.00	0.00	0.00	0.00	0.00
31	0.00	0.00	0.00	0.00	0.00
32	0.00	0.00	0.00	0.08	12.75
33	0.00	0.00	0.00	0.42	0.00
34	0.00	0.00	0.00	0.00	8.00
35	0.08	0.08	0.00	11.00	3.00
36	0.00	0.00	0.00	0.00	0.00
37	0.00	0.00	3.50	0.25	5.17
38	0.00	0.00	0.00	0.00	0.00
39	7.42	0.17	2.92	0.58	1.00
40	0.00	0.00	0.00	0.00	0.00
41	0.00	0.00	0.00	0.00	0.00
42	0.00	0.00	0.00	0.00	0.00
43	0.00	0.08	0.00	0.42	0.00
44	0.00	0.00	0.00	0.00	0.00
45	16.67	27.17	0.17	16.42	0.00
46	3.50	22.58	0.00	1.42	0.92
47	0.00	0.25	0.00	0.08	0.00

SPECIES NUMBER	SHIELD	SOUTH ANGLE	VERETENO	WATTS	WEDDELL
1	0.00	0.00	0.00	0.17	0.00
2	0.08	0.00	0.00	1.83	0.00
3	0.00	2.25	0.58	0.58	0.00
4	0.67	0.25	0.00	11.00	0.00
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.08	0.00	0.00	0.00
8	0.08	1.25	0.00	0.67	2.17
9	0.08	0.58	0.00	0.42	1.83
10	0.08	0.00	0.00	0.75	0.00
11	0.08	0.17	0.17	0.00	0.00
12	1.33	2.25	0.50	0.58	1.92
13	0.42	0.00	0.00	0.08	0.00
14	16.17	41.58	0.25	3.58	46.00
15	0.08	0.00	0.08	0.50	0.00
16	0.75	0.67	0.00	0.08	0.08
17	2.00	1.00	0.00	0.00	33.17
18	1.92	0.00	0.00	0.00	0.08
19	0.00	0.00	0.00	0.00	0.00
20	16.50	10.50	0.00	0.00	1.17
21	0.00	0.00	0.42	0.00	0.25
22	0.00	0.17	0.00	0.17	0.08
23	0.42	11.92	0.00	0.25	0.08
24	0.00	0.33	0.00	0.42	0.00
25	0.00	0.00	0.00	0.00	0.42
26	0.75	0.00	0.00	1.08	0.00
27	0.25	0.00	0.33	0.75	0.00
28	0.33	0.00	0.25	0.33	0.08
29	0.92	1.25	0.00	0.58	0.00
30	0.00	0.00	0.00	3.00	0.00
31	0.00	0.00	0.00	0.00	0.00
32	0.25	0.08	0.00	0.00	0.00
33	0.17	0.00	0.00	0.00	0.00
34	0.00	0.00	1.58	0.00	0.00
35	0.08	0.33	82.75	19.17	0.00
36	0.00	0.00	0.00	0.08	0.00
37	0.08	0.00	0.00	0.00	3.33
38	0.00	0.00	0.00	0.00	0.00
39	1.58	0.83	0.00	0.00	2.83
40	0.00	0.08	0.00	0.00	0.00
41	0.00	0.00	0.00	0.00	2.08
42	0.08	1.25	0.00	0.25	0.08
43	0.00	0.25	0.00	0.25	0.00
44	0.00	0.00	0.00	0.00	0.08
45	31.67	20.25	2.00	17.00	0.00
46	11.00	0.83	9.75	32.42	0.50
47	0.08	0.00	0.00	0.17	0.00

SPECIES NUMBER	WILLIAMS
1	0.00
2	0.00
3	0.08
4	2.33
5	0.00
6	1.50
7	0.00
8	4.25
9	2.25
10	0.00
11	0.83
12	3.08
13	0.33
14	16.58
15	0.00
16	0.83
17	8.33
18	0.00
19	0.00
20	18.25
21	0.17
22	2.08
23	0.00
24	0.00
25	0.00
26	1.83
27	0.17
28	0.50
29	0.42
30	0.08
31	0.00
32	0.00
33	0.00
34	0.00
35	0.25
36	0.00
37	0.00
38	0.00
39	3.83
40	0.00
41	1.58
42	2.00
43	0.00
44	0.00
45	23.33
46	1.00
47	0.08

Appendix 3: Species List with Authorities.

Pennales

Achnanthes abundans Manguin
Achnanthes brevipes Agardh
Amphora veneta Kützing
Amphora species a
Amphora species b
Amphora species c
Amphora species d
Amphora species e
Berkeleya adeliensis Medlin
Cocconeis costata Gregory
Cocconeis fasciolata (Ehrenberg) Brown
Cocconeis pinnata Gregory
Cocconeis species a
Diploneis splendida (Gregory) Cleve
Diploneis species b
Entomoneis kjellmanii Cleve
Fragilaria construens (Ehrenberg) Grunow var. *venter* (Ehrenberg) Grunow
Fragilaria species a
Fragilariopsis angulata Hasle
Fragilariopsis curta (Van Heurck) Hustedt
Fragilariopsis cylindrus (Grunow) Krieger
Gomphonemopsis species a
Gyrosigma subsalsum (Wislouch & Kolbe) Cardinal, Poulin & Bérard-Therriault
Hantzschia virgata (Roper) Grunow
Navicula directa (W. Smith) Ralfs
Navicula glaciei Van Heurck
Navicula mutica Kützing/*muticopsis* Van Heurck
Navicula perminuta Grunow
Navicula seminulum Grunow
Navicula tripunctata (Müller) Bory
Navicula species a
Navicula species b
Navicula species c
Navicula species d
Navicula species e
Navicula species f
Navicula species g
Navicula species h
Navicula species i
Neodelphineis ? species a
Nitzschia lecointei Van Heurck
Nitzschia perminuta Grunow
Nitzschia species b

Pinnularia cymatopleura West and West
Pinnularia lundii Hustedt
Pinnularia microstauron (Ehrenberg) Cleve
Pinnularia microstauron var. *microstauron* (Ehrenberg) Cleve
Pinnularia quadratarea var. *constricta* (Østrup) Heiden
Pinnularia quadratarea (Schmidt) Cleve var. a
Pinnularia viridis (Nitzsch) Ehrenberg
Pinnularia viridis (Nitzsch) Ehrenberg var. "constricta"
Pleurosigma species a
Stauroforma inermis Flower, Jones and Round
Stauroneis anceps Ehrenberg
Stauroneis cf. *salina* W. Smith
Stauroneis species a
Synedra species b
Trachyneis aspera (Ehrenberg) Cleve
Tryblionella marginulata (Grunow) Mann
Unidentified Genus and species a

Centrales

Actinocyclus actinochilus (Ehrenberg) Simonsen
Asteromphalus hyalinus Karsten
Chaetoceros vegetative cells
Chaetoceros resting spores
Eucampia antarctica (Castracane) Mangin
Porosira glacialis (Grunow) Jørgensen
Thalassiosira antarctica Comber
Thalassiosira gracilis (Karsten) Hustedt
Thalassiosira species a

Other Algal Taxa

Chrysophyte cyst
Dictyocha speculum Ehrenberg

Appendix 4: Taxonomy & Plates.

In total, 71 algal taxa were identified from the surface sediments of the 33 lakes analysed herein. Of these taxa, 69 diatom species, from 27 genera (plus an unidentified genus), were identified (47 of which were included in numerical analyses based on a threshold of ≥2% in any single sample). The terms abundant, common, frequent and rare used herein refer to >50%, >10%, >2% and <2% relative abundance respectively.

BACILLARIOPHYTA

Pennales
(valves bilaterally symmetrical)

Achnanthes

Achnanthes is a heterovalvar (one raphid and one rapheless valve per frustule) predominantly marine genus with a few freshwater species (Round *et al.*, 1990).

Achnanthes abundans Manguin
Plate 1 Figure 1
Lange-Bertalot & Krammer (1989, p. 20-21, 278-279, 288-295)
Oppenheim (1994, p. 1736-1737)

Taxonomy

Shape: Frustules are heterovalvar. Both valves are elliptic-linear with "squared" apices. Average length is 13 µm (9-17 µm Oppenheim, 1994), average width is 4 µm (4-6 µm Oppenheim, 1994).

Raphe: The raphe is simple and central. The rapheless valve has a linear psuedoraphe with a slightly wider central region.

Striae: Striae (lines of pores) are punctate and parallel, sometimes maybe slightly radiate in the central region. There are approximately 30 striae in 10 µm (on both valves) (32-36 in 10 µm Oppenheim, 1994). The striae in the central region are characteristically shortened.

Areolae: Areolae (pores through the valve wall) are rounded to square, approximately 5 per striae.

Ecology: Characteristic of freshwater with a salinity optimum of 0.6 ‰ and a tolerance range of 0.2–2.1 ‰ herein.

Distribution: Found in 5 of the 33 lakes sampled with a maximum relative abundance of 64 % in Lichen Lake (freshwater).

Comments: This species is also found as a common member of the maritime Antarctic freshwater lake flora (Oppenheim, 1994) and the Larsemann Hills freshwater lake flora (V. Jones, *pers. comm.*, 1997).

Achnanthes brevipes Agardh

Plate 1 Figure 2

Lange-Bertalot & Krammer (1989, p. 34, 184-191)

Andreoli *et al.* (1995, p. 467)

Synonym : *Achnanthes brevipes* var. *intermedia* (Kütz) Cleve

Taxonomy

Shape: Frustules are heterovalvar. Valves are linear, linear - lanceolate to linear - elliptical, that are slightly constricted at the centre with smoothly rounded apices. Average valve length is 30 µm (15 - 125 µm, John 1983) and average valve width is 6 µm (5 - 15 µm, John 1983). The raphed valve has a linear axial area and a central area extending as a rectangular stauros to the margins. Valve shape, valve apices and size are subject to wide variation within this species.

Raphe: The raphe is straight with expanded, pore-like central fissures (external central endings of the raphe) separated by a wide central area. The terminal raphe fissures (apical raphe endings) are slightly deflected.

Striae: There are approximately 7 striae in 10 µm (on both valves) (9 - 11, John 1983). They are rectangular, mostly parallel, becoming weakly radiate towards the apices.

Areolae: Striae are composed of single rows of coarse areolae (11 - 13 in 10 µm (both valves) (John, 1983)) which are arranged parallel to radiate.

Ecology: *A. brevipes* was not abundant enough to be used in numerical analyses but is known to have a narrow salt tolerance (Jones, 1996).

Distribution: Found in 17 of the 33 lakes sampled at a maximum relative abundance of 1.5 %, this species has no apparent salinity preference.

Comments: *A. brevipes* has been found in the Ross Sea, Antarctica (Andreoli *et al.*, 1995). *A. brevipes* var. *intermedia* has been found in Lake Miers (a permanently ice covered thermally stratified freshwater lake in South Victoria Land, Antarctica (Baker, 1967), saline lakes of the Syowa Oasis (Watanuki, 1979) and the variation in the Antarctic forms of *A. brevipes* var. *intermedia* has been described in Ko-Bayashi (1963b).

Amphora

This genus has valves arranged so that both raphe systems lie on the same side (ventral) of the cell. Epiphytic (living on plants), epilithic (living on rocks) or epipelic (living freely on sediment), it is largely a marine genus with relatively few representatives in freshwater (Round *et al.*, 1990).

Amphora veneta Kützing

Plate 1 Figure 3

Krammer & Lange-Bertalot (1986a, p. 348, 744-745)

Taxonomy

Shape: Valves are semi-elliptic with smoothly arched dorsal margins and straight or slightly concave ventral margins. Average valve length is 30 µm (10 - 40 µm John, 1983). Valve width is extremely variable from 2.5-10 µm. The apices also vary a great deal from rounded to slightly produced subcapitate (several intermediate forms were also observed).

Raphe: The raphe is slightly sinuous. Central fissures are inclined dorsally, and widely separated. Terminal fissures are deflected towards the dorsal side after the last stria.

Striae: Dorsal striae are radiate and punctate, with approximately 14 - 20 in 10 µm. Central striae are more widely spaced than the others. Ventral striae are small with striae denser towards the apices, 24 in 10 µm (John, 1983).

Areolae: Dorsal striae are areolate while the ventral striae are composed of a single row of puncta.

Ecology: This species is presented by Krammer and Lange-Bertalot (1986) as a cosmopolitan littoral species with preferences for water with a higher electrolyte content. Cleve-Euler (1951-1955) found it in eutrophic and brackish water and Kuylenstierna (1989, 1990) calls it a fresh water form (Wasell & Håkansson, 1992). It is characteristic of hyposaline water with a salinity optimum of 6.7 ‰ and a tolerance range of 1.5–29 ‰ herein.

Distribution: Found in 21 of the 33 lakes sampled, this species is most common in the hyposaline lakes of the Vestfold Hills, reaching a maximum abundance of 32 % in hyposaline Lake Hand.

Comments: This species has a broad variability from a very low to a very high dorsal side cf. Wasell and Håkansson (1992) and is also commonly found in the Larsemann Hills freshwater flora (V. Jones, *pers. comm.*, 1997) and the Bunger Hills freshwater lake flora (Z. Pushina, *pers. comm.*, 1997).

Amphora sp. a
Plate 1 Figure 4

Taxonomy

Shape: Valves have a smoothly arched dorsal margin, with a slightly to moderately concave ventral margin . Apices are rounded. The axial area is narrow, linear and dorsally arched in each valve half. Average valve length is 35 µm and average width is 12 µm.

Raphe: The raphe is filiform with dorsally reflected raphe ends.

Striae: There are approximately 12 - 14 striae in 10 µm.

Areolae: The striae are composed of elongate "slit-like" areolae.

Ecology: Most characteristic of hypersaline water with a salinity optimum of 36.8 ‰ and a large tolerance range of 6.1–221 ‰ herein.

Distribution: Found in 12 of the 33 lakes sampled with a maximum relative abundance of 2.25 %, this species was found most characteristically in those lakes with occasional marine influence and a few others in rare amounts.

Amphora sp. b
Plate 1 Figure 5

Taxonomy

Shape: Valves are semi-elliptic with smoothly arched dorsal margins and straight or slightly concave ventral margins. Average valve length is 12 µm, average valve width is 1-2 µm.

Raphe: Central fissures are inclined dorsally, and narrowly separated.

Striae: This species is similar in appearance to *A. veneta* with dash-like striae.

Areolae: Areolae are large, elongate openings in the valve.

Ecology: Characteristic of hypersaline water with a salinity optimum of 39.6 ‰ and a tolerance range of 17.4–90 ‰.

Distribution: Found in 6 of the 33 lakes sampled with a maximum relative abundance of 5 % in hypersaline Ekho Lake, this species is frequently found in hypersaline assemblages.

Amphora sp. c
Plate 1 Figure 6

Taxonomy

Shape: The valves are semi-elliptic with smoothly arched dorsal margins and straight or slightly concave ventral margins. Average valve length is 12 µm, average width is 2.5 µm.

Raphe: In this species the raphe-sternum is extended over the valve externally as a short conopeum (a skin-like covering over the raphe) (Round *et al.*, 1990)).

Striae: Striae are characteristically bare with 2 puncta on the far side from the raphe, distinguishing this species from the other *Amphora* species described.

Areolae: Central puncta are slightly more widely spaced apart than other puncta.

Ecology: A specifically hyposaline species with a salinity optimum of 15.5 ‰ and a tolerance range of 6.8–35 ‰ herein.

Distribution: This small *Amphora* species was found in 3 of the 33 lakes sampled (Burton Lake, Pendant Lake and Williams Lake) and was particularly common (27 %) in Pendant Lake.

Amphora sp. d
Plate 1 Figure 7

Taxonomy

Shape: The valves are semi-elliptic with smoothly arched dorsal margins and straight ventral margins. Apicies are bulbous. Average valve length is 30 µm and average width is 8 µm.

Raphe: The raphe is straight.

Striae: This species is similar in appearance to *A. veneta* with dash-like striae (approximately 22 in 10 µm) but dissimilar in that the striae are more defined than those of *A. veneta.*

Areolae: The areolae are elongate and "slit-like".

Ecology: Characteristic of hypersaline water with a salinity optimum of 54.5 ‰ and a tolerance range of 27.5–108 ‰ herein.

Distribution: Found to be rare in Ekho Lake and South Angle Lake only.

Amphora sp. e
Plate 1 Figure 8

Taxonomy

Shape: Valves are semi-elliptic with smoothly arched dorsal margins and straight or slightly concave ventral margins. Average valve length is 25 µm, average valve width is 5 µm.

Raphe: Central fissures are slightly dorsally inclined and terminal fissures are hooked dorsally.

Striae: Striae are thick and obviously areolate with approximately 16 in 10 µm.

Areolae: There are two rows of tiny round areolae in each striae.

Ecology: *Amphora* sp. e was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found to be rare in Burton Lake, Lake Franzmann and Vereteno Lake.

Berkeleya

Brackish to marine, abundant worldwide: epilithic and epiphytic (Round *et al.*, 1990). Several species from Antarctic waters are discussed in Medlin (1990).

Berkeleya adeliensis Medlin
Plate 1 Figures 9 and 10
Medlin (1990)

Taxonomy

Shape: Valves linear to linear-lanceolate with bluntly rounded or slightly capitate poles. Average valve length is 55 µm, average valve width is 10 µm.

Raphe: The raphe slits are short and separated by a narrow axial sternum. External raphe endings are straight.

Striae: Striae are composed of single rows of poroids.

Areolae: Simple poroids approximately 80 nm in diameter (Plate 1 Figure 10).

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found only in Burton Lake, a marine lagoon, as a rare species.

Comments: This marine species is commonly found on the underside of fast ice in the Antarctic (Medlin, 1990).

Cocconeis

The genus *Cocconeis* is a heavily silicified genus with a wide size range and is characteristic of both freshwater and marine environments (Vinyard, 1979; Round *et al.*, 1990).

Cocconeis costata Gregory
Plate 2 Figure 1
Romero & Rivera (1996, p. 321-335)

Taxonomy

Shape: Frustules are heterovalvar. Valves shape is characteristically elliptical - almost circular. Average valve length is 40 µm and average width is 30 µm, although a large size variation exists within this species (cf. Wasell & Håkansson, 1992).

Raphe: The raphe-sternum and pseudoraphe are usually similar in shape although the latter is often wider; both are central, and straight or slightly sigmoid. Terminal fissures are absent. External central fissures are simple or slightly expanded.

Striae: Striae are coarse, containing small round areolae. There are approximately 4 in 10 µm.

Areolae: There are two rows of areolae in each striae. They become "bundled together" at the outer extremity of each striae.

Ecology: Usually characteristic of marine Antarctic water this species has a hypersaline lakewater salinity optimum of 52.2 ‰ and a large tolerance range of 16.4–166 ‰ herein.
Distribution: This species occurred both as fragmented and abraded specimens and whole specimens throughout 15 of the 33 lakes sampled, with a maximum abundance of 4.25 %.

Cocconeis fasciolata (Ehrenberg) Brown
Plate 2 Figure 2
Harwood (1986, p. 315)

Taxonomy

Shape: Frustules are heterovalvar. The raphed valve has a characteristic central thickening.

Raphe: The central raphe fissures are deflected in opposite directions and the terminal fissures are slightly deflected. The raphed valve is divided into 2 sections, the inner striate section with striae containing small round poroids

and the outer section composed of a "clustering" of areolae. These zones are separated by a thickened area. Average valve length is 55 µm and average valve width is 45 µm.

Striae: The striae are complex, changing in structure across the valve.

Areolae: Areolae occur in two rows on the inner section of the valve and in clusters on the outer section.

Ecology: Similarly to *C. costata*, *C. fasciolata* is typically a marine Antarctic diatom but herein has a hyposaline lakewater salinity optimum of 23.6 ‰ with a large tolerance range of 6.2–89 ‰.

Distribution: *C. fasciolata* occurs throughout 12 of the 33 lakes sampled with one marked occurrence of 4.75 % in McNeill Lake.

Comments: The araphid valve of this species is difficult to distinguish from *C. costata* in light microscope specimens.

Cocconeis pinnata Gregory

Plate 2 Figure 3

Van Heurck (1962, p. 288-289)

Romero & Rivera (1996, p. 335-338)

Taxonomy

Shape: Frustules are heterovalvar. This smaller *Cocconeis* species has an average valve length of 20 µm and average width of 12 µm.

Raphe: The pseudoraphe is much more thickened in this species.

Striae: Striae are coarse, occurring in bands of 6 in 10 µm.

Areolae: There are two rows of areolae per striae.

Ecology: This freshwater species has a salinity optimum of 1.5 ‰ and a small tolerance range of 0.5-4.7 ‰ herein.

Distribution: Found in Grace Lake, Shield Lake and Watts Lake only with a maximum relative abundance of 2 %.

Cocconeis sp. a

Plate 2 Figures 4 and 5

Taxonomy

Shape: Frustules are heterovalvar. Valves are elliptic to narrow - elliptic with broadly rounded apices. Average valve length is 8 µm and average width is 3 µm.

Raphe: The raphed valve has a straight raphe which is slightly expanded at the centre; terminal fissures are "comma-like". The raphless valve has a pseudoraphe of similar dimensions to the raphe.

Striae: Striae are coarse with approximately 12 - 15 in 10 µm.

Areolae: There are 3 rows of areolae per striae.

Ecology: Characteristic of hypersaline water with a salinity optimum of 39.2 ‰ and a tolerance range of 11.5–134 ‰ herein.

Distribution: Found in 9 of the 33 lakes sampled with a maximum relative abundance of 3.25 % in Franzmann Lake (hypersaline) this species is frequent in lakes with occasional marine influence in the Vestfold Hills.

Diploneis

Diploneis (also a heavily silicified genus) is predominantly a marine genus with few fresh water species (Round *et al.*, 1990). However, none of the *Diploneis* species herein were abundant enough for numerical analyses and therefore little is known of their lakewater salinity affinities.

Diploneis splendida (Gregory) Cleve

Plate 2 Figure 6

Harwood (1986, p. 315)

Taxonomy

Shape: Valves are panduriform (constricted in centre) with bluntly rounded poles. Average valve length is 80 µm. Average valve width is 18 µm across the centre and 25 µm across the broadest part of valve.

Raphe: The raphe-sternum is central with terminal fissures deflected slightly. On each side of the raphe there is a continuous longitudinal canal within the valve structure.

Striae: Striae are complex, changing in structure across the valve and containing loculate areolae. There are approximately 5 striae in 10 µm. A light microscope photo taken at 1000 x magnification shows the patterning of the striae on the outer valve wall (Plate 2 Figure 6).

Areolae: Areolae are round, or transversely elongate, forming longitudinal patterns.

Distribution: This species was found as a rare component of several lakes (6 of the 33 sampled), with no apparent salinity preference although many of the lakes it occurs in are influenced at times by sea water incursions.

Diploneis sp. b
Plate 2 Figure 7

Taxonomy

Shape: Valves are elliptic. Average valve length is 40 μm, average valve width is 15 μm.

Raphe: The raphe is straight with central fissures simple and terminal fissures hooked (although this is difficult to see clearly in light microscope specimens).

Striae: Striae are composed of double rows of areolae, approximately 10 in 10 μm.

Areolae: Each row per striae is composed of simple poroids, approximately 12 per row.

Distribution: This species occurred in Anderson and Burton Lake, both as a single occurrence.

Entomoneis

Entomoneis is a fairly large epipelic genus of brackish marine sediments and is occasionally found in freshwaters (Round *et al.*, 1990).

Entomoneis kjellmanii Cleve
Plate 2 Figure 8
Andreoli *et al.* (1995, p. 467)
Synonym: *Amphiprora kjellmanii* Cleve

Taxonomy

Shape: The valve is twisted about the apical axis and usually lies in girdle view (cf. Round *et al.*, 1990).

Raphe: Raphe fissures, both central and terminal, straight and not or only slightly expanded.

Striae: It is difficult at this resolution to distinguish between biseriate or multiseriate striae (Plate 2 Figure 8).

Areolae: As above, areolae are difficult to distinguish at these magnifications (Plate 2 Figure 8).

Ecology: *E. kjellmanii* was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: This species was found as a rare component of several lakes (6 of the 33 sampled), with no apparent salinity preference.

Comments: *E. kjellmanii* is characteristic of Antarctic fast ice samples (Scott *et al.*, 1994).

Fragilaria

The genus *Fragilaria* is predominantly freshwater but Hustedt (1930) point out the occurrence also in slightly brackish waters and according to Simonsen (1962) the species is oligohalobous (indifferent), and mesoeuryhaline (Gerloff & Cholnoky, 1970).

Fragilaria construens (Ehrenberg) Grunow var. ***venter*** (Ehrenberg) Grunow
Plate 3 Figure 1
Van Heurck (1962, p. 325)
Synonym: *Staurosira construens* (Ehrenberg) Grunow
Taxonomy

Shape: Valves are elliptic - circular. The axial area is distinct, linear - lanceolate. Average valve length is 4 μm (5 - 9 Patrick & Reimer, 1966) and average valve width is 3.5 μm (3 - 6 Patrick & Reimer, 1966).
Raphe: The pseudoraphe is distinct, linear to lanceolate in shape.
Striae: Striae on the valve surface are slightly radiate, with approximately 3 in 1 μm.
Areolae: Areolae are circular or elliptical. Marginal spines are conspicuous, occurring singly or in pairs between the areolae, spathulate or dichotomously branched. Apical pore fields are present on the valve apices, consisting of few or many rows of poroids.

Ecology: This species is a common freshwater genus in lakes and rivers (Round *et al.*, 1990); widely distributed, preferring oligo - mesotrophic waters (Patrick & Reimer, 1966). This species has a lakewater salinity optimum of 35.7 ‰ and a tolerance range of 13–97 ‰ herein.
Distribution: Found in 12 of the 33 lakes sampled with a maximum relative abundance of 7 % in hyposaline Pendant Lake.

Fragilaria species a
Plate 3 Figure 2

Taxonomy

Shape: Valves are elliptical to linear with rounded apices. Valve length varies between 3 and 35 μm and width varies between 2 and 6 μm.
Raphe: The pseudoraphe is narrow, sometimes widened to a small lanceolate space at the centre of the valve.

Striae: Striae are radiate at the apices, almost parallel in the middle portion of the valve, crossed by fire lines (approximately 20 in 10 μm). There are approximately 7 - 12 striae in 10 μm.

Areolae: Areolae are circular - elongate openings. Apical pore fields are present as small groups of pores on the valve apices.

Ecology: Characteristic of hypersaline water with a salinity optimum of 51 ‰ and a tolerance range of 17.8–147 ‰ herein.

Distribution: This species was found in 25 of the 33 lakes sampled with a maximum relative abundance of 7.5 % in Burton Lake, a marine lagoon. It was found to be generally frequent in marine - hypersaline lakes of the Vestfold Hills and rare in hyposaline lakes.

Fragilariopsis

This marine planktonic or benthic genus is particularly abundant in Antarctic waters (Round *et al.*, 1990).

Fragilariopsis angulata Hasle

Plate 3 Figure 3

Medlin & Priddle (1990, p. 181-189)

Synonym: *Nitzschia angulata* Hasle

Taxonomy

Shape: Valves are broadly lanceolate; apical axis is isopolar. Average valve length is 25 μm (8 - 53 μm Medlin & Priddle, 1990) and average valve width is 10 μm (7 - 13 μm Medlin & Priddle, 1990). Central nodule is absent.

Raphe: The raphe is diagonally positioned on opposing valves of the cell.

Striae: Striae have 2 rows of areolae.

Areolae: Areolae are distinctly round.

Ecology: *F. angulata* was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found in 4 of the 33 lakes sampled as a rare occurrence.

Comments: *F. angulata* is a common plankton and ice species with bipolar distribution.

Fragilariopsis curta (Van Heurck) Hustedt

Plate 3 Figure 4

Medlin & Priddle (1990, p. 181-182, 192-193)

Synonym: *Nitzschia curta* (Van Heurck) Hasle

Taxonomy

Shape: Valves are heteropolar (one pole broader than the other) with an average length of 20 μm (10 - 40 μm Medlin & Priddle, 1990) and an average valve width of 5 μm (3.5 - 6 μm Medlin & Priddle, 1990). A central nodule is absent.

Raphe: Raphe is eccentric.

Striae: There are 9 - 12 striae in 10 μm, composed of 2 rows of areolae. There are approximately 9 - 12 fibulae in 10 μm

Areolae: The areolae are distinctly round.

Ecology: This marine species is common in Antarctic plankton and ice communities and particularly characteristic of Antarctic pack ice samples (Scott *et al.*, 1994). It has a lakewater salinity optimum of 34.2 ‰ with a large tolerance to salinity range of 9.7–121 ‰ herein (as would be expected with an ice associated species).

Distribution: Found in 16 of the 33 lakes sampled at a maximum abundance of 3 %.

Fragilariopsis cylindrus (Grunow) Krieger

Plate 3 Figure 5

Medlin & Priddle (1990, p. 181-182, 192-193, 196)

Synonyms: *Fragilaria cylindrus* Grunow; *Nitzschia cylindrus* (Grunow) Hasle

Taxonomy

Shape: Valves are linear and isopolar with rounded apices. Average valve length is 20 μm (3 - 48 μm Medlin & Priddle, 1990) and average valve width is 3 μm (2 - 4 μm Medlin & Priddle, 1990). The central nodule is absent.

Raphe: The raphe is eccentric.

Striae: There are 13 - 17 striae and 13 - 17 fibulae in 10 μm.

Areolae: Areolae occur in 2 - 4.

Ecology: Again, this species is characteristic of Antarctic ice assemblages and has a lakewater salinity optimum of 33.2 ‰ and a similarly high tolerance range to salinity as *F. curta* of 10.2–108 ‰ herein.

Distribution: Found in 18 of the 33 lakes sampled at a maximum abundance of 32 % in Ace Lake, characterised by marine epilimnion salinities.

Gomphonemopsis

This small marine genus is widespread in temperate to tropical seas (Round *et al.*, 1990).

Gomphonemopsis sp. a
Plate 3 Figure 6

Taxonomy

Shape: Valves are distinctly heteropolar, the length from the central nodule to the apex less than the length from the central apex to the base, the upper half usually broader than the lower. Average valve length is 10 µm and average width is 2.5 mm (across middle).

Raphe: The raphe is simple and straight, central endings are expanded and pore-like, terminal fissures the same.

Striae: Striae are composed of single areolae.

Areolae: There is a single row of puncta either side of the central axis, distinct in light microscope.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found as rare specimens in 9 of the 33 lakes sampled.

Gyrosigma

Principally epipelic, this genus can be found living in brackish habitats but also may extend into marine and freshwaters (Round *et al.*, 1990).

Gyrosigma subsalsum (Wislouch & Kolbe) Cardinal, Poulin & Bérard-Therriault
Plate 3 Figures 7 and 8
Wasell & Håkansson (1992, p. 177, 169)
Synonym: *Pleurosigma subsalsum* Wislouch & Kolbe

Taxonomy

Shape: Valves slightly sigmoid, linear to lanceolate. Average valve length is 0.15 mm and average valve width is 12 µm.

Raphe: The raphe system is very eccentric and sigmoid.

Striae: The fine and dense striae are composed of single rows of areolae, approximately 25 in 10 µm. No oblique striae are observed.

Areolae: Simple poroids approximately 30 per striae.

Ecology: This species was also not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found in 2 of the 33 lakes sampled at a maximum abundance of <2 %.

Comments: "*Pleurosigma*" *subsalsum* is classified by Cleve-Euler (1952) as halophilic and euryhaline while Kolbe (1948) classified it as halophilic to mesohalobous, but Tynni (1978) also found it in eutrophic freshwater (Wasell & Håkansson, 1992).

Hantzschia

This genus is widely distributed in the marine and freshwater epipelon, especially in the intertidal sand, but extending into subaerial habitats (Round *et al.*, 1990).

Hantzschia virgata (Roper) Grunow
Plate 3 Figure 9
Krammer & Lange-Bertalot (1986b, p. 130-131, 396-397)

Taxonomy

Shape: Frustules are linear lanceolate and weakly curved. Valves are asymmetrical with respect to the apical axis with a slightly convex dorsal margin and a concave ventral margin with sub capitate apices. Average valve length is 65 µm (50 - 100 µm Krammer & Lange-Bertalot, 1986 a), average width is 10 µm (5 - 18 µm Krammer & Lange-Bertalot, 1986 a).

Raphe: The raphe is positioned along the same margin of opposing valves of a frustule. It is associated with the ventral margin and is subtended by fibulae. The keel puncta (conspicuous pores lying below the canal raphe) are short, more distantly arranged at the middle of the valve, becoming longer and more closely arranged towards the apices (approximately 3 - 7 in 10 µm). Marginal costae (ribs or thickenings) are short and long, intermingling with each other.

Striae: The valve surface is striate, two to three striae alternating with each costa, 10 - 14 in 10 µm.

Areolae: The striae are distinctly punctate with puncta arranged in parallel.

Ecology: Hustedt (1930) mention this species to be a saline lake form, whilst Simonsen (1962) classifies it as polyhalobous and mesoeuryhaline (Wasell & Håkansson, 1992). Herein it is characteristic of hypersaline water with a salinity optimum of 38.7 ‰ and a tolerance range of 11.5–131 ‰.

Distribution: Found in 11 of the 33 lakes sampled at a maximum abundance of 4.25 %.

Navicula

The genus *Navicula* shows a high degree of morphological variation in the valve, axial and central features. Striation is also variable: areolate, alveolate or lineate, uniserate or biserate, in longitudinal or decussating rows, radiate, parallel or convergent. Species characteristic of freshwater - hypersaline habitats are found herein.

Navicula directa (W. Smith) Ralfs

Plate 4 Figure 1

Poulin & Cardinal (1982b, p. 2836-2837, 2828)

Synonym: *Pinnularia directa* W. Smith

Taxonomy

Shape: Valves are linear lanceolate with subacute apices. The axial area is linear and narrow. Average valve length is 45 µm although variable (47 - 74 John, 1983), average width is 9 µm and also variable (7 - 9 µm John, 1983).

Raphe: The central fissures are closely arranged and slightly expanded; terminal fissures are hooked, curving in the same direction.

Striae: Striae are coarse and prominent with clearly lineate and parallel arrangement throughout. There are approximately 8 striae in 10 µm (8 - 9 in 10 µm John, 1983).

Areolae: Areolae are elongate, approximately 10 per striae.

Ecology: This cosmopolitan species is more common in colder waters (Fenner *et al.*, 1976) and is characteristic of markedly hypersaline water with the third highest salinity optimum of the species in the numerical analyses herein of 77.5 ‰ and a large tolerance range of 28.4–211 ‰.

Distribution: This species is a common marine, periphytic, bottom sea-ice species found in the Arctic, at temperate latitudes and the Antarctic. Found in 28 of the 33 lakes sampled herein, *N. directa* was found to be common in freshwater, hyposaline and marine lakes in the Vestfold Hills but was particularly abundant in the hypersaline lakes (reaching a maximum abundance of 60 % in Burch Lake).

Comments: A wide range of variation exists within this cosmopolitan marine species, with minor morphological differences difficult to determine in light microscope, making accurate identification difficult. As a result, all species observed to have the general properties of *N. directa* in light microscopy (particularly the characteristic parallel arrangement of striae) are classified as *N. directa* .

Navicula glaciei Van Heurck

Plate 4 Figure 2

Whitaker & Richardson (1980)

Poulin & Cardinal (1982b, p. 2837, 2830)

Taxonomy

Shape: Valves are lanceolate - linear lanceolate with rounded cuneate apices. Average valve length is 22 µm (29-42 µm Poulin & Cardinal, 1982b), average width is 6 µm (7-13 µm Poulin & Cardinal, 1982b).

Raphe: The raphe is straight; central endings are slightly expanded and pore-like; terminal fissures are hooked towards the same direction.

Striae: Striae are distinct, comprising single rows of puncta, 15 in 10 μm (14-15 in 10 μm Poulin & Cardinal, 1982b).

Areolae: Areolae are distinct with a single pore in the central region. The areolae are also shortened in the central region (giving the impression of a stauros at low magnitude (Poulin & Cardinal, 1982b)).

Ecology: This species is typically found in Antarctic ice assemblages. It has a hypersaline lakewater salinity optimum of 44.8 ‰ and a large tolerance range (again expected due to its ice association) of 13.8–146 ‰.

Distribution: Found in 13 of the 33 lakes sampled with a maximum abundance of 17 % this sea-ice associated species was frequent in Pointed (hyposaline), Burton Lake (a marine incurred hypersaline lake) and Oblong Lake (hypersaline) and particularly common in Lake Fletcher and Franzmann Lake (both hypersaline lakes with marine incursions occasionally).

Comments: The characteristic feature of this species is the distinct shorter striae in the central region.

Navicula mutica Kützing/***Navicula muticopsis*** Van Heurck

Plate 4 Figures 4, 5 and 6

Krammer & Lange-Bertalot (1986a, p. 149, 546-547, 562-563)

Synonyms: *Luticola mutica* (Kützing) Mann; *N. cohnii* Hilse

Taxonomy

Shape: Valves are linear, lanceolate or elliptical with rounded to capitate apices. The axial area is linear and narrow, with a variable length between 15 and 30 μm (12 - 24 John, 1983).

Raphe: The raphe-sternum is fairly narrow and expanded, which is thickened centrally to form a short stauros, penetrated on one side by a single stigma. Central external raphe endings are deflected, curved or abruptly bent away from the stigma. External pole endings usually curved in the opposite direction from the central endings.

Striae: Striae are punctate and radiate. There are approximately 16 striae in 10 μm (14 - 18/10 μm John, 1983). The striae are uniserate, each containing several more-or-less round poroids on the valve mantle. Central striae short, reduced to few small puncta.

Areolae: The poroids of the valve face are occluded by hymenes, which are confluent within a stria, forming a transapical strip across the valve; the mantle pores have their own hymenes.

Ecology: This species is almost specific to hyposaline lakes. It has a salinity optimum of 10.6 ‰ and a tolerance range of 2.9–39.3 ‰ herein.

Distribution: Found in 25 of the 33 lakes sampled with a maximum abundance of 23 % in Lake Hand.

Comments: Ko-Bayashi (1962, 1963a,b) has shown several names for this common Antarctic diatom in the literature but each form of the *N. mutica/N. muticopsis/ N. cohnii* group are all fresh water. To differentiate among all the species, varieties and forms in the *N. mutica/muticopsis/cohnii* complex (transferred to *Luticola* D. G. Mann by Round *et al.*, 1990) is difficult (Wasell & Håkansson, 1992). The species and infra-specific taxa are differentiated via subtle variation in the form of the raphe, valve outline and the form and placement of the stigma; thus for instance, *N. mutica* should have an elongate stigma and *N. muticopsis* (also *N. cohnii* Hilse (Lange-Bertalot (1986)) a punctate stigma (Wasell & Håkansson, 1992). *N mutica* f. *cohnii* and *N. muticopsis* were found in Lake Miers (a permanently ice covered thermally stratified freshwater lake in South Victoria Land, Antarctica (Baker, 1967) and *N. mutica/muticopsis* valves are also a common feature of the Larsemann Hills freshwater lake flora (V. Jones, *pers. comm.*, 1997) and the saline lake flora of the Syowa Oasis (Watanuki, 1979).

Navicula perminuta Grunow

Plate 4 Figure 3

Krammer & Lange-Bertalot (1986a, p. 112, 510-511)

Synonyms: *Navicula cryptocephala* var. *perminuta* (Grunow) Cleve; *Navicula diserta* Hustedt; *Navicula dulcis* Patrick; *Navicula mendotia* Van Landingham

Taxonomy

Shape: Valves are narrow-lanceolate - narrow elliptic. Average valve length is 15 µm (8 - 45 µm Wasell & Håkansson, 1992), average width is 2.5 µm (2.5 - 3 µm Wasell & Håkansson, 1992).

Raphe: The raphe is central with expanded pore-like central endings; terminal fissures are "question mark" shaped, hooking in the same direction as the central fissures.

Striae: There are approximately 16 striae in 10 µm (26 - 36 in 10 µm Wasell & Håkansson, 1992); there are 10 - 16 fibulae (internal bridges of silica) in 10 µm (Wasell & Håkansson, 1993), the middle fibulae are distant from each other.

Areolae: Areolae are distinct, approximately 4 in each striae.

Ecology: Characteristic of hyposaline water with a salinity optimum of 27.1 ‰ and a tolerance range of 9.8–75 ‰ herein.

Distribution: Found in 15 of the 33 lakes sampled at a maximum abundance of 7 % in Pendant Lake (hyposaline) and rarely in fresh, hypersaline and the remaining hyposaline lakes.

Comments: This species is differentiated from *N. frustulum* and *N. alpina* (which have equidistant fibulae) by slight differences in the number of striae in 10 μm as outlined in Wasell & Håkansson (1992). N. perminuta is also found to be a common member of the Martime Antarctic lake flora (V. Joñes, *pers. comm.*, 1997).

Navicula seminulum Grunow

Plate 4 Figure 7

Krammer & Lange-Bertalot (1986a, p. 230, 592-593)

Synonyms: *Navicula saugerii* Desmazières; *Navicula seminulum* var. *fragilariodes* Grunow; *Navicula atomoides* Grunow

Taxonomy

Shape: Valve narrow elliptic - elliptic - slightly rhombic with broadly rounded apices. External pole endings of the valve are usually curved in the opposite direction from the central endings. Length varies from 15 - 20 μm, width varies from 5 - 8 μm.

Raphe: The raphe is filiform and hooked at the poles in the same direction.

Striae: Striae are uniseriate with approximately 20 - 25 in 10 μm. They are radiate tending to slightly convergent at the poles with the middle striae shortened. The central area is transversely expanded and bordered by short striae.

Areolae: Areolae are distinctly rounded in single rows.

Ecology: This species is characteristic of hyposaline and freshwaters with a salinity optimum of 8.3 ‰ and a tolerance range of 2.7–26 ‰ herein.

Distribution: Found in McNeil Lake only at an abundance of 8.5 %.

Comments: This species was found in Lake Miers (a permanently ice covered thermally stratified freshwater lake in South Victoria Land, Antarctica (Baker, 1967) and is also found in maritime Antarctic lake flora (=*N. seminulum* var. *radiosa* V. Jones, *pers. comm.*, 1997).

Navicula tripunctata (Müller) Bory

Plate 4 Figures 8 and 9

Krammer & Lange-Bertalot (1986a, p. 95, 494-495)

Synonyms: *Vibrio tripunctatus* Müller; *Navicula gracilis* Ehrenberg; *Schizonema neglectum* Thwaites

Taxonomy

Shape: Valves are lanceolate to linear, with blunt, rostrate or capitate apices. The axial area is narrow to linear and distinct. Valve length is variable from 15 - 30 μm, average width is 6 μm.

Raphe: The raphe is straight; terminal fissures are turned to one side in a "question mark" shape.

Striae: Striae are uniserate or rarely biserate. There are approximately 16 - 21 striae in 10 μm. These are lineate and slightly radiate towards the middle of the raphe but parallel towards the apices; central striae are shorter than the others.

Areolae: The striae contain apically elongate, linear poroids, which are closed by hymenes at their inner apertures.

Ecology: Most characteristic of hyposaline water with a salinity optimum of 26.7 ‰ but a large tolerance range of 7.4–97 ‰ herein.

Distribution: This species is commonly found in freshwater and marine epipelic habitats (Round *et al.*, 1990). It was common in hyposaline lakes and abundant in marine and hypersaline lakes of the Vestfold Hills, being found in 29 of the 33 lakes sampled at a maximum abundance of 55 %.

Comments: This species shows considerable variation in valve shape, apical shape and size.

Navicula sp. a

Plate 5 Figure 1

Taxonomy

Shape: Valves are lanceolate to linear, with rounded apices. Average valve length is 30 μm, average width is 6 μm.

Raphe: Raphe is central with slightly expanded central fissures; terminal fissures are "question mark" shaped.

Striae: Striae are uniserate, radiate and coarse, approximately 16 in 10 μm; central striae are shorter than the others.

Areolae: The striae contain apically elongate, linear poroids, which are closed by hymenes at their inner apertures.

Ecology: Specific to markedly hypersaline water with the highest salinity optimum herein of 122.3 ‰ and a tolerance range of 49.5–301.8 ‰.

Distribution: Found in 11 of the 33 lakes sampled with a maximum abundance of 30 % in Johnstone Lake.

Navicula sp. b
Plate 5 Figure 2

Taxonomy

Shape: Valves are linear with rounded slightly subcapitate apices. Average valve length is 10 - 15 µm, average valve width is 2 µm.

Raphe: The raphe is central; both central endings and terminal fissures simple.

Striae: The striae are fine and parallel near apices tending to radial at centre, approximately 80 in 10 µm.

Areolae: Areolae are indistinct at this magnification (Plate 5 Figure 2)

Ecology: Characteristic of markedly hypersaline water with a salinity optimum of 65.2 ‰ and a tolerance range of 25.4–167 ‰ herein.

Distribution: Found in 24 of the 33 lakes sampled with a maximum abundance of 30 % in Admin Lake.

Comment: Greater magnification is required for further investigation of this species.

Navicula sp. c
Plate 5 Figure 3

Taxonomy

Shape: Valves are lanceolate to elliptical-lanceolate with rostrate ends. The axial area is narrow; the central area is not distinct. Average valve length is 20 µm, average width is 7 µm.

Raphe: The raphe is simple; central endings simple with indistinct terminal fissures.

Striae: Striae are parallel, approximately 30 in 10 µm.

Areolae: Areolae are not distinct at this magnification.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found as rare specimens in 7 of the 33 lakes sampled.

Navicula sp. d
Plate 5 Figure 4

Taxonomy

Shape: Valves are lanceolate to elliptical-lanceolate with rostrate ends. Average length is 20 µm, average width is 5 µm.

Raphe: The raphe is central; central endings are slightly expanded; terminal fissures are hooked towards the same direction.

Striae: Striae are parallel, composed of distinct puncta.

Areolae: There are single distinct puncta on the sternum slightly above and between the central raphe endings.

Ecology: Characteristic of hyposaline water with a salinity optimum of 13.7 ‰ and a tolerance range of 8.0–23.4 ‰ herein.

Distribution: Found in 20 of the 33 lakes sampled with a maximum abundance of 21 % in Camp Lake.

Navicula sp. e

Plate 5 Figure 5

Taxonomy

Shape: Valves are elliptic - lanceolate with rounded apices. Average length is 13 µm, average width is 5 µm.

Raphe: The raphe is central with central endings expanded and pore-like. Terminal fissures are "question mark" shaped and hooked markedly towards the same direction.

Striae: Striae are coarse and slightly radiate. There are approximately 15 in 10 µm. The central striae are shortened slightly.

Areolae: Striae are composed of puncta although dissolution is apparent and may obscure this.

Ecology: The second highest salinity optimum species herein with a markedly hypersaline optima of 82.7 ‰ and a tolerance range of 24.7–276 ‰.

Distribution: This species is found in 17 of the 33 lakes sampled with a maximum abundance of 12 % in markedly hypersaline South Angle Lake.

Navicula sp. f

Plate 5 Figure 6

Taxonomy

Shape: Valves are lanceolate with capitate - rostrate ends. Average valve length is 40 µm, average width is 10 µm.

Raphe: The raphe is central with both endings and terminal fissures simple.

Striae: Striae are fine, slightly radiate, approximately 35 in 10 µm.

Areolae: Higher magnification is needed to determine more about these features.

Ecology: Characteristic of hyposaline water with a salinity optimum of 18 ‰ and a tolerance range of 10–32.5 ‰.
Distribution: This species is commonly distorted when observed and was found in Lake Abraxas, Admin Lake and Weddell Lake at a maximum abundance just over 2 %.
Comments: The striae and areolae are hard to distinguish in light microscope.

Navicula sp. g
Plate 5 Figure 7

Taxonomy

Shape: Valves are linear lanceolate. Average valve length is 50-60 µm and average width is 10 µm.
Raphe: The central fissures are closely arranged and slightly expanded; terminal fissures are hooked, curving in the same direction.
Striae: Striae are very coarse and prominent with clearly lineate and parallel arrangement throughout. There are approximately 10 striae in 10 µm.
Areolae : The striae contain apically elongate, linear poroids although this is hard to see is light microscope.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.
Distribution: Found in 10 of the 33 lakes sampled with a maximum relative abundance < 2 %.

Navicula sp. h
Plate 5 Figure 8

Taxonomy

Shape: Valve is diamond shaped (rhombic) with rounded apicies. Average valve length is ~ 50 µm and average width is ~ 20 µm.
Raphe: Raphe appears straight with simple terminal fissures in central and terminal areas in light microscope view.
Striae: Striae are radiate throughout but more closely spaced at the apicies.
Areolae: Not distinguishable in light microscope view.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.
Distribution: Present as a single occurrence in Oblong Lake only.

Navicula sp. i
Plate 5 Figure 9

Taxonomy

Shape: Valves are lanceolate with rostrate to capitate ends. Average valve length is 25 μm and average valve width is 5 μm. The axial area is narrow with a small central area, often only slightly wider than the axial area.

Raphe: The raphe is central with simple central pores. Terminal fissures are slightly deflected in the same direction.

Striae: Striae are parallel. There are approximately 22 striae in 10 μm.

Areolae: Areolae are arranged in single parallel rows.

Ecology: Characteristic of hyposaline and freshwaters with a salinity optimum of 5.7 ‰ and a tolerance range of 1.2–27 ‰ herein.

Distribution: Found in 5 of the 33 lakes sampled with a maximum relative abundance 5.25 % in Highway Lake.

Neodelphineis

This araphid genus is typical of marine plankton (Round *et al.*, 1990).

Neodelphineis (?) sp.
Plate 6 Figure 1

Taxonomy

Shape: Valves are linear, the valve face is flat with a shallow mantle.

Raphe: Sternum is narrow and central.

Striae: Striae are uniserate, sunk between external ribs and alternate.

Areolae: Areolae are circular, a single row occurring on the valve mantle. There are no apical pore fields.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities.

Distribution: Found as a rare specimen in Oval Lake only.

Comments: Round *et al.* (1990) also classify this genus by short spines on the edge of the valve face between the striae and a rimoportula (hole) at each apex, to one side of the sternum. As this can not be determined from the specimen seen this species is tentatively placed in the *Neodelphineis* genus.

Nitzschia

This genus is freshwater to marine and usually epipelic or planktonic (Round *et al.*, 1990).

Nitzschia lecointei Van Heurck
Plate 6 Figures 2 and 3
Medlin & Priddle (1990, p. 177-180)

Taxonomy

Shape: Median part of the valve is rhomboid to lanceolate, smaller cells with short or almost no rosta, longer cells with long rosta. Average valve length is 55 µm (21 - 112 µm Medlin & Priddle, 1990) and average valve width is 2.5 µm (2.5 - 5 µm Medlin & Priddle, 1990).

Raphe: The raphe is eccentric.

Striae: There are 51 - 55 striae and 5 - 14 fibulae in 10 µm.

Ecology: This ice associated species has a hypersaline lakewater salinity optimum of 48.4 ‰ and a large tolerance range of 19.4–120.6 ‰ herein.

Distribution: Found in 18 of the 33 lakes sampled with a maximum abundance of 5.5 % in Lake Fletcher, a lake which receives occasional marine incursion.

Comments: This species has a characteristic central nodule (pseudonodulus) indicated by a greater distance between the two middle fibulae (keel puncta). This species also exhibits stadial variation in valve view.

Nitzschia perminuta Grunow
Plate 6 Figure 4
Krammer & Lange-Bertalot (1986b, p. 99-100, 360-361)

Synonyms: *Nitzschia palea* var. *perminuta* Grunow; *Nitzschia frustulum* var. *tenella* Grunow; *Nitzschia* (*frustulum* var.) *minutula* Grunow; *Nitzschia frustulum* var. *asiatica* Hustedt; *Nitzschia hiemalis* Hustedt

Taxonomy

Shape: Valves are linear with tapering apices. Average valve length is 35 µm, average valve width is 3.5 µm.

Raphe: The raphe is eccentric.

Striae: There are 20 striae and 10 fibulae in 10 µm.

Ecology: Characteristic of hyposaline water with a salinity optimum of 23.9 ‰ and a tolerance range of 5.8–98 ‰ herein.

Distribution: Found in 20 of the 33 lakes sampled with a maximum abundance of 4 % in Pointed Lake.

Nitzschia sp. b
Plate 6 Figure 5

Taxonomy

Shape: Valves are broadly elliptical with the middle part almost straight and a shorter tapering part. Average valve length is 25 µm and average valve width is 5 µm. A central nodule is absent.

Raphe: The raphe is eccentric.

Striae: There are 6 - 11 striae and 6 - 11 fibulae in 10 µm.

Areolae: The areolae occur in rows of 2 or 3.

Ecology: Characteristic of hyposaline water with a salinity optimum of 11.2 ‰ and a tolerance range of 1.3–96 ‰ herein.

Distribution: Found in 5 of the 33 lakes sampled with a maximum abundance of 3 %.

Pinnularia

This genus is a very large epipelic genus occurring in freshwater and (rarely) marine habitats (Round *et al.*, 1990). The species identified here are all hyposaline salinity indicators.

NB : The genus *Pinnularia* has multiseriate striae that are usually also chambered (alveolate). Each alveolae has an outer appearance of small round poroids occluded by hymenes but these are often difficult to differentiate in light microscope and the striae appear structureless (Round *et al.*, 1990).

Pinnularia cymatopleura West and West
Plate 6 Figure 6
Kellogg *et al.* (1980, p. 185, 176-177)

Taxonomy

Shape: Valves are linear - linear elliptic with rounded slightly subcapitate apices. Average valve length is 22 µm, average width is 5 µm.

Raphe: The raphe is central with slightly expanded pore-like endings and hooked terminal fissures (hooking in same direction).

Striae: There are 20-21 striae in 10 µm. These are parallel throughout.

Ecology: Specific to hyposaline water with a salinity optimum of 9.3 ‰ and a tolerance range of 5.0–17.4 ‰ herein.

Distribution: West & West (1911) describe this species from Clear Lake on the west side of McMurdo Sound (Wasell, 1993). It is a common member of the diatom

communities in the hyposaline lakes of the Vestfold Hills, occurring in 15 of the 33 lakes sampled with a maximum abundance of 16 % in Lake Hand.

Comments: This species was found in Lake Miers (a permanently ice covered thermally stratified freshwater lake in South Victoria Land, Antarctica (Baker, 1967) and is apparently endemic to Antarctic inland waters (Kellogg *et al.*, 1980).

Pinnularia lundii Hustedt

Plate 6 Figure 7

Krammer & Lange-Bertalot (1986a, p. 415, 818-819, 856-857)

Synonyms: *Pinnularia globiceps* var. *crassior* Grunow; *Pinnularia interupta* var. *crassior* (Grunow) Cleve; *Pinnularia iatriaensis* Foged

Taxonomy

Shape: Valves are linear - linear elliptic; valve sides are predominantly parallel to concave but can also be lightly-strongly convex, apices are rounded. Average valve length is 42 µm (30 - 60 µm Krammer & Lange-Bertalot, 1986b) and average valve width is 12 µm (9 - 13 µm Krammer & Lange-Bertalot, 1986b). The axial area is small and linear, the central area is wide.

Raphe: The raphe is weakly lateral and almost straight in the middle area. The central raphe pores are expanded; the terminal fissures are "comma" shaped.

Striae: The striae are radial in the middle to parallel - convergent near the poles. There are approximately 14 in 10 µm (10 - 14 in 10 µm Krammer & Lange-Bertalot, 1986b).

Ecology: Characteristic of hyposaline water with a salinity optimum of 13.2 ‰ and a tolerance range of 3.7–46.8 ‰ herein.

Distribution: A cosmopolitan littoral species found on sea coasts, this species favours fresh - brackish water (Krammer & Lange-Bertalot, 1986 b). It was found to occur frequently in the hyposaline lakes in this study being found in 11 of the 33 lakes sampled with a maximum abundance of 8 % in Lake McNeil.

Pinnularia microstauron (Ehrenberg) Cleve

Plate 6 Figure 8

Krammer & Lange-Bertalot (1986a, p. 425, 826-829)

Synonyms: *Stauroptera microstauron* Ehrenberg; *Pinnularia viridis* var. *caudata* Boyer

Taxonomy

Shape: Valves are linear with rounded apices. Valves are of average length 50 - 60 µm (35 - 40 µm John, 1983), and average width 15 µm (6 - 8 µm

John, 1983). The axial area is linear and narrow, widening towards the central area.

Raphe: The raphe branches slightly lateral in the middle; terminal fissures are "comma" like. The central area is dilated to the margins as a fascia.

Striae: The striae radiate towards the middle of the valve and are convergent towards the apices. There are approximately 12 striae in 10 µm (10 - 13/10 µm John, 1983).

Ecology: Characteristic of hyposaline and freshwaters with a salinity optimum of 3.2 ‰ and a restricted tolerance range of 1.2–8.7 ‰ herein.

Distribution: This species is a common benthic diatom which tolerates a wide range of pH and mineral content, but seems to prefer oligotrophic, slightly acid waters (Patrick and Reimer, 1966) and is found as a frequent member of the fresh-hyposaline lake diatoms from the Vestfold Hills, although occurring in many of the lakes sampled (21 of the 33) with a maximum abundance of 83 % in Vereteno Lake.

Comments: This species is identified by its central area but there is a wide variation on the length of striae present in this area. Therefore, those species with bare central margin are called *P. microstauron* var. *microstauron* (Plate 6 Figure 9) and those with any amount of striae in this area are termed *P. microstauron* (Plate 6 Figure 8). *Pinnularia microstauron* var. *microstauron* has a higher salinity optimum (10.8 ‰) and wider tolerance (4.6–25.4 ‰), although still hyposaline, than *Pinnularia microstauron* and occurs in fewer lakes (5 of the 33 sampled) with a much lower maximum abundance (8 %) than *P. microstauron*. Both forms are also common in the Larsemann Hills freshwater flora (V. Jones, *pers. comm.*, 1997).

Pinnularia quadratarea var. ***constricta*** (Østrup) Heiden

Plate 7 Figure 1

Poulin & Cardinal (1982a, p. 1272 -1275)

Synonyms: *Navicula pinnularia* var. *constricta* Østrup; *Navicula pinnularia* var. *subconstricta* Østrup

Taxonomy

Shape: Valves are elliptic - panduriform with cunate apices. Average length is 60 µm (40-83 µm Poulin & Cardinal, 1982a) and average width is 20 µm (14-17 µm Poulin & Cardinal, 1982a).

Raphe: The raphe is almost central with slightly expanded endings; the terminal fissures are slightly hooked in the same direction.

Striae: The valves are coarsely striate, with 8 in 10 µm (8-9 in 10 µm Poulin & Cardinal, 1982a). These striae are parallel - convergent on either side of a bare central area.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.
Distribution: Typical marine, periphytic, bottom sea-ice species common in Arctic ecosystems (Poulin & Cardinal, 1982a) but also present at temperate latitudes and in some Antarctic areas (Fukushima, 1965). It was found as a single specimen in Anderson Lake and Lake Hand.

Pinnularia quadratarea (Schmidt) Cleve var. a
Plate 7 Figure 2

Comments: This species has similar properties as *Pinnularia quadratarea* var. *constricta* but is distinctly thinner, ie. average width approximately 10 µm (half that of *Pinnularia quadratarea* var. *constricta*). Valves are linear - panduriform with more rounded apices.
Ecology: Characteristic of hyposaline water with a salinity optimum of 8.6 ‰ and a tolerance range of 2.3–31.7 ‰ herein.
Distribution: Found in 5 of the 33 lakes sampled with a maximum abundance of 6 % in Lake McNeil.

Pinnularia viridis (Nitzsch) Ehrenberg
Plate 7 Figures 3 and 4
Krammer & Lange-Bertalot (1986a, p. 428, 832-835)
Synonym: *Bacillaria viridis* Nitzsch
Taxonomy

Shape: Valves are linear with slightly attenuated rounded apices. Average valve length is 50 - 110 µm (80 - 124 mm John, 1983) and average width is 20 µm (16 - 19 µm John, 1983). The axial area is distinct, fairly broad, and abruptly narrows before reaching the apices. The central area is broad and lanceolate; terminal nodules are large.

Raphe: The raphe branches broadly and laterally; central fissures are closely located and slightly curved towards one side; terminal fissures are the "question mark" type.

Striae: Striae are costa like, crossed by a longitudinal band through the middle. They are radiate towards the middle of the valve and highly convergent towards the apices. There are approximately 9 striae in 10 µm (8 - 9 µm John, 1983).

Ecology: Specific to hyposaline water with a salinity optimum of 13.8 ‰ and a tolerance range of 6.2–30.6 ‰ herein.

Distribution: Widely distributed and common in fresh water, hyposaline and hypo-marine lakes, occurring in 17 of the 33 lakes sampled with a maximum abundance of 30 % in Lake Abraxas. A low abundance (3 %) was also observed in hypersaline Weddell Lake.

Comments: This species is variable in terms of form and structure, see *P. viridis* var. "*constricta*".

Pinnularia viridis Nitzsch var "***constricta***"

Plate 7 Figures 5 and 6

Comments: This species is a morphological variant from *Pinnularia viridis* as Figures 3 - 6 (Plate 7) show. It is characterised by similar properties as *Pinnularia viridis* but with a constriction of the central region.

Ecology: This variation of P. viridis has a slightly higher salinity optimum (15.9 ‰) and its tolerance extends into the hypersaline range (5.1–49.6 ‰) herein.

Distribution: This species was found only in the Lake Abraxas diatom assemblage, occurring as a common member at 14 % relative abundance.

Pleurosigma

This large genus is typical of marine and brackish waters, usually epipelic on sand or silt but occasionally planktonic (Round *et al.*, 1990).

Pleurosigma sp. a

Plate 7 Figures 7 and 8

Taxonomy

Shape: Valves sigmoid, linear to lanceolate. Average valve length is ~0.12 mm and average valve width is ~6 µm.

Raphe: The raphe system is along the valve middle and hence also sigmoid.

Striae: Composed of single rows of areolae, approximately 20 in 10 µm. This species has oblique striae readily observed in light microscope.

Areolae: Simple poroids approximately 7 per striae. Areolae are equally spaced and separated except for two closely spaced terminal areolae.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: Found as a rare specimen in Ace Lake only.

Stauroforma

Stauroforma inermis Flower, Jones and Round
Plate 7 Figure 9
Flower *et al.* (1996, p. 54, 50-52)
Synonyms: *Fragilaria virescens* var. *exigua* Grunow; *Fragilaria exiguiformis* (Grunow) Lange-Bertalot
Taxonomy

Shape: Valves range from elliptic/lanceolate to lanceolate with slightly extended apicies. Average valve length is 20 µm, average valve width 5 µm.
Raphe: The narrow sternum is almost undistinguishable in some light microscope specimens.
Striae: The fine striae are parallel, approximately 20 in 10 µm. Apical pore fields are distinguishable in SEM specimens.
Areolae: Areolae are simple poroids, 8 per striae.

Ecology: This species is specific to freshwater with a salinity optimum of 0.7 ‰ and a tolerance range of 0.1–3.1 ‰ herein.
Distribution: Found in 6 of the 33 lakes sampled with a maximum abundance of 12 % in freshwater Lichen Lake.
Comments: This species is also a common member of the maritime Antarctic freshwater lake flora (V. Jones, *pers. comm.*, 1997) and was placed in a new genus by Flower *et al.* (1996) as it is the non-spinose form of the spinose form of the *Fragilaria exiguiformis* populations observed in the United Kingdom.

Stauroneis

This genus is a freshwater epipelic genus, with some subaerial forms in soil and moss (Round *et al.*, 1990).

Stauroneis anceps Ehrenberg
Plate 8 Figure 1
Krammer & Lange-Bertalot (1986a, p. 240, 614-617)
Taxonomy

Shape: Valves are elliptical or elliptical-lanceolate with apices rostrate-capitate. The stauros is broad and dilated near its extremities. Average valve length is 35 µm, average valve width 7 µm.
Raphe: The raphe is simple, surrounded by a broad hyaline zone.

Striae: The striae are delicate and strongly radiant.

Areolae: Areolae are "squared" creating dashed striae, 5-8 per striae.

Ecology: Characteristic of hyposaline and freshwaters with a salinity optimum of 1.4 ‰ and a tolerance range of 0.2–9.7 ‰ herein.

Distribution: Van Heurck (1962) classifies this species as freshwater everywhere but not abundant. It was found to occur in 5 of the 33 lakes sampled herein with a maximum abundance of 3 % in freshwater Lichen Lake.

Comments: This species was found in Lake Miers (a permanently ice covered thermally stratified freshwater lake in South Victoria Land, Antarctica (Baker, 1967) and is also a common member of the Larsemann Hills freshwater lake flora (Jones, *pers. comm.*, 1997) and the Bunger Hills freshwater lake flora (Z. Pushina, *pers. comm.*, 1997).

Stauroneis cf. ***salina*** W. Smith

Plate 8 Figure 2

Krammer & Lange-Bertalot (1986a, p. 250, 622-623)

Taxonomy

Shape: Valves are broadly lanceolate, with narrowed capitate apices. Average valve length is 55 µm, average valve width is 12 µm . The stauros is narrow, only slightly or not enlarged at extremities.

Raphe: The raphe is central and simple with simple pore openings in the centre and slightly hooked terminal fissures.

Striae: The striae are delicate. There are approximately 20 in 10 µm. These are scarcely radiate.

Areolae: Areolae are simple pores, approximately 20-30 per striae.

Ecology: Characteristic of hypersaline water with a salinity optimum of 49 ‰ and a tolerance range of 20–119 ‰ herein.

Distribution: A marine species, but found on brackish sea coasts, Hustedt (1927-1966) classified it as a mesohalobous and euryhaline species (Wasell, 1993). Van Heurk (1896) also classifies this species as marine. It was found to occur in 8 of the 33 lakes sampled herein, with a maximum abundance of just over 2 % in Camp Lake.

Stauroneis sp. a

Plate 8 Figures 3 and 4

Taxonomy

Shape: Valves are elongate - linear with rounded apices. Length is extremely variable from ~ 50 - 75 µm, average width 8 - 10 µm.

Raphe: The raphe is central and straight with distinct polar and central nodules. The central area is broadened into a stauros (clear area).

Striae: Striae are parallel and uniseriate, approximately 30 in 10 μm.

Areolae: Areolae are very slightly squared, approximately 12 per striae.

Ecology: Characteristic of many of the lake waters herein with a salinity optimum of 37.5 ‰ and a large tolerance range of 13.7–103 ‰.

Distribution: Found to occur in 26 of the 33 lakes sampled, with a maximum abundance of 13.5 % in hypersaline Ekho Lake.

Comments: This species is very similar to*Tropidoneis laevissima* West & West. West & West (1911) recorded *Tropidoneis laevissima* in both fresh and saline Antarctic lakes (Wasell, 1993) and Watanuki (1979) recorded Tropidoneis *laevissima* in saline lakes from the Syowa Oasis. *Tropidoneis laevissima* is probably an endemic Antarctic species (Kellogg *et al.*, 1980) and the variation in the Antarctic forms of this species has been described in Ko-Bayashi (1963b).

Synedra

This araphid genus is freshwater in distribution (Round *et al.*, 1990).

Synedra sp. b
Plate 8 Figure 5

Taxonomy

Shape: Valves needle-like and linear, variable valve length (0.08 - 0.25 mm) and width (5-10 μm) with average length ~ 0.15 μm and average width ~ 8 μm.

Raphe: This araphid species has a vary narrow sternum which is sometimes indistinguishable in light microscope.

Striae: Perpendicular to narrow sternum and absent from the central area.

Areolae: Areolae are not discernible in light microscope specimens.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: Occurs as a rare component of the Oblong Lake and Burton Lake assemblages only.

Trachyneis

This small genus is a distinctive member of the marine littoral habitat, where it lives epipelically on sand (Round *et al.*, 1990).

Trachyneis aspera (Ehrenberg) Cleve

Plate 8 Figure 6

Cleve (1965, p. 191)

Taxonomy

Shape: Valves are linear to linear-elliptical, with acutely rounded or blunt poles. Average valve length is 86 µm with average valve width 16 µm. Valve structure often interrupted centrally by a broad oval or "bow tie" shaped plain area (Round *et al.*, 1990).

Raphe: The raphe system is central. External raphe fissures are often sinuous near the centre; terminal fissures are hooked.

Striae: Striae are basically uniseriate.

Areolae: Each areolae opens to the inside by a single round hole and to the exterior by a series of slit-like poroids, which are closed by hymenes. The slits are often aligned longitudinally to produce 'lineolate striae'.

Ecology: Characteristic of markedly hypersaline water with a salinity optimum of 60 ‰ and a tolerance range of 17–211 ‰ herein.

Distribution: This species was found in 6 of the 33 lakes sampled with a maximum abundance of 2 %.

Tryblionella

This genus is a fairly large epipelic genus, widespread but not often common in brackish and marine sediments; also present in high-conductivity fresh waters (Round *et al.*, 1990).

Tryblionella marginulata (Grunow) Mann

Plate 8 Figure 7

Krammer & Lange-Bertalot (1986b, p. 45, 282-283)

Taxonomy

Shape: Frustules are diagonally symmetrical about the median valvular plane ("nitzschoid" symmetry). Valves are linear - pandurifom, with bluntly rounded or apiculate poles. Average valve length is 40 µm (30 - 80 µm Krammer & Lange-Bertalot, 1986b) and average width is 10 µm (15 - 25 µm Krammer & Lange-Bertalot, 1986b). The valve face often bears warts or ridges externally.

Raphe: Valves are bounded on one side by the keeled raphe system; on the other side often bearing a marginal ridge at its junction with the extremely shallow distal mantle.

Striae: The striae are uniserate.

Areolae: Striae are composed of simple areolae interrupted by sterna.

Ecology: Characteristic of hyposaline water with a salinity optimum of 17.8 ‰ and a tolerance range of 6.8–46.4 ‰ herein.

Distribution: Found in 10 of the 33 lakes sampled with a maximum abundance of 12 % in Lake Abraxas.

Unidentified Genus and Species

This species appears to have affinities with the genera *Navicula* and *Pinnularia.*

Unidentified genus and species a
Plate 8 Figure 8

Taxonomy

Shape: Valves are linear with rounded - slightly rostrate apices. Average valve length is 15 µm and average valve width is 3 µm.

Raphe: The raphe is central and straight; central endings are slightly expanded; terminal fissures are strongly hooked in the same direction.

Striae: There are a parallel row of wide puncta either side of the raphe-sternum, approximately 16 in 10 µm. There is a distinct widened area lacking puncta in central region.

Areolae: Areolae are one single large valve opening.

Ecology: This species has a lakewater salinity optimum of 9.2 ‰ and a tolerance range of 7.3–11.6 ‰ herein.

Distribution: This tiny species is found to be specific to Lake Collerson (a hyposaline habitat) and comprises 64 % of the relative abundance of species within this lake.

Centrales
(valves radially symmetric)

Actinocyclus

This genus is often encountered in nearshore plankton assemblages (Round *et al.*, 1990).

Actinocyclus actinochilus (Ehrenberg) Simonsen
Plate 9 Figure 1
Priddle & Fryxell (1985, p. 101-103)

Taxonomy

Shape: Valve diameter is 10 - 30 µm (20 - 112 µm Medlin & Priddle, 1990).

Areolae: Areolation is fine comprising radiating rows of unequal length, 5 - 11 in 10 µm (Medlin & Priddle, 1990). Marginal striation is very fine and is obvious only with EM resolution (Priddle & Fryxell, 1985).

Processes: Marginal labiate processes are conspicuous but the pseudonodulus is often impossible to resolve using the light microscope (Priddle & Fryxell, 1985).

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: This species has a known Antarctic ice edge distribution (Medlin & Priddle, (1990) but a single specimen was found in Johnstone Lake, a lake subject to occasional marine incursion.

Comments: Variation within the species observed were considerable.
Detailed observations are provided by Simonsen (1982) who transferred this species to *Actinocyclus* from *Charcotia*, the name under which it appears in much of the Antarctic literature (Priddle & Frxyell, 1985).

Asteromphalus

The species within this small genus are generally marine planktonic in warm waters, never occurring in large quantities (Round *et al.*, 1990).

Asteromphalus hyalinus Karsten
Plate 9 Figure 2
Priddle & Fryxell (1985, p. 120-121)

Taxonomy

Shape: Valve diameter < 30 µm (cf. Priddle & Fryxell, 1985) with four broad hyaline rays and a single narrow hyaline ray.

Areolae: There are ~ 13-15 large areolae in 10 µm.

Processes: Labiate processes can be seen on each of the broad rays.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: A single specimen was found in Lake Franzmann, a lake subject to occasional marine incursion.

Chaetoceros

An important marine planktonic genus with many species (175 - Stockwell & Hargraves, 1984), although a few species have been recorded in freshwater (Round *et al.*, 1990). Members of this genus are widespread and abundant members of the Antarctic phytoplankton.

Chaetoceros (Ehrenberg) vegetative cells

Plate 9 Figure 3 and 4

Priddle & Fryxell (1985, p. 16-53)

Observations: All cells are single, not in chains. Cell length average is 4 µm , width is 2.5 µm with long setae spreading from opposite sides of the cell.

Ecology: This typically marine planktonic species has a high lakewater salinity optimum of 44.4 ‰ and an extremely wide tolerance of 14.5-136 ‰ herein.

Distribution: Found in 21 of the 33 lakes sampled with a maximum abundance of 62 % in Lake .

Comments: All *Chaetoceros* vegetative cells were grouped together for ease of analysis. Almost exclusively cells were of *C. simplis* affinity (Plate 9 Figure 3) but the odd *C. bulbosum* was observed (Plate 9 Figure 4).

Chaetoceros (Ehrenberg) resting spores

Not Illustrated

Stockwell & Hargraves (1984)

Observations: Resting spores are known from several species and where observed are recorded as *Chaetoceros* spore. No attempt was made to identify spores to species level.

Ecology: *Chaetoceros* spores exhibit a lower salinity optimum (34 ‰) but a wider salinity tolerance range (6.7-170 ‰) than the vegetative cells (as would be expected for a resting spore).

Distribution: Found to be less abundant than *Chaetoceros* vegetative cells, occurring with a maximum abundance of 32 %, but shares a similar distribution throughout the lakes studied (in 27 of the 33 lakes sampled).
Comments: About one third of the 175 species of *Chaetoceros* are known to produce resting spores which are thought to be morphologically distinct (Stockwell & Hargraves, 1984).

Eucampia

A common marine planktonic genus of only 5 species (Round *et al.*, 1990).

Eucampia antarctica (Castracane) Mangin
Plate 9 Figures 5 and 6
Priddle & Fryxell (1985, p. 66-67)
Medlin & Priddle (1990, p. 129-131)

Taxonomy

Shape: Flattened normal to the girdle with elevated valve extremities. Apical axis diameter is ~ 50 µm (18-92 µm Medlin & Priddle, 1990).
Areolae: Valves are only lightly ornamented with 3-10 areolae in 10 µm.
Processes: Single marginal labiate process with no external tube.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.
Distribution: Found in 6 of the 33 lakes sampled with a maximum abundance < 2%.
Comments: This species forms coarsely silicified resting spores and can be divided into winter and summer growth stages (Fryxell, 1991) on the basis of the extent of silicification of the valve (Plate 9 Figures 5 and 6). Fryxell *et al.* (1989) discuss the complex taxonomical history of this species.

Porosira

This genus is marine planktonic (Round *et al.*, 1990).

Porosira glacialis (Grunow) Jørgensen
Plate 10 Figure 1
Priddle & Fryxell (1985, p. 141-143)

Taxonomy

Shape: Cell diameter is 40 µm (cf. 23 - 70 µm Priddle & Fryxell, 1985; 36 - 64 µm (Medlin & Priddle, 1990).

Areolae: Areolation is fine (25 in 10 µm - Medlin & Priddle, 1990) and radial.

Processes: Strutted processes are unevenly distributed across the valve face, being more dense near the margin. Threads from the strutted processes join adjacent cells to form short chains. Labiate processes are conspicuous and radial. There are no marginal processes (Priddle & Fryxell, 1985).

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: Found in Lake McNeil and Watts Lake only at < 2 % abundance.

Comments: Individual cells are united by 15 - 20 threads of mucilage which does not preserve well, hence colonies will usually not be seen in preserved material.

Thalassiosira

The species within this large genus are mostly marine (Round *et al.*, 1990).

Thalassiosira antarctica Comber

Plate 10 Figures 2 and 3

Hasle & Heimdal (1968)

Fryxell *et al.* (1981)

Medlin & Priddle (1990, p. 98-99, 102-103)

Taxonomy

Shape: Valve is ~40 µm in diameter (16-56 µm - Medlin & Priddle, 1990).

Areolae: There are 15 - 24 areolae in 10 µm in a radial bifurcating pattern (Medlin & Priddle, 1990).

Processes: Occluded processes may be present, but are difficult to discern. There are 8 - 16 strutted processes in 10 µm on the mantle (outer ring) with a central cluster of 4 - 14 strutted processes. One labiate process is positioned inside the inner ring and there are 0.4 occluded processes in 10 µm.

Ecology: This centric marine species has a hyposaline lakewater salinity optimum of 18 ‰ and a large tolerance range of 4.5–73 ‰.

Distribution: This species has an Antarctic, near ice distribution (Medlin & Priddle, 1990) and was found to be the most commonly occurring centric diatom in the lakes studied, occurring in rare amounts (with a maximum abundance just > 2%) throughout 8 of the 33 lakes sampled.

Comments: *Thalassiosira antarctica* resting spores (Plate 10 Figure 3) are sometimes present in a sample, identified by their heavily silicified cell, approximately 30 µm diameter with 7-12 areolae in 10 µm (Medlin & Priddle, 1990; Hasle & Heimdal, 1968).

Thalassiosira gracilis (Karsten) Hustedt

Plate 10 Figure 4

Medlin & Priddle (1990, p. 98-99)

Taxonomy

Shape: Valve diameter ~ 30 μm (5-28 μm Medlin & Priddle, 1990).

Areolae: Marginal areolae (5-10 in 10 μm Medlin & Priddle, 1990) but central areolae are very coarse with 8 in 10 μm (8-12 in 10 μm Medlin & Priddle, 1990).

Processes: One central strutted process and labiate process almost marginal, difficult to see.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: A few valves found in Burton Lake, a marine lagoon, only.

Thalassiosira species a

Plate 10 Figure 5

Taxonomy

Shape: Valve is ~15 μm in diameter.

Areolae: Simple and radiate, approximately 30 in 10 μm.

Processes: A ring of marginal strutted processes and an offset from centre labiate process are visible, although slightly obscured by mucilage/spines on the valve face.

Ecology: This species was not abundant enough to be used in the numerical analyses, therefore little is known of its salinity affinities herein.

Distribution: Found in Watts Lake, a freshwater lake with marine terraces, only.

Other Taxa

Chrysophyta

Chrysophyte cyst
Plate 10 Figure 6

Observations: Chrysophytes are common in many freshwaters (including Arctic lakes - Douglas *et al.*, 1996) and although described in temperate regions as typically euplanktonic (Sandgren, 1988) are thought to be periphytic in high latitudes (e.g. Douglas & Smol, 1995). The siliceous resting cycts of chrysophyte algae have a species-specific morphology, are resistant to dissolution and are abundant and diverse in most lake sediments (Zeeh *et al.*, 1996), hence are also useful palaeoindicators. Smol (1995) provides a comprehensive overview of chrysophyte-based palaeolimnology.
Distribution: Chrysophyte cysts were found to occur in 31 of the 33 lakes sampled with a maximum relative abundance of 24 % of the algal flora enumerated in the hyposaline lake Lake Abraxas. In general, these cysts are common in the fresh and hyposaline lakes, frequent in marine lakes and lakes with occasional marine inputs, but rare in the hypersaline lakes of the Vestfold Hills.
Comments: Chrysophyte cysts were also observed throughout the sediment cores analysed, although apparently more common in the freshwater sections (cf. Arctic sediment cores - Douglas *et al.*, 1996).

Dictyocha speculum Ehrenberg
Plate 10 Figure 7
Moestrup & Thomsen (1990)
cf. Haq & Riley (1976, p. 682, 688-691)
Synonym: *Distephanous speculum* (Ehrenberg) Haeckel
Observations: Silicoflagellates constitute a small group of marine flagellates which occur in all seas (Moestrup, 1995). *Dictyocha speculum* has a hexagonal basal ring, two opposing radial spines that are longer than the other four, and an apical ring of moderate proportions (cf. *Distephanous speculum* - Haq & Riley, 1976). Variation in *Distephanus speculum* morphology is discussed in Van Der Spoel *et al.* (1973).
Distribution: This species of silicoflagellate was found in 5 of the 33 lakes sampled at abundances < 2 %.
Comments: Silicoflagellates are commonly found in areas of high diatom concentration, being most abundant in areas of upwelling and in equatorial waters, but are also abundant in high latitudes (Lipps, 1987). Fluctuations in diatom abundance are generally accompanied by similar changes in the abundance of silicoflagellates (Lipps, 1987).

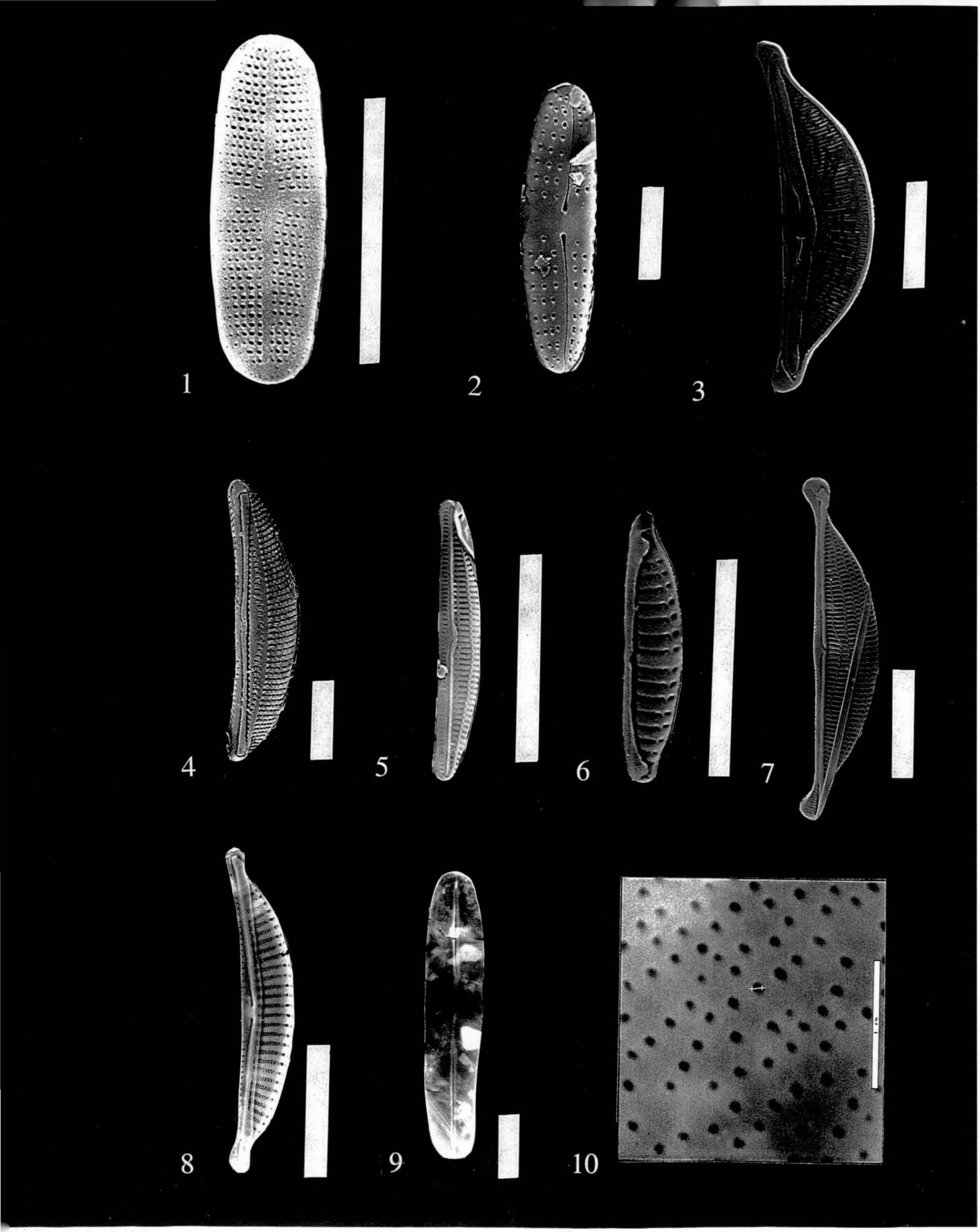


Plate 1

Figure 1: *Achnanthes abundans*; Figure 2: *Achnanthes brevipes* (raphid valve); Figure 3: *Amphora veneta*; Figure 4: *Amphora* species a; Figure 5: *Amphora* species b; Figure 6: *Amphora* species c; Figure 7: *Amphora* species d; Figure 8: *Amphora* species e; Figure 9: *Berkeleya adeliensis*; Figure 10: *Berkeleya adeliensis* (poroids). Figure 10 scale bar = 1 µm (+ - + = 80 nm). All other scale bars = 10 µm.

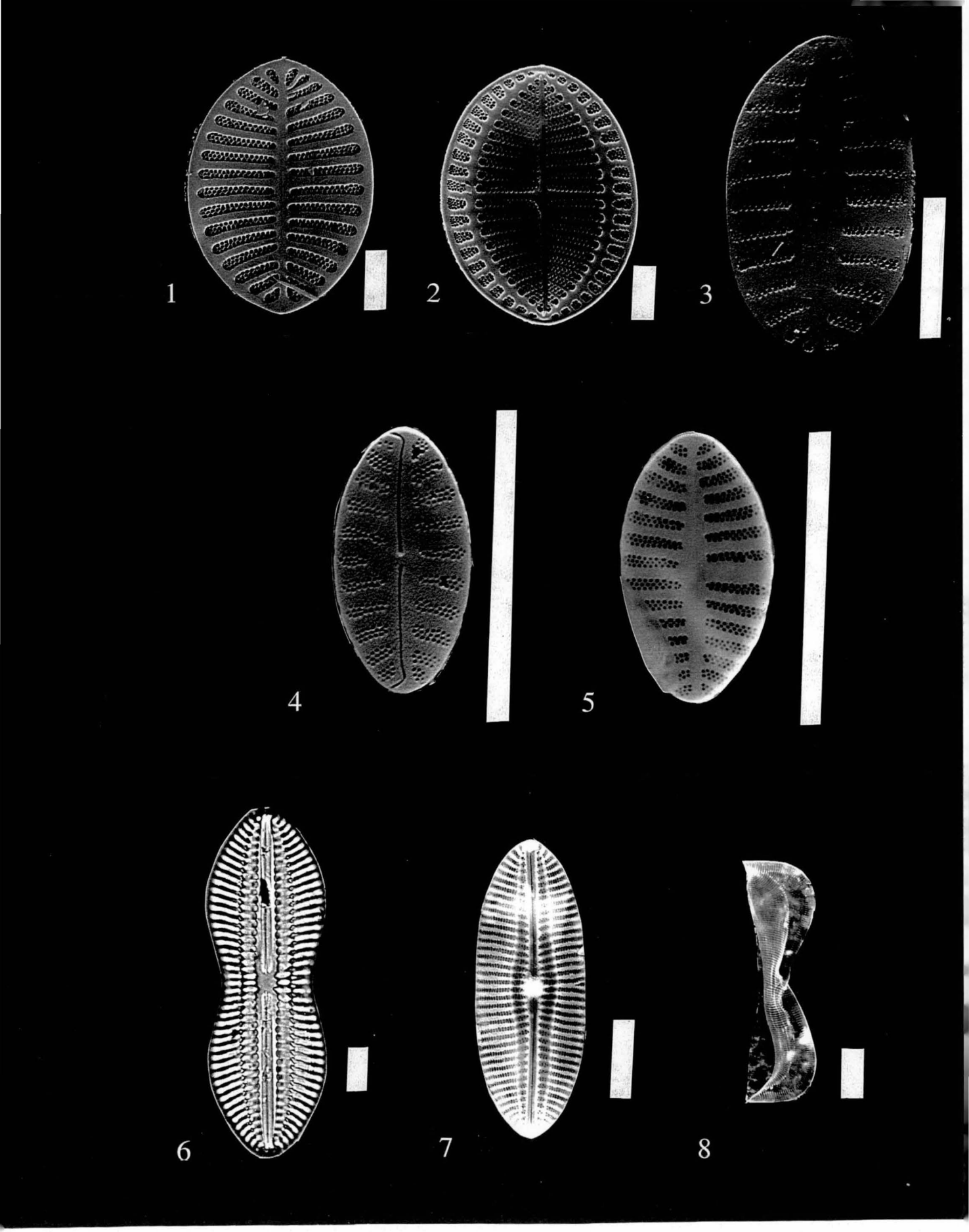


Plate 2

Figure 1: *Cocconeis costata*; Figure 2: *Cocconeis fasciolata*; Figure 3: *Cocconeis pinnata*; Figure 4: *Cocconeis* species a (raphid valve); Figure 5: *Cocconeis* species a (araphid valve); Figure 6: *Diploneis splendida* (LM); Figure 7: *Diploneis* species b; Figure 8: *Entomoneis kjellmanii*. All scale bars = 10 µm.

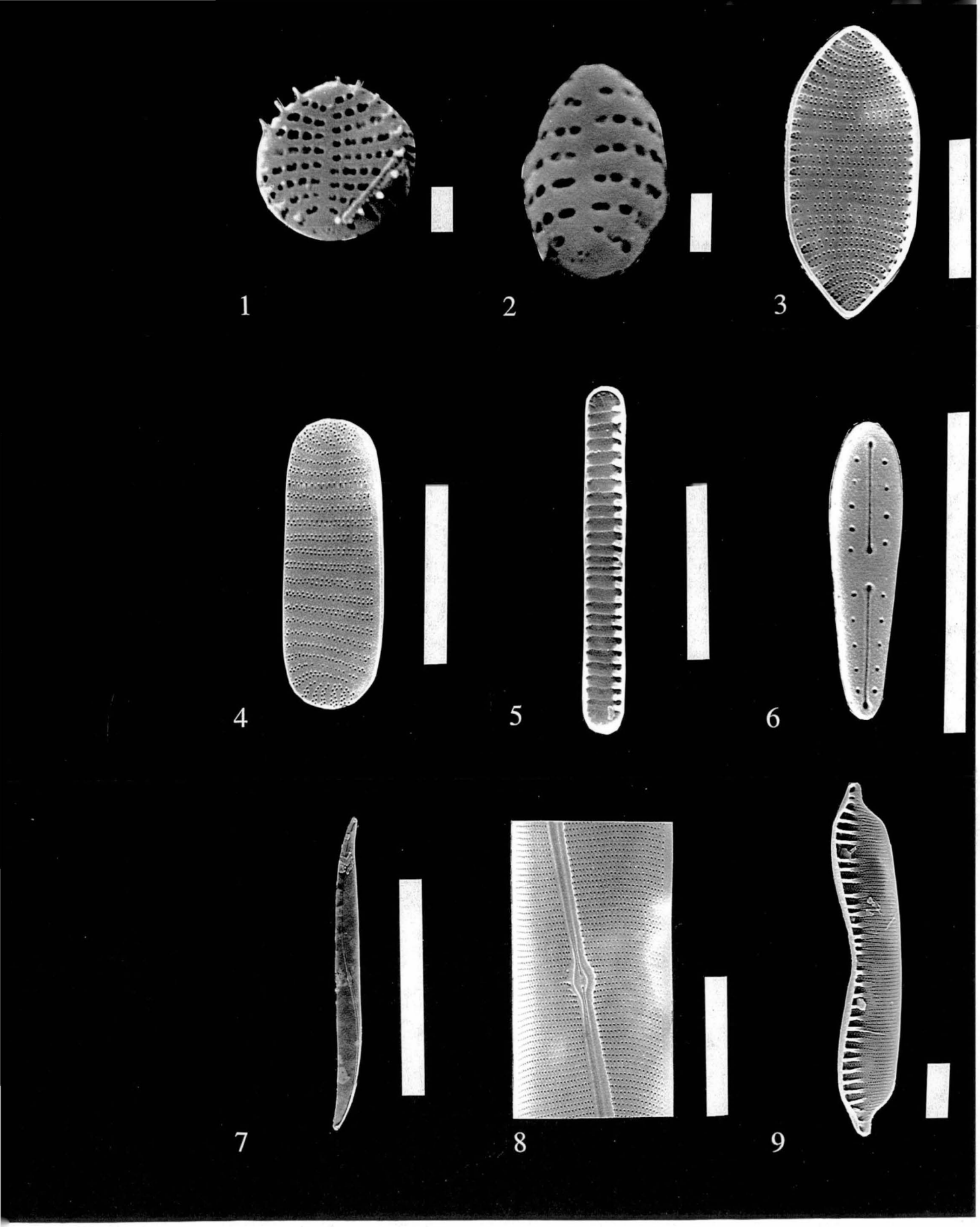


Plate 3

Figure 1: *Fragilaria construens* var. *venter*; Figure 2: *Fragilaria* species a; Figure 3: *Fragilariopsis angulata*; Figure 4: *Fragilariopsis curta*; Figure 5: *Fragilariopsis cylindrus*; Figure 6: *Gomphonemopsis* species a; Figure 7: *Gyrosigma subsalsum*; Figure 8: *Gyrosigma subsalsum* (central area); Figure 9: *Hantzschia virgata* . Figure 1 and 2 scale bar = 1 µm. Figure 7 scale bar = 0.1 mm. All other scale bars = 10 µm.

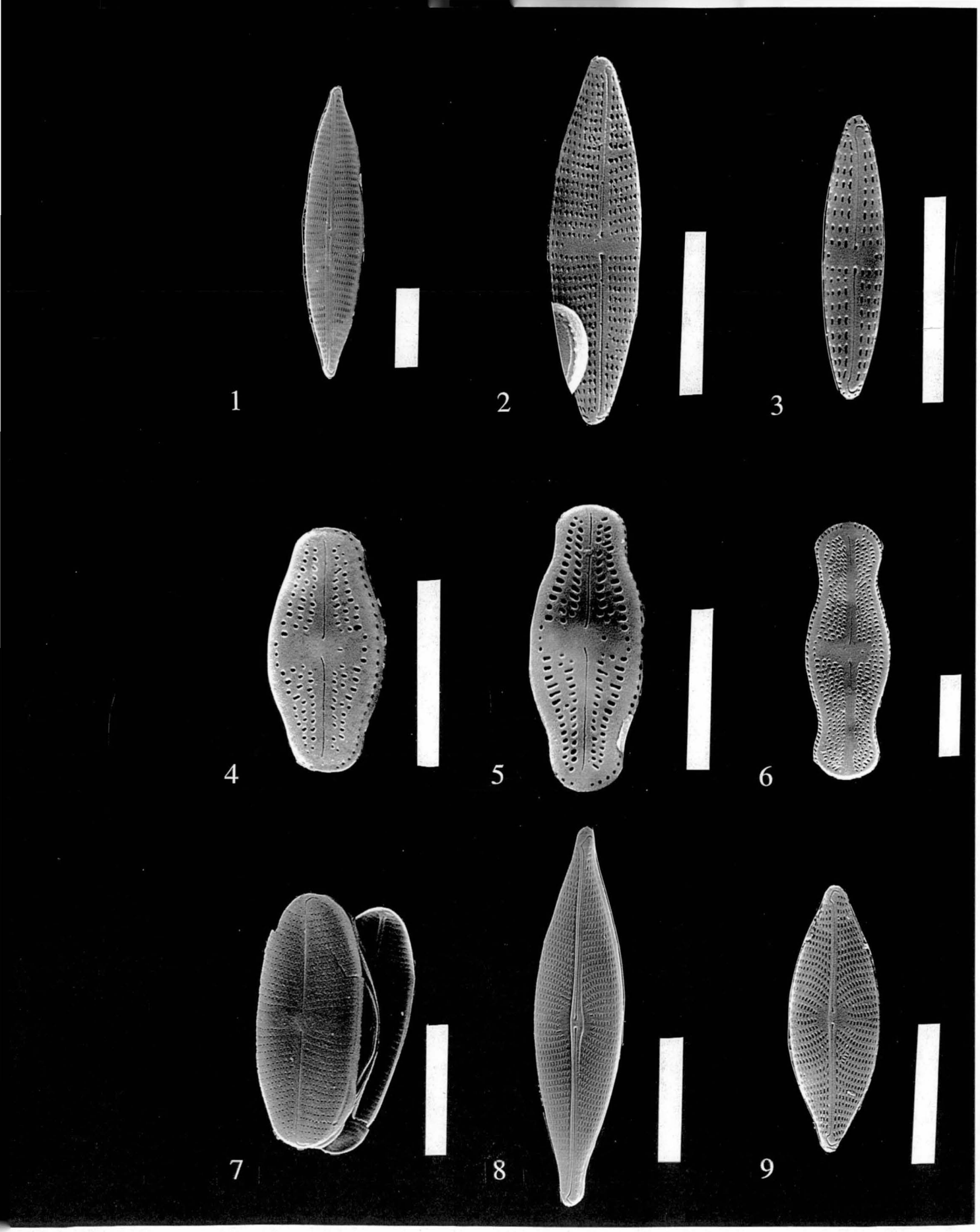


Plate 4

Figure 1: *Navicula directa*; Figure 2: *Navicula glaciei*; Figure 3: *Navicula perminuta*; Figure 4,5,6: *Navicula mutica /muticopsis*; Figure 7: *Navicula seminulum*; Figure 8,9: *Navicula tripunctata* . All scale bars = 10 µm.

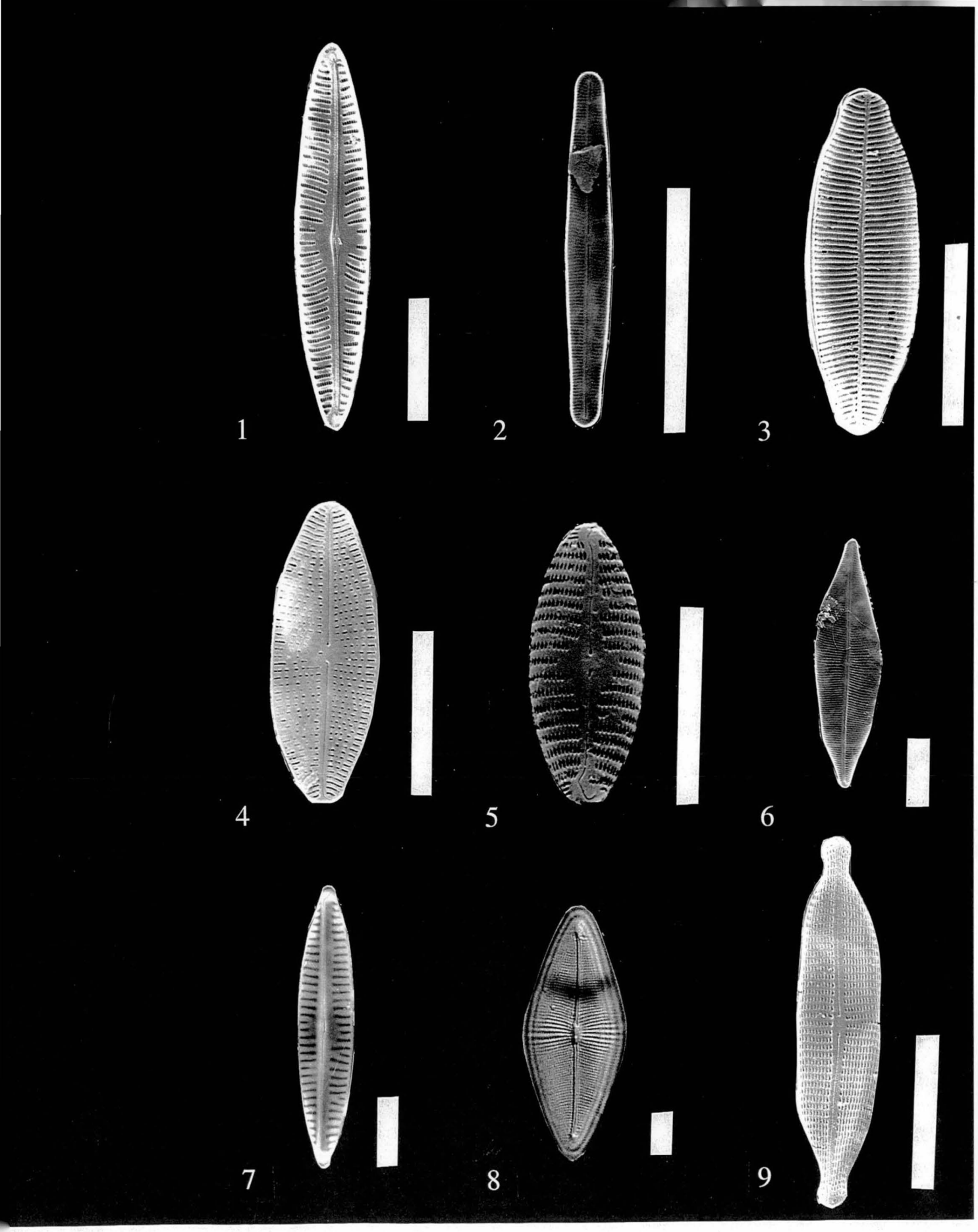


Plate 5

Figure 1: *Navicula* species a; Figure 2: *Navicula* species b; Figure 3: *Navicula* species c; Figure 4: *Navicula* species d; Figure 5: *Navicula* species e; Figure 6: *Navicula* species f; Figure 7: *Navicula* species g; Figure 8: *Navicula* species h (LM); Figure 9: *Navicula* species i. All scale bars = 10 μm.

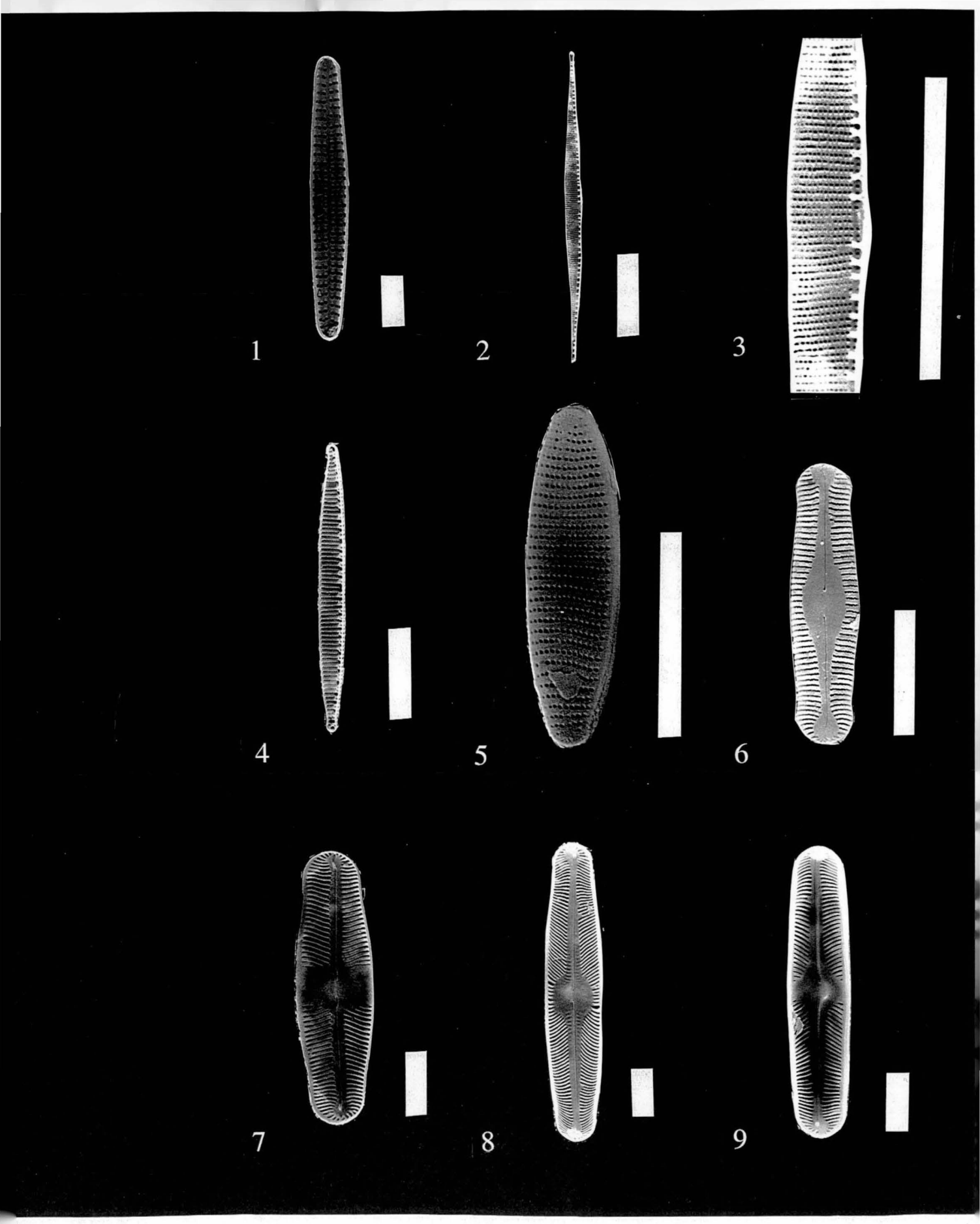


Plate 6

Figure 1: *Neodelphineis* ? species a; Figure 2,3: *Nitzschia lecointei*; Figure 4: *Nitzschia perminuta*; Figure 5: *Nitzschia* species b; Figure 6: *Pinnularia cymatopleura* ; Figure 7: *Pinnularia lundii*; Figure 8: *Pinnularia microstauron*; Figure 9: *Pinnularia microstauron* var. *microstauron*. All scale bars = 10 µm.

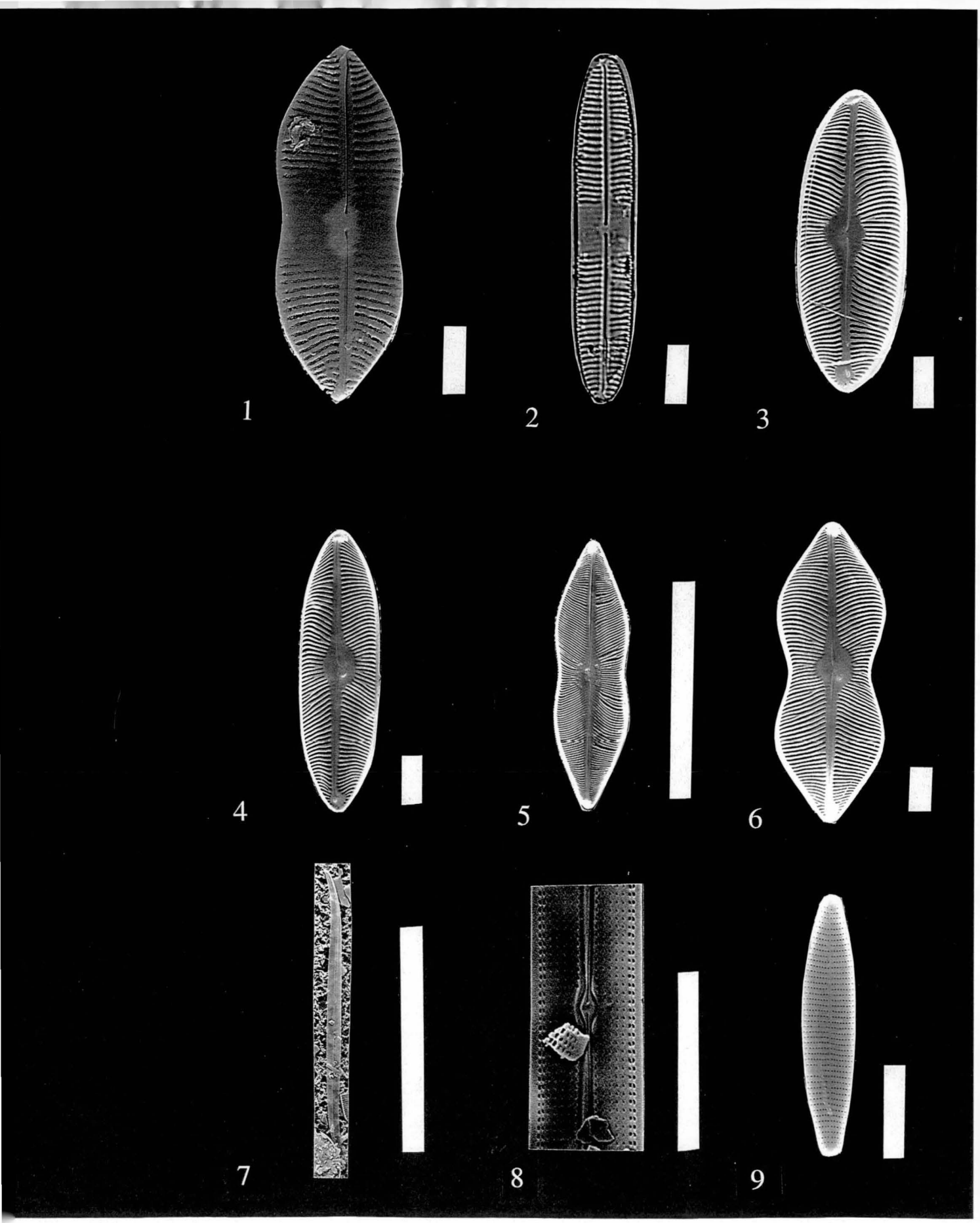


Plate 7

Figure 1: *Pinnularia quadratarea* var. *constricta*; Figure 2: *Pinnularia quadratarea* var. a (LM); Figure 3,4: *Pinnularia viridis*; Figure 5,6: *Pinnularia viridis* var. "*constricta*"; Figure 7,8: *Pleurosigma* species a; Figure 9: *Stauroforma inermis*. Figure 7 scale bar = 0.1 mm. All other scale bars = 10 μm.

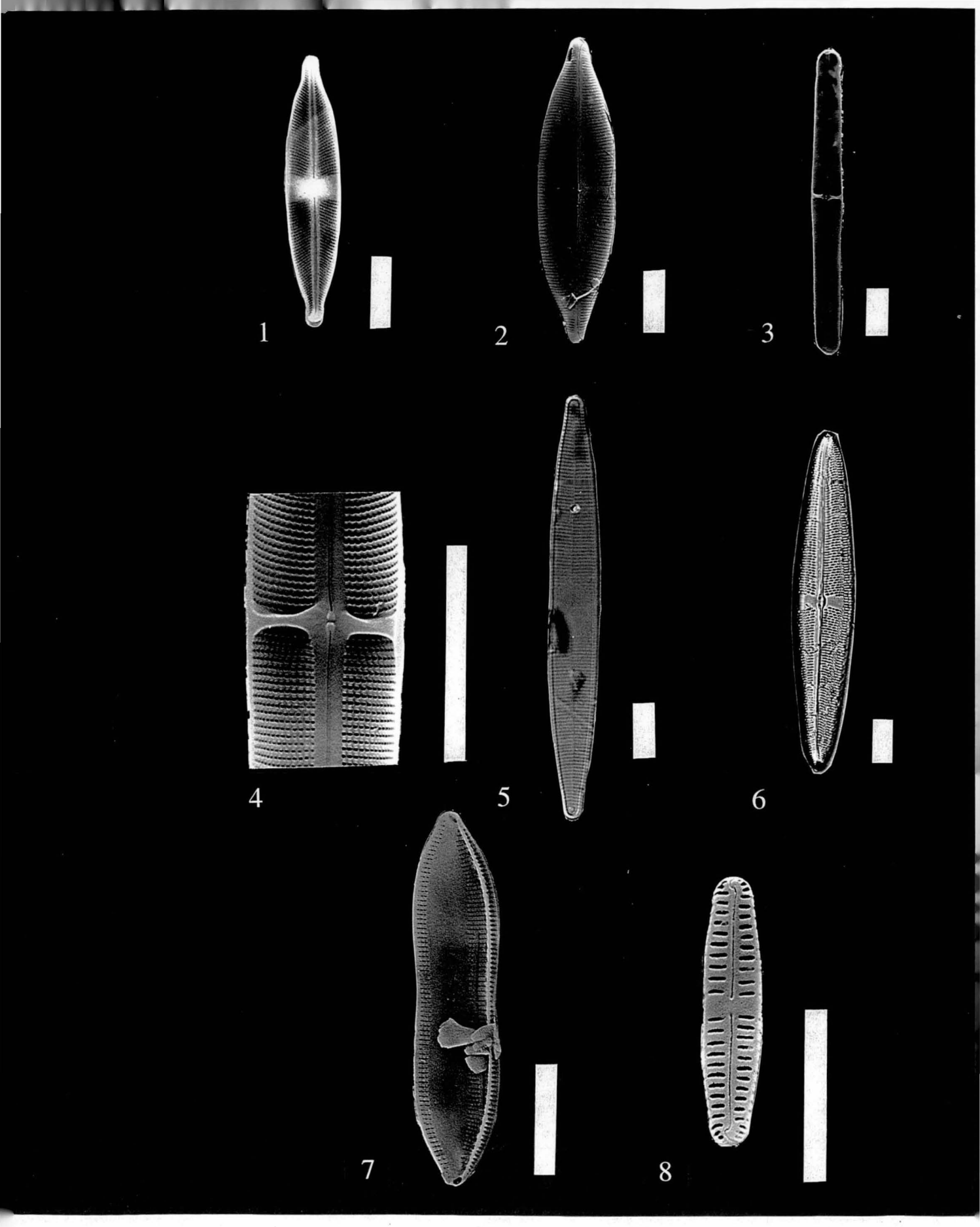


Plate 8

Figure 1: *Stauroneis anceps*; Figure 2: *Stauroneis* cf. *salina*; Figure 3,4: *Stauroneis* species a; Figure 5: *Synedra* species b (LM) ; Figure 6: *Trachyneis aspera* (LM); Figure 7: *Tryblionella marginulata*; Figure 8: Unidentified Genus and species a. All scale bars = 10 µm.

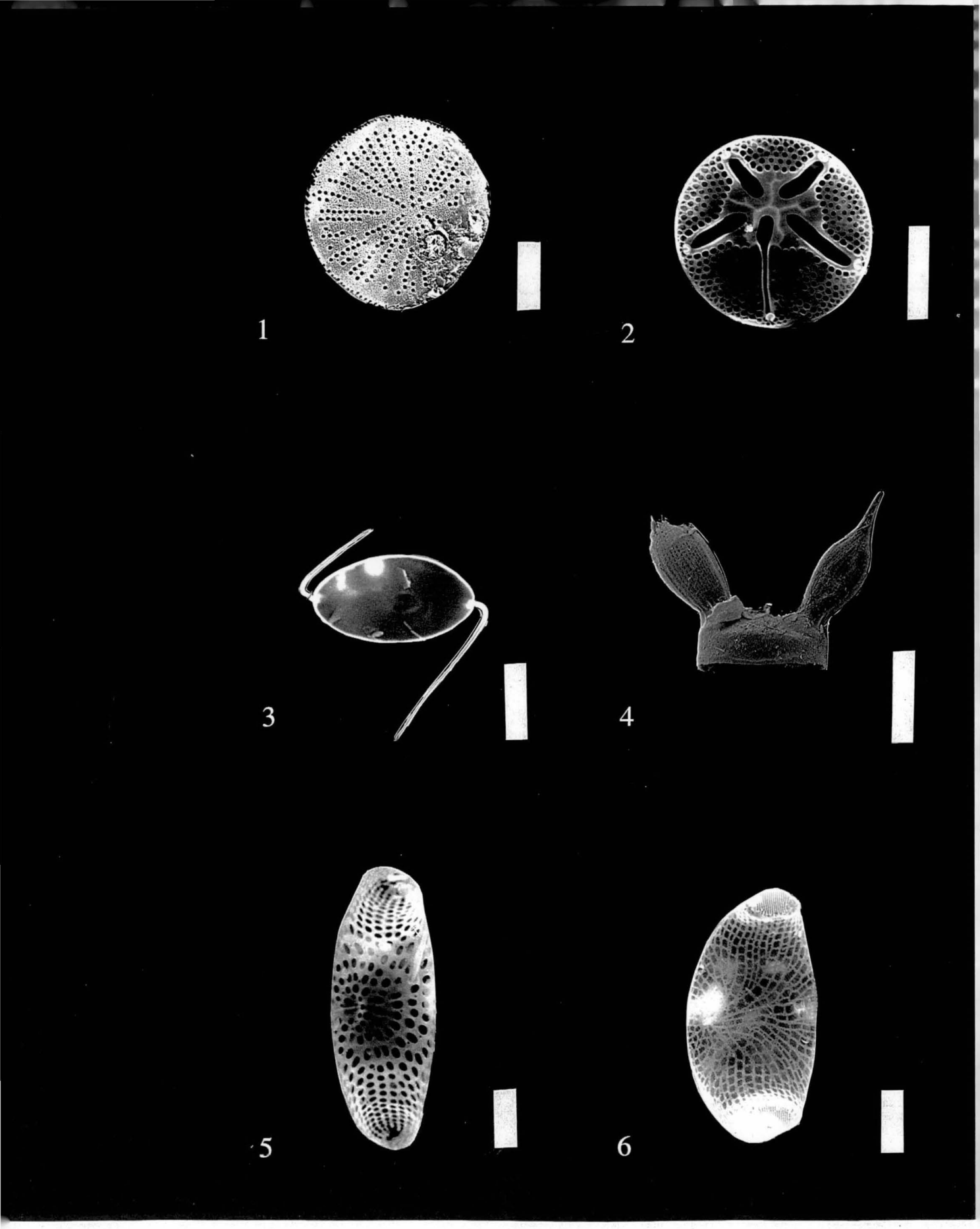


Plate 9

Figure 1: *Actinocyclus actinochilus*; Figure 2: *Asteromphalus hyalinus*; Figure 3: *Chaetoceros* vegetative cell; Figure 4: *Chaetoceros bulbosum*; Figure 5: *Eucampia antarctica* (winter valve); Figure 6: *Eucampia antarctica* (summer valve). All scale bars = 10 μm.

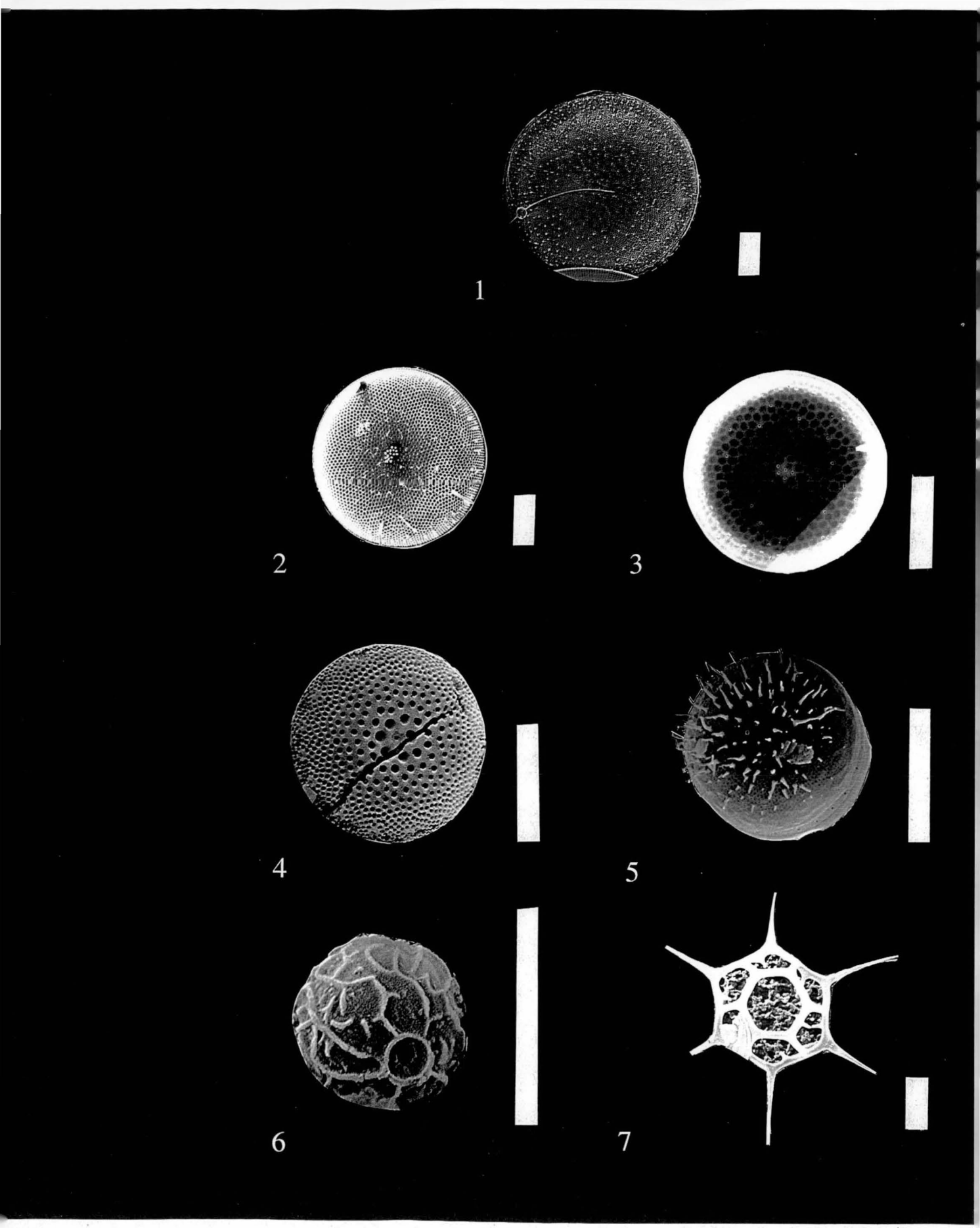


Plate 10

Figure 1: *Porosira glacialis*; Figure 2: *Thalassiosira antarctica* (vegetative cell); Figure 3: *Thalassiosira antarctica* (resting cyst); Figure 4: *Thalassiosira gracilis*; Figure 5: *Thalassiosira* species a; Figure 6: *Chrysophyte* cyst; Figure 7: *Distephanus speculum*. All scale bars = 10 μm.

Appendix 5: ^{210}Pb Dating of Ace Lake.

LEAD-210

Date & Time spreadsheet printed = 18-Jun-97 15:41

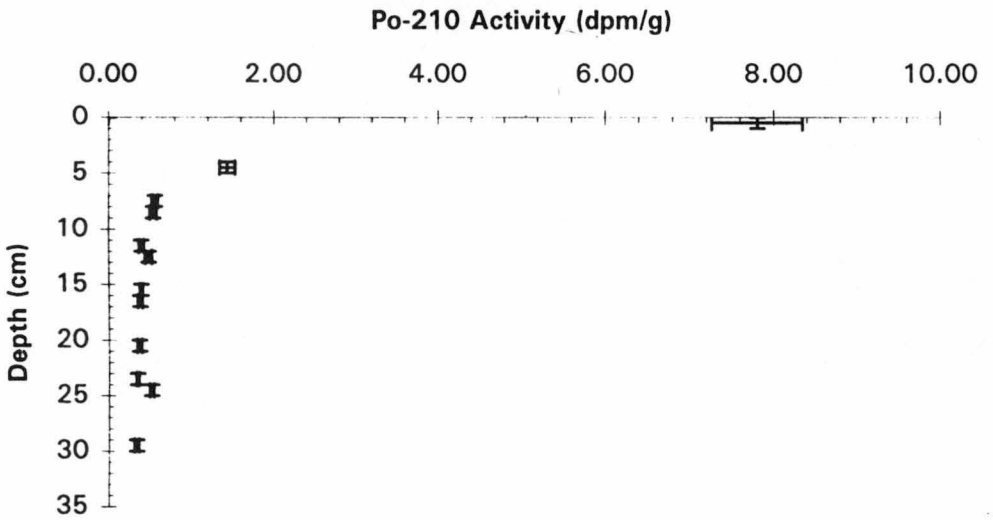
Client: Andrew McMinn — Sedimentation Rate Calculation — Spreadsheet last modified on 21-Feb-96

Project: Ace Lake — CIC Model 0.09 cm/year

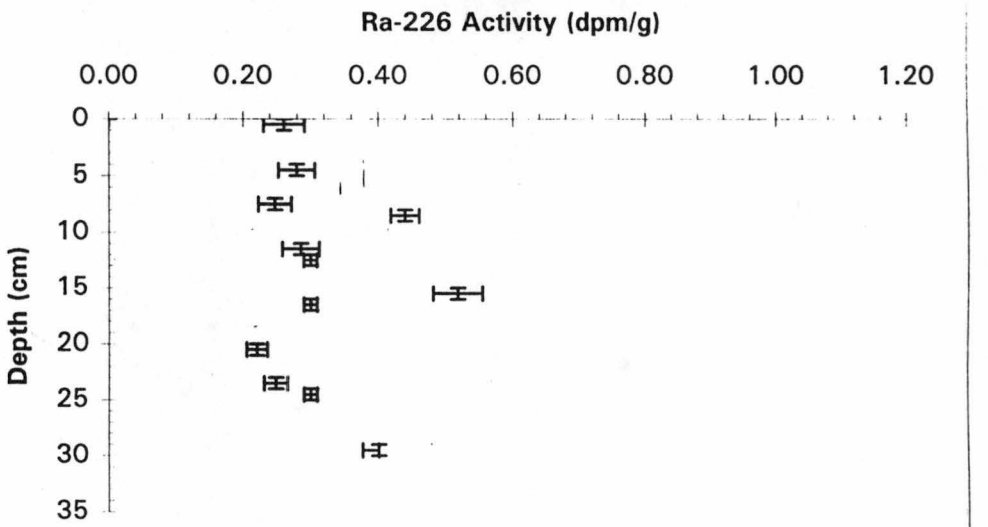
Year of study: 1995 — CRS Model (average) 0.04 g/cm^3/year

Sample Identification	LH Number	Slice Thickness (cm)	Depth (cm)	Water content (%) as decimal	Porosity	Dry bulk density (g/cm^3)	Po-210 (dpm/g)	Po-210 error (dpm/g)	Po-210 yield (%)	Ra-226 (dpm/g)	Ra-226 error (dpm/g)	Ra-226 yield (%)	Excess Pb-210 (dpm/g)	Excess Pb-210 err (dpm/g)
0-1cm	4404	1	0.5	0.915	0.964	0.090	7.8053	0.5420		0.2609	0.0303	87	7.5444	0.5428
4-5cm	4408	1	4.5	0.865	0.941	0.147	1.4323	0.0942		0.2797	0.0267	67	1.1526	0.0979
7-8cm	4411	1	7.5	0.807	0.913	0.218	0.5548	0.0362		0.2476	0.0245	49	0.3072	0.0437
8-9cm	4412	1	8.5	0.810	0.914	0.214	0.5354	0.0401		0.4400	0.0210	11	0.0954	0.0453
11-12cm	4415	1	11.5	0.784	0.901	0.248	0.3933	0.0290		0.2859	0.0274	49	0.1074	0.0399
12-13cm	4416	1	12.5	0.784	0.901	0.248	0.4774	0.0407		0.3000	0.0100	fake	0.1774	0.0419
15-16cm	4419	1	15.5	0.772	0.894	0.264	0.3902	0.0184		0.5180	0.0365	32	-0.1278	0.0409
16-17cm	4420	1	16.5	0.734	0.873	0.317	0.3789	0.0270		0.3000	0.0100	fake	0.0789	0.0288
20-21cm	4424(2)	1	20.5	0.758	0.887	0.283	0.3697	0.0263		0.2209	0.0153	97	0.1488	0.0304
23-24cm	4427	1	23.5	0.725	0.868	0.330	0.3463	0.0144		0.2485	0.0172	31	0.0978	0.0224
24-25cm	4428	1	24.5	0.728	0.870	0.325	0.5169	0.0249		0.3000	0.0100	fake	0.2169	0.0268
29-30cm	4432(2)	1	29.5	0.709	0.859	0.353	0.3335	0.0265		0.4012	0.0238	86	-0.0677	0.0356

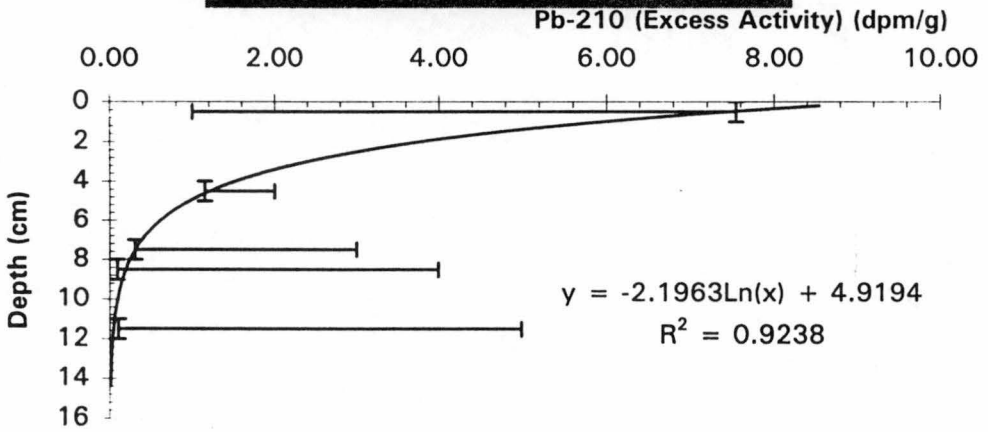
Plot of Po-210 Activity vs Depth



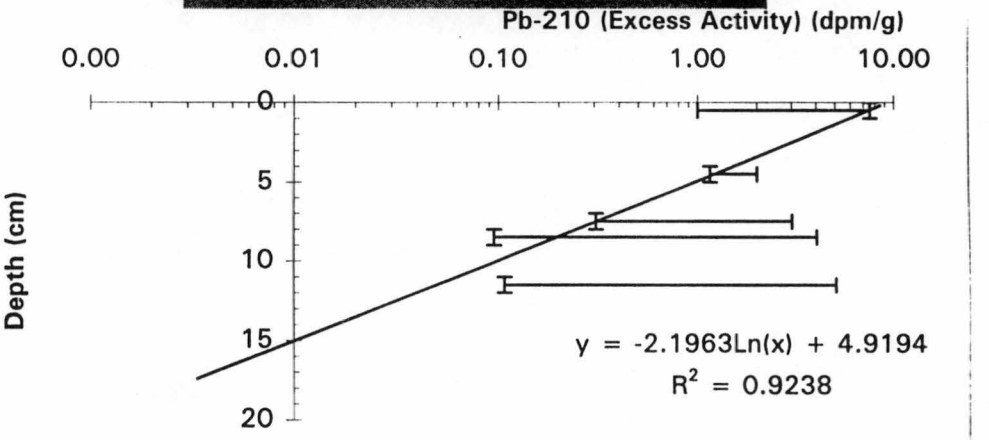
Plot Ra-226 Activity vs Depth



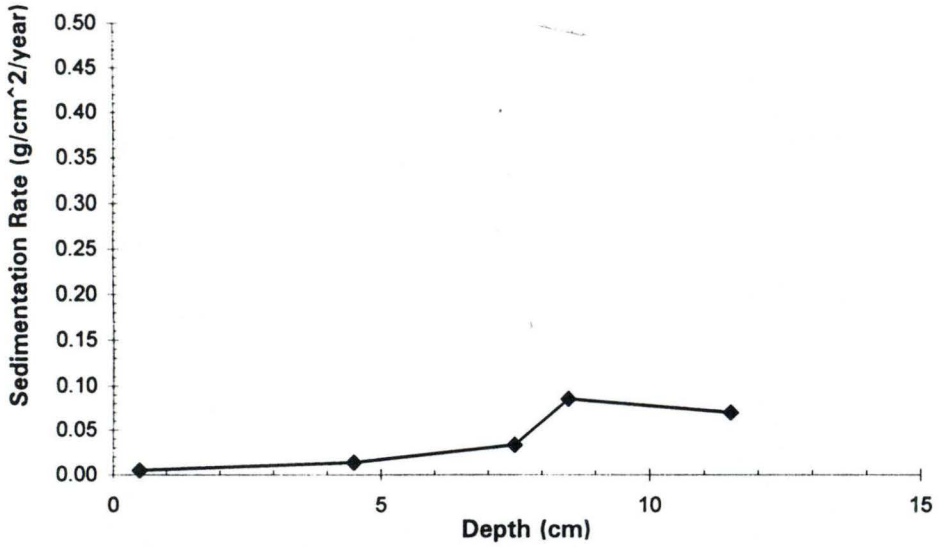
Plot Pb-210 (Excess Activity) vs Depth [Linear-Linear Scale]



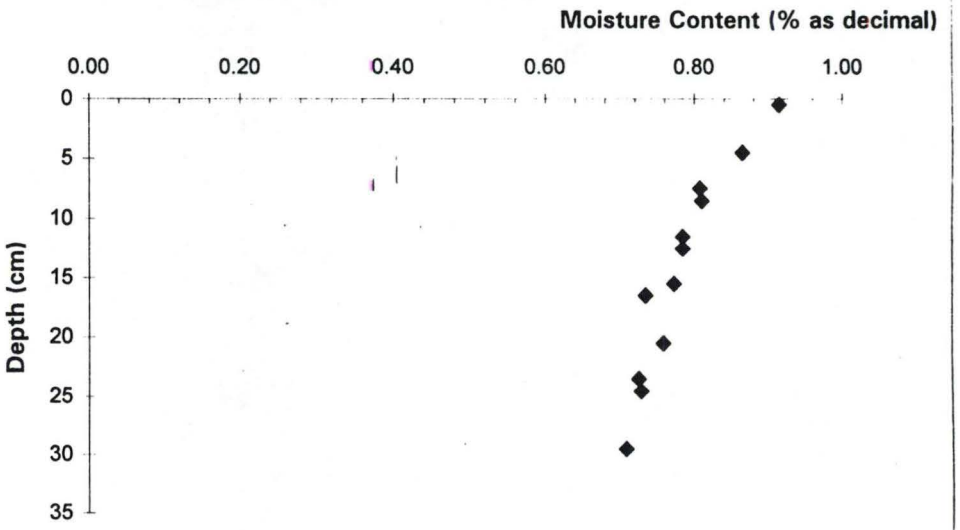
Plot Pb-210 (Excess Activity) vs Depth [Log-Linear Scale]



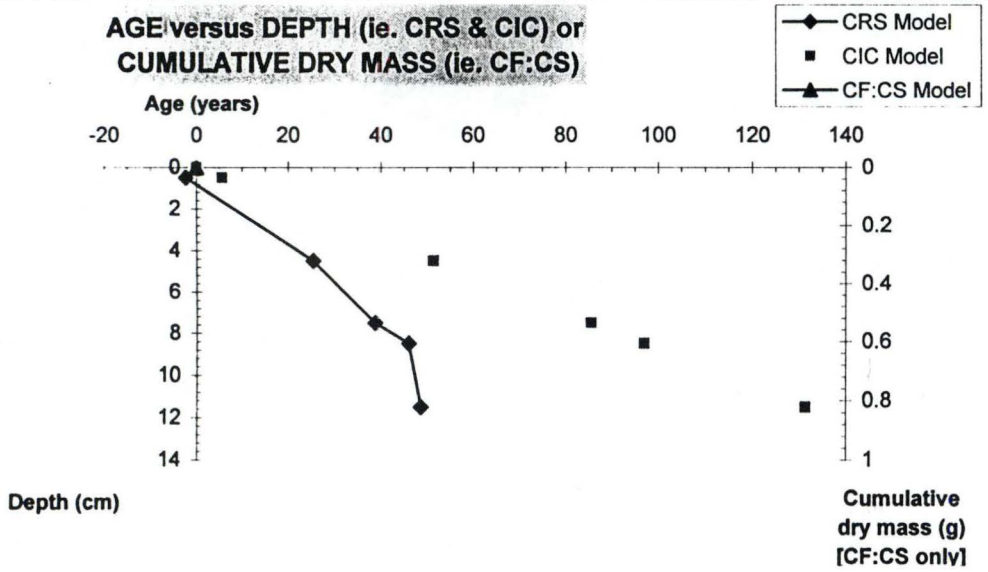
Sedimentation Rate (CRS Model) vs Depth



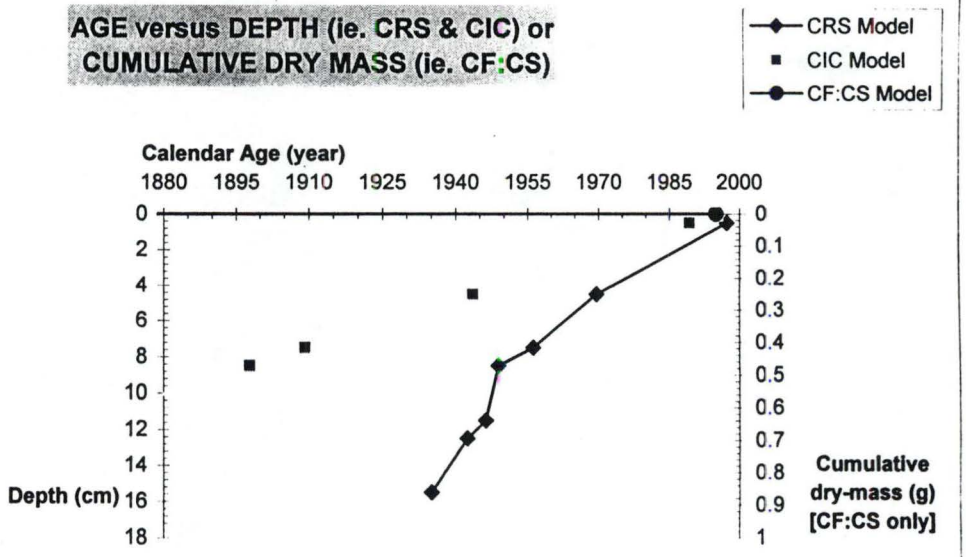
Moisture Content versus Depth



AGE versus DEPTH (ie. CRS & CIC) or CUMULATIVE DRY MASS (ie. CF:CS)



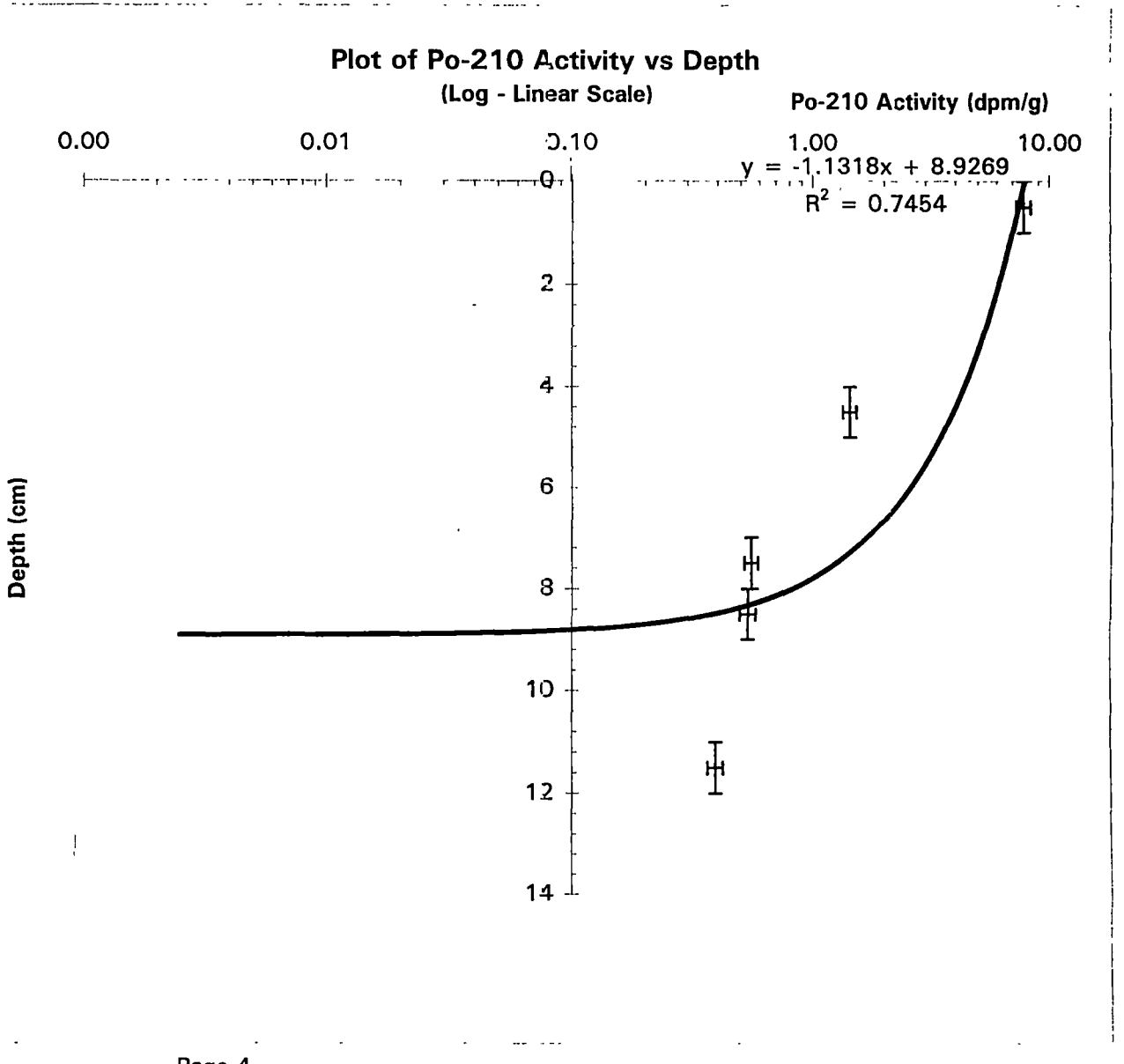
AGE versus DEPTH (ie. CRS & CIC) or CUMULATIVE DRY MASS (ie. CF:CS)



POLONIUM-210 DATA

Client: Andrew McMinn
Project: Ace Lake

LH Number	Po-210 (dpm/g)	Po-210 Error (dpm/g)	Depth (cm)	Depth Error (cm)
4404	7.8053	0.5420	0.5	0.5
4408	1.4323	0.0942	4.5	0.5
4411	0.5548	0.0362	7.5	0.5
4412	0.5354	0.0401	8.5	0.5
4415	0.3933	0.0290	11.5	0.5
4416	0.4774	0.0407	12.5	0.5
4419	0.3902	0.0184	15.5	0.5
4420	0.3789	0.0270	16.5	0.5
4424(2)	0.3697	0.0263	20.5	0.5
4427	0.3463	0.0144	23.5	0.5
4428	0.5169	0.0249	24.5	0.5
4432(2)	0.3335	0.0265	29.5	0.5
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0

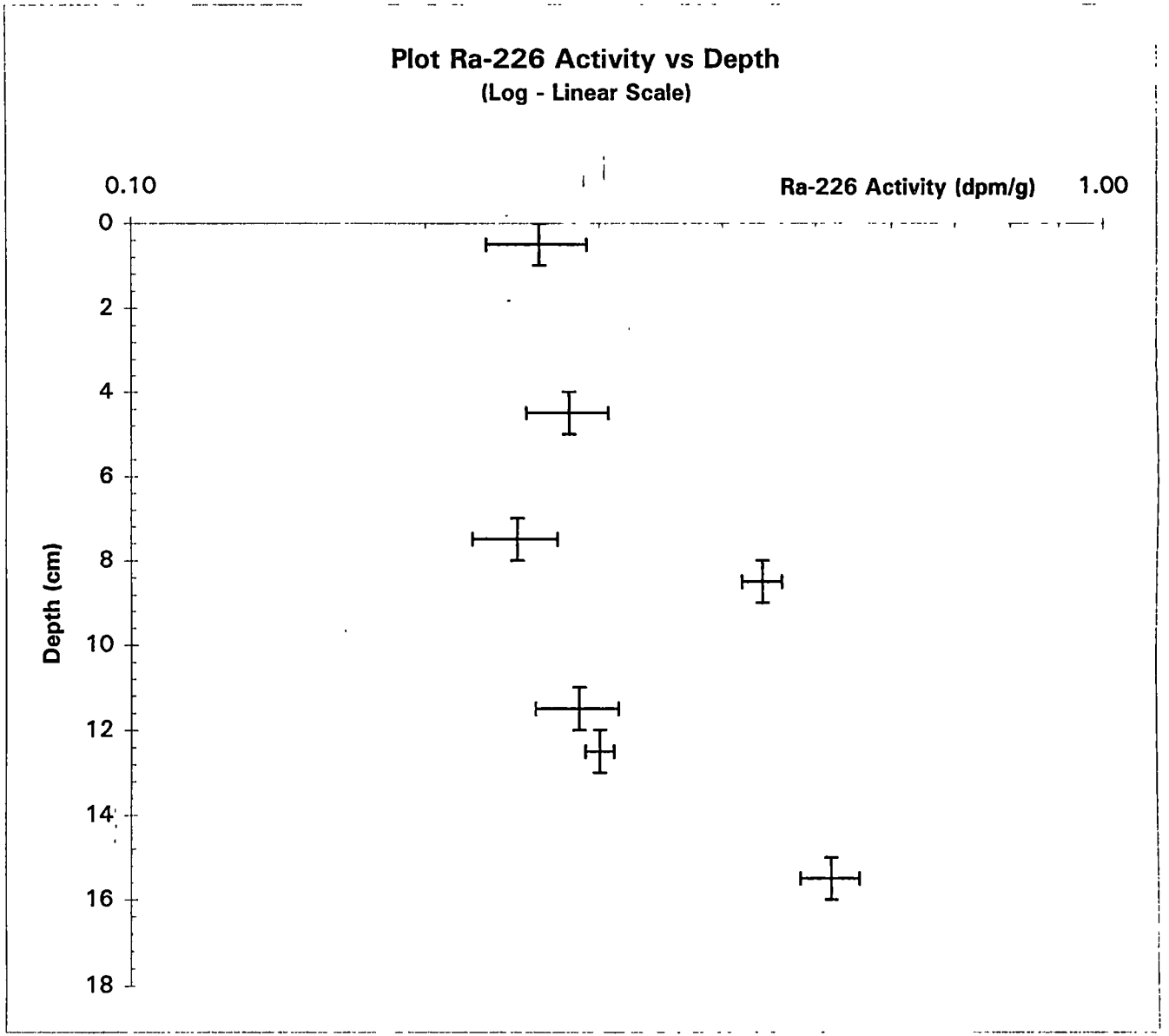


RADIUM-226 DATA

Client: Andrew McMinn

Project: Ace Lake

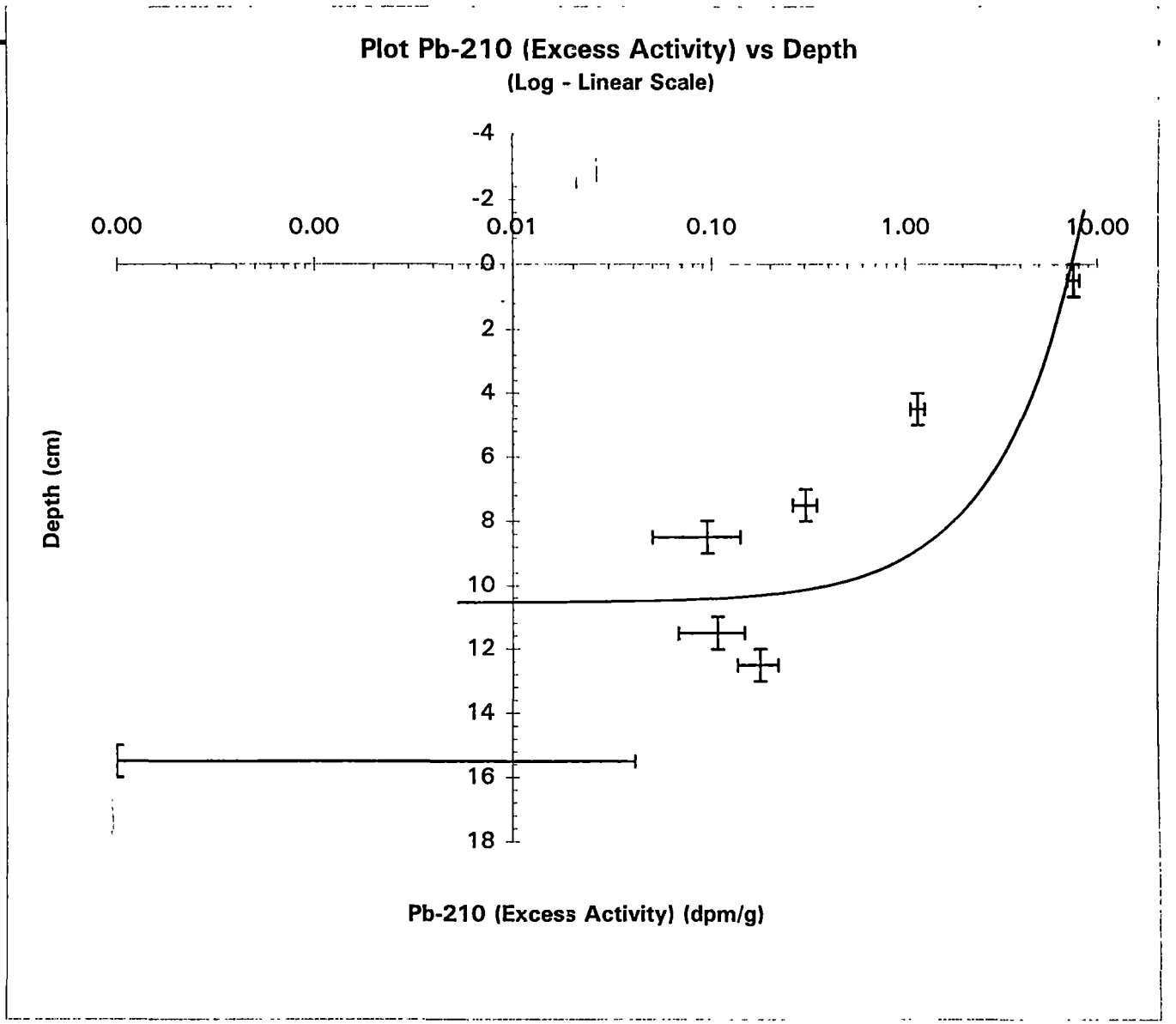
LH Number	Ra-226 (dpm/g)	Ra-226 Error (dpm/g)	Depth (cm)	Depth Error (cm)
4404	0.2609	0.0303	0.5	0.5
4408	0.2797	0.0267	4.5	0.5
4411	0.2476	0.0245	7.5	0.5
4412	0.4400	0.0210	8.5	0.5
4415	0.2859	0.0274	11.5	0.5
4416	0.3000	0.0100	12.5	0.5
4419	0.5180	0.0365	15.5	0.5
4420	0.3000	0.0100	16.5	0.5
4424(2)	0.2209	0.0153	20.5	0.5
4427	0.2485	0.0172	23.5	0.5
4428	0.3000	0.0100	24.5	0.5
4432(2)	0.4012	0.0238	29.5	0.5
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0
0	0.0000	0.0000	0	0



UNSUPPORTED LEAD-210 DATA

Client: Andrew McMinn
Project: Ace Lake

LH Number	Corrected Excess Pb-210 (dpm/g)	Excess Pb error (dpm/g)	Depth (cm)	Depth Error (cm)
4404	7.5444	0.5428	0.5	0.5
4408	1.1526	0.0979	4.5	0.5
4411	0.3072	0.0437	7.5	0.5
4412	0.0954	0.0453	8.5	0.5
4415	0.1074	0.0399	11.5	0.5
4416	0.1774	0.0419	12.5	0.5
4419	0.0001	0.0409	15.5	0.5
4420	0.0789	0.0288	16.5	0.5
4424(2)	0.1488	0.0304	20.5	0.5
4427	0.0978	0.0224	23.5	0.5
4428	0.2169	0.0268	24.5	0.5
4432(2)	0.0001	0.0356	29.5	0.5
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0
0	0.0001		0	0



CONSTANT RATE OF SUPPLY (CRS) MODEL

This model assumes that there is a constant net rate of supply of Pb-210 from the lake waters to the sediments, irrespective of changes which may have occured in the net dry mass sedimentation rate

Client: Andrew McMinn
Project: Ace Lake

Row number of last valid point: 13

d Depth (cm)	ρ Dry bulk density (g/cm^3)	C Excess Pb-210 Corrected Activity (dpm/g)	ρC (dpm/cm^3)	Σ ρC from depth (d) to the bottom Ax (dpm/cm^2)	Σ ρC from surface to the bottom Ao (dpm/cm^2)	Ao/Ax	ln(Ao/Ax)	1/λ.ln(Ao/Ax) Age of Sediment Layer (year)	Error in Age Estimate (year)	Calendar age from 1995	λ.Ax/C Sedimentation Rate at each Age (g/cm^2/year)
0.5	0.0898	7.5444	0.6777	1.1752	1.0950	0.9318	-0.0706	-2.2682	-0.1931	1997	0.00485
4.5	0.1470	1.1526	0.1695	0.4975	(from graph	2.2012	0.7890	25.3385	2.5609	1970	0.01344
7.5	0.2179	0.3072	0.0669	0.3280	next page)	3.3385	1.2055	38.7149	3.2217	1956	0.03325
8.5	0.2145	0.0954	0.0205	0.2611		4.1946	1.4338	46.0457	3.7203	1949	0.08521
11.5	0.2481	0.1074	0.0266	0.2406		4.5513	1.5154	48.6667	3.7971	1946	0.06976
12.5	0.2479	0.1774	0.0440	0.2140	Ln(2)/22.26	5.1181	1.6328	52.4357	3.9604	1943	0.03755
15.5	0.2640	0.0001	0.0000	0.1700	λ	6.4422	1.8629	59.8251	4.4820	1935	52.92857
16.5	0.3171	0.0789	0.0250	0.1700	(1/year)	6.4432	1.8630	59.8301	4.0601	1935	0.06707
20.5	0.2834	0.1488	0.0422	0.1449	0.03114	7.5554	2.0223	64.9436	4.2642	1930	0.03033
23.5	0.3298	0.0978	0.0323	0.1028		10.6563	2.3662	75.9876	5.2288	1919	0.03272
24.5	0.3249	0.2169	0.0705	0.0705		15.5309	2.7428	88.0843	6.7228	1907	0.01012
29.5	0.3528	0.0001	0.0000	0.0000	λ.Ao	#########	10.3428	332.1540	########	1663	0.01099
0	0.0000	0.0001	0.0000	0.0000	Mean Pb-210	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	supply rate	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	(dpm/cm^2/y)	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	0.0341	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	Average	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	Sedimentation	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	Rate by CRS	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	Model	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	(g/cm^2/year)	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000	0.0413	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000
0	0.0000	0.0001	0.0000	0.0000		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.00000

CRS MODEL (Continued)

To determine Ao [= Σ ρC from the surface to the bottom of the profile]
the Nat. Log of Ax [= Σ ρC from depth (d) to the bottom of the profile]
is plotted against depth and linear regression is used to find the equation
of the line which allows Ao to be derived from the intercept (b).

ln(Ax)
0.16141
-0.69823
-1.11475
-1.34302
-1.42463
-1.54200
-1.77209
-1.77225
-1.93148
-2.27537
-2.65205
-10.25206
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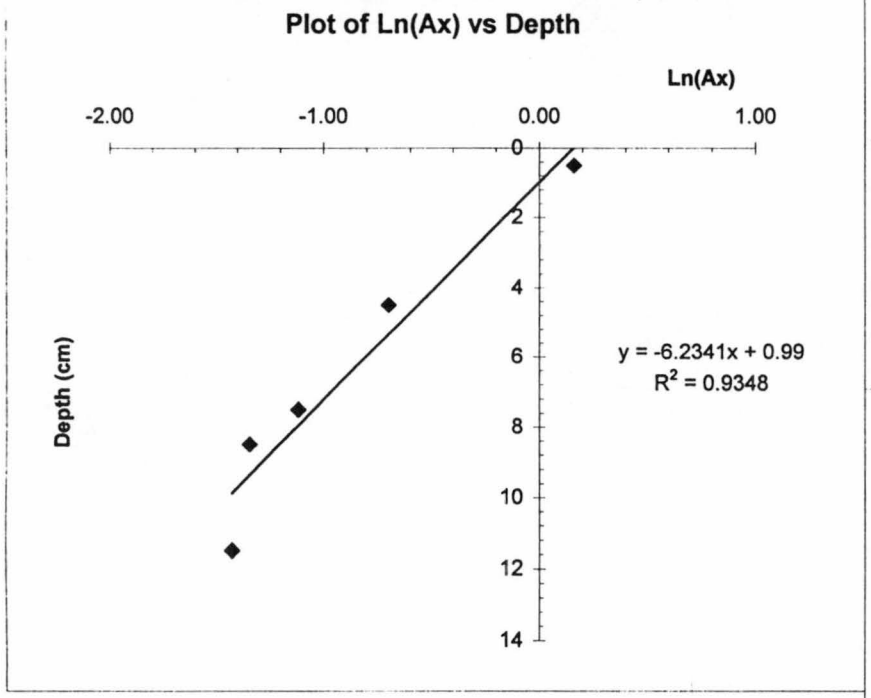
#NUM!

Number of data points displayed below should = 5

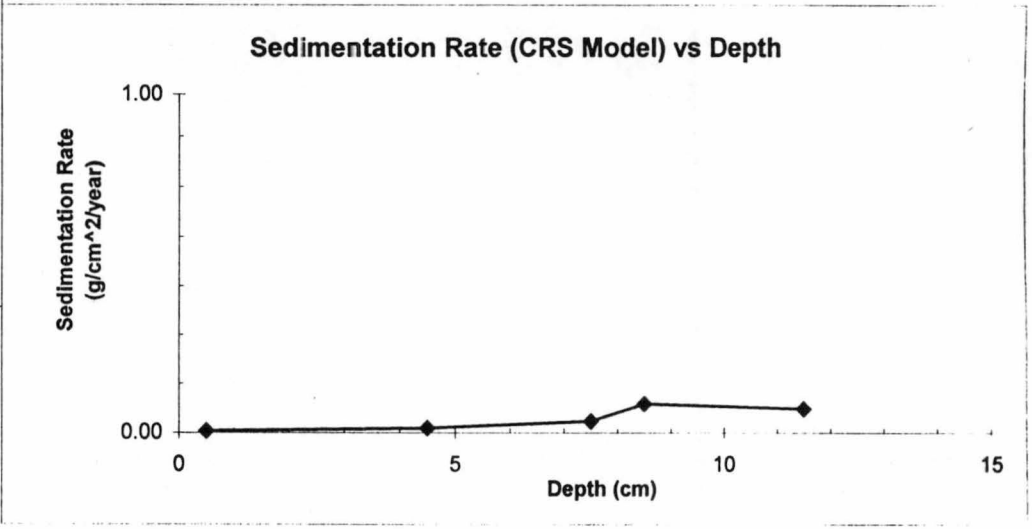


= = = = = = REGRESSION (y = mx + b) = = = = = =			
m_n ------->	-0.14994247	0.090782753	<-------- b
se_n ------->	0.022869551	0.171521633	<-------- se_b
r^2 ------->	0.934763738	0.191340392	<-------- se_y
F ------->	42.98669353	3	<-------- df
SSreg ->	1.573792094	0.109833437	<- SSresid

From linear regression the equation of the line is:
Ln (Ax) = -0.14994247 x depth + 0.090782753

When the depth = 0 (ie. at the sediment - water interface)
and hence Ao can be substituted for Ax the X-intercept is given by:
Ln (Ao) 0.090782753

Raising both sides of the equation to the power of "e" gives
Ao = 1.095031087 dpm/g



CONSTANT INITIAL CONCENTRATION (CIC) MODEL

Client: Andrew McMinn

Project: Ace Lake

This model assumes that each horizon in the sediment is derived from material having the same initial unsupported Pb-210 activity. This would be the case if the Pb-210 flux to the sediment-water interface and the sediment accumulation rate are both constant or if they change proportionally to maintain constant the initial unsupported Pb-210 activity

Ln(Excess corrected Pb-210) (dpm/g)	d Depth (cm)	d/(sed. rate) Age Of Sediment layer (y)	Error In Age Estimate	Calendar age from 1995
2.020806	0.5	5.7106	7.09111	1989
0.14202	4.5	51.3950	38.2643	1944
-1.180256	7.5	85.6584	63.3177	1909
-2.349677	8.5	97.0795	71.6954	1898
-2.231195	11.5	131.3428	96.86	1864
-1.729348	12.5	142.7639	105.254	1852
-9.21034	15.5	177.0273	130.448	1818
-2.539574	16.5	188.4484	138.849	1807
-1.905152	20.5	234.1329	172.458	1761
-2.324831	23.5	268.3962	197.67	1727
-1.528319	24.5	279.8173	206.074	1715
-9.21034	29.5	336.9229	248.1	1658
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0
-9.21034	0	0.0000	#DIV/0!	0

= = = = = = REGRESSION (y=mx + b) = = = = = =

m_n ------>	-0.355639	1.4403315	<------- b
se_n ---->	0.130906	1.0971954	<------ se_b
r^2 ------>	0.786796	0.6545319	<------ se_y
F ------>	7.380674	2	<-------- df
SSreg --->	3.16197	0.856824	<-- SSresid

For explanation of symbols and how this array works refer to last page of spreadsheet

(To "FIX" the regression formula hold down the SHIFT & CONTROL keys and then press ENTER

From linear regression the equation of the line is:

Ln(unsupported Pb-210) = -0.355639 x depth + 1.440332 .... [1]

Correlation coefficient = 0.787

When the depth = 0 (ie. at the sediment - water interface) the following holds: ln(Ao)

Ln(unsupported Pb-210) = 1.4403315

Raising both sides of the equation to the power of "e" gives Ao

unsupported Pb-210 = 4.2220953 dpm/g

After one half-life the activity will have decayed to half of this figure Ao/2

unsupported Pb-210 after 22.26 y = 2.1110476 dpm/g

Taking the natural log of both sides gives: ln(Ao/2)

Ln(unsupported Pb-210) = 0.7471843

Substituting this figure back into equation [1] and solving for d gives: $\{ln(Ao/2)-b\}/m_n$

depth after one half-life = 1.9490215 cm

Hence the sedimentation rate is: 1.9490215 22.26 0.09 cm/year

Multiply by mean particle density (g/cm^3) of 2.500 gives 0.22 g/cm^2/year

CONSTANT FLUX:CONSTANT SEDIMENTATION (CF:CS) MODEL

Client: Andrew McMinn
Project: Ace Lake

This model assumes that a constant flux of unsupported Pb-210 is coupled with an assumed constant dry-mass sedimentation rate

Ln(Excess corrected Pb-210) (dpm/g)	Total dry mass of slice (g)	m Cumulative dry mass of slice (g)	-m/(sed. rate) Age Of Sediment layer (y)	Calendar age from 1995
2.0208056		0	#NUM!	#NUM!
0.1420203		0	#NUM!	#NUM!
-1.180256		0	#NUM!	#NUM!
-2.349677		0	#NUM!	#NUM!
-2.231195		0	#NUM!	#NUM!
-1.729348		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-2.539574		0	#NUM!	#NUM!
-1.905152		0	#NUM!	#NUM!
-2.324831		0	#NUM!	#NUM!
-1.528319		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!
-9.21034		0	#NUM!	#NUM!

REGRESSION (y = mx + b)

m_n ---->	#NUM!	#NUM!	<---------- b
se_n ---->	#NUM!	#NUM!	<---------- se_b
r^2 ---->	#NUM!	#NUM!	<---------- se_y
F ---->	#NUM!	#NUM!	<---------- df
SSreg ---->	#NUM!	#NUM!	<---------- SSresid

For an explanation of the symbols and how the array works refer to the last page of this spreadsheet

From linear regression the equation of the line is:

Ln(unsupported Pb-210) = #NUM! x cum. mass + #NUM!

Correlation coefficient = #NUM!

When the cumulative dry mass = 0 (ie. at the sediment - water interface) we have:

Ln(unsupported Pb-210) = #NUM!

Raising both sides of the equation to the power of "e" gives

unsupported Pb-210 = #NUM! dpm/g

After one half-life the activity will have decayed to half of this figure

unsupported Pb-210 after 22.26 y = #NUM! dpm/g

Taking the natural log of both sides gives:

Ln(unsupported Pb-210) = #NUM!

Substituting this figure back into the equation of the line of best fit and solving for d gives:

cumulative mass after one half-life = #NUM! g

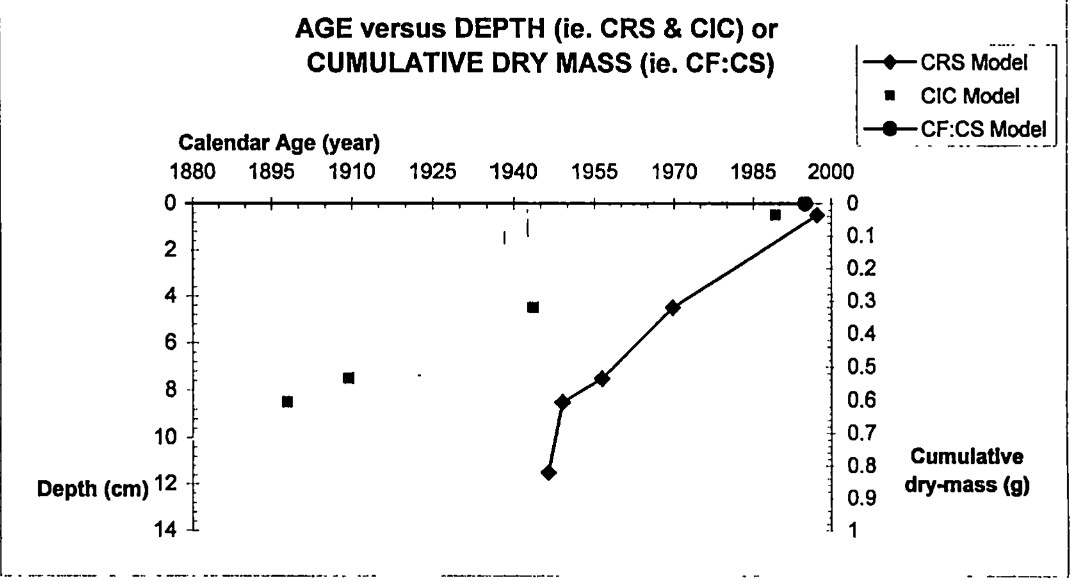
Hence the cumulative dry-mass sedimentation rate is:

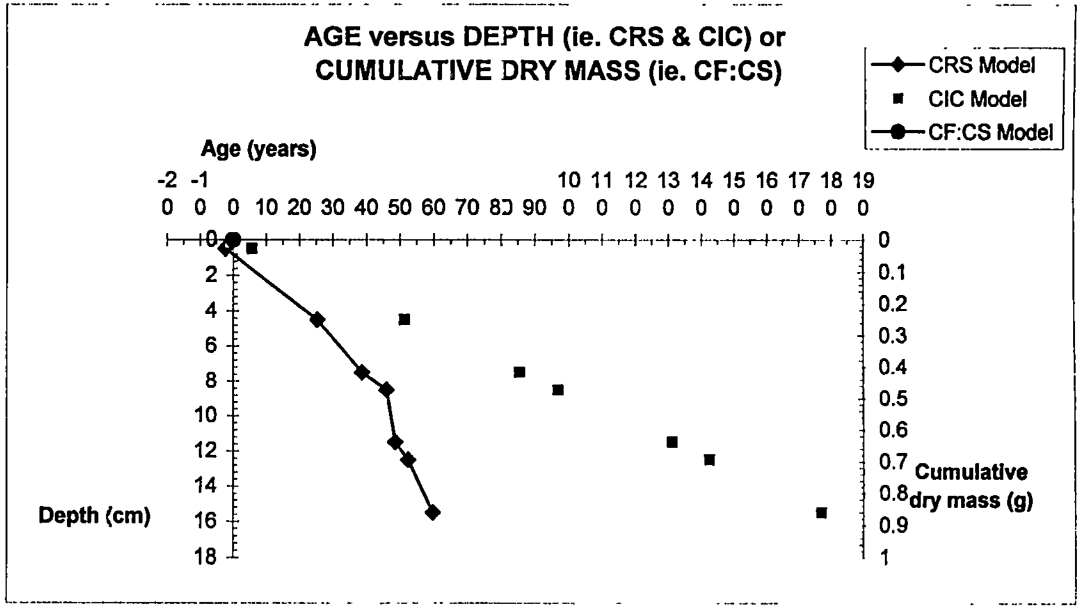
#NUM! 22.26 #NUM! g/year

CALCULATED AGES DERIVED FROM THE CRS, CIC & CF:CS MODELS

Client: Andrew McMinn
Project: Ace Lake

	Series 1 (◆)		Series 2 (■)		Series 3 (●)	
Depth (cm)	Model CRS (year)	Calendar age from 1995	Model CIC (year)	Calendar age from 1995	Model CF:CS (year)	Calendar age from 1995
0	0.0	1995	0.0	1995	0.0	1995
0.5	-2.3	1997	5.7	1989	#NUM!	#NUM!
4.5	25.4	1970	51.4	1944	#NUM!	#NUM!
7.5	38.8	1956	85.7	1909	#NUM!	#NUM!
8.5	46.1	1949	97.1	1898	#NUM!	#NUM!
11.5	48.8	1946	131.3	1864	#NUM!	#NUM!
12.5	52.5	1943	142.8	1852	#NUM!	#NUM!
15.5	59.9	1935	177.0	1818	#NUM!	#NUM!
16.5	59.9	1935	188.4	1807	#NUM!	#NUM!
20.5	65.1	1930	234.1	1761	#NUM!	#NUM!
23.5	76.1	1919	268.4	1727	#NUM!	#NUM!
24.5	88.2	1907	279.8	1715	#NUM!	#NUM!
29.5	332.8	1663	336.9	1658	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!
0	0.0	0	0.0	0	#NUM!	#NUM!





ERROR CALCULATIONS FOR THE CRS MODEL

If the error in **a** is **x** and the error in **b** is **y** (ie. **a** +/- **x** and **b** +/- **y**)

then the error calculation of the following operations are:

a + b	(a+b)	+/- SQRT(x^2 + y^2)
a - b	(a-b)	+/- SQRT(x^2 + y^2)
a . b	(ab)	+/- ((ab)(SQRT{[x/a]^2 + [y/b]^2}))
a / b	(a/b)	+/- ((ab)(SQRT{[x/a]^2 + [y/b]^2}))

You must adjust the SUM length for Ax to include the full data set (ie. both supported and unsupported)

Excess Pb-210 error (dpm/g)	Dry bulk density error (g/cm^3)							
Ci	ρi	ρci	ρci^2	Ax	Ao/Ax	Ln(Ao/Ax)	λ	Age estimate
0.5428	0.00000	0.048763	0.002378	0.05949	0.066707	0.066706513	0.0003077	-0.19307027
0.0979	0.00000	0.014396	0.000207	0.03407	0.187474	0.079360608		2.56089143
0.0437	0.00000	0.009525	9.07E-05	0.03088	0.356885	0.099609068		3.22168691
0.0453	0.00000	0.009708	9.42E-05	0.02938	0.517577	0.114976549		3.72033981
0.0399	0.00000	0.009897	9.8E-05	0.02773	0.57286	0.11728365		3.79707968
0.0419	0.00000	0.010389	0.000108	0.0259	0.67154	0.122261934		3.96042015
0.0409	0.00000	0.010791	0.000116	0.02372	0.956474	0.138344809		4.4820299
0.0288	0.00000	0.009129	8.33E-05	0.02113	0.864876	0.12507664		4.06005089
0.0304	0.00000	0.008624	7.44E-05	0.01905	1.064372	0.131269383		4.26421889
0.0224	0.00000	0.007398	5.47E-05	0.01699	1.842704	0.161128973		5.22877256
0.0268	0.00000	0.008718	7.6E-05	0.0153	3.45978	0.207576854		6.72280793
0.0356	0.00000	0.012568	0.000158	0.01257	11053914	331.8975548		10658.6886
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0!
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0
	0.00000	#VALUE!	#VALUE!	#VALUE!	#DIV/0!	#DIV/0!		#DIV/0

ERROR CALCULATIONS FOR THE CIC MODEL

$SQRT[(se_n)^2(dF+2)]$	Error in Age
b	estimate
0.2618	7.09111485
	38.2643295
	63.3177221
	71.6954248
	96.8599966
	105.254496
	130.448396
	138.848781
	172.457702
	197.669507
	206.074099
	248.100477
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!
	#DIV/0!

ERROR CALCULATIONS FOR THE CS:CF MODEL

OTHER

Corrected Excess Pb-210 (dpm/g)
7.5444
1.1526
0.3072
0.0954
0.1074
0.1774
0.0001
0.0789
0.1488
0.0978
0.2169
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001
0.0001

This operation checks to see if the value for unsupported Pb-210 (which is calculated from the activity of Po-210 minus the activity of Ra-226) is greater than zero. If the figure is less than or equal to zero it assigns a value of 0.0001 so that proceeding operations which take the natural logarithm of this number do not result in error messages.

DETERMINATION OF WATER CONTENT

Client: Andrew McMinn

Project: Ace Lake

Error in reading balance: 0.00002

LH Number	Depth (cm)	Mass of empty beaker (g)	Mass of beaker and wet sample (g)	Mass of beaker and dry sample (g)	M_{wet} Mass of wet sample only (g)	M_{dry} Mass of dry sample only (g)	M_{water} Mass of water (g)	M_{water} / M_{wet} Moisture Content (w) % (as decimal)
4404	0.5	83.8836	91.86980	84.56430	7.9862	0.6807	7.3055	0.91477
4408	4.5	80.9067	96.35970	82.99460	15.453	2.0879	13.3651	0.86489
4411	7.5	90.49970	109.10790	94.08570	18.6082	3.586	15.0222	0.80729
4412	8.5	83.4646	100.67390	86.73460	17.2093	3.27	13.9393	0.80999
4415	11.5	101.01870	118.98770	104.89880	17.969	3.8801	14.0889	0.78407
4416	12.5	77.9990	98.86110	82.50100	20.8621	4.502	16.3601	0.78420
4419	15.5	90.40570	110.08720	94.89100	19.6815	4.4853	15.1962	0.77211
4420	16.5	81.8998	101.62210	87.15360	19.7223	5.2538	14.4685	0.73361
4424(2)	20.5	85.1686	107.20290	90.50620	22.0343	5.3376	16.6967	0.75776
4427	23.5	91.26460	111.21800	96.75780	19.9534	5.4932	14.4602	0.72470
4428	24.5	81.1591	101.74950	86.75760	20.5904	5.5985	14.9919	0.72810
4432(2)	29.5	74.1944	96.22470	80.60960	22.0303	6.4152	15.6151	0.70880
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000
0	0				0	0	0	0.00000

Error calculations for water content

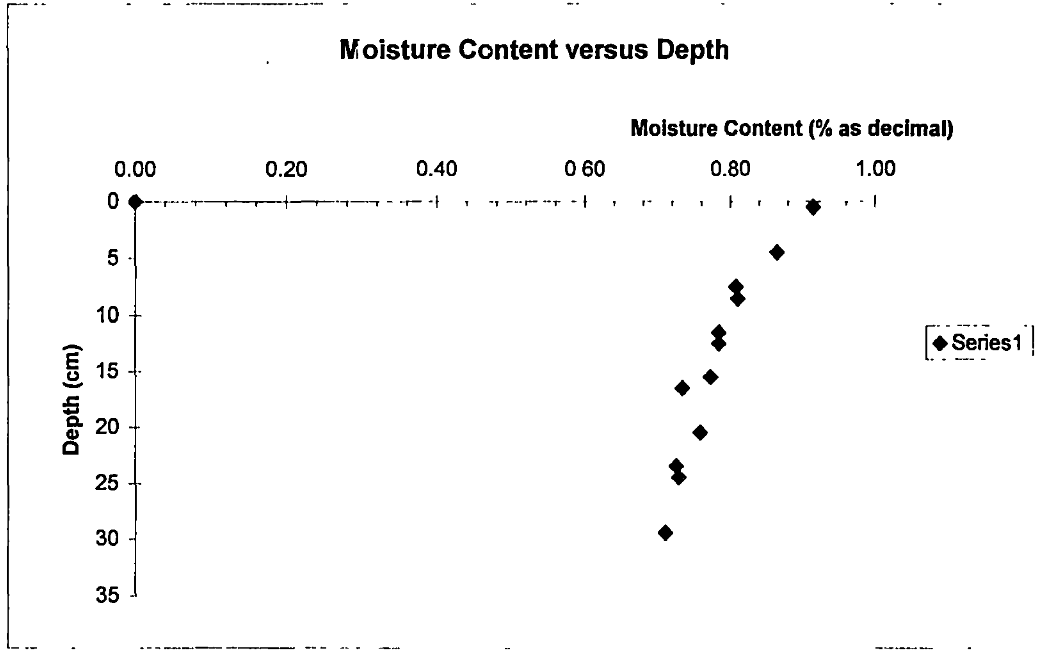
If the error in a is x and the error in b is y (ie. a +/- x and b +/- y) then the error calculation of the following operations are:

a + b	(a+b)	+/-	SQRT(x^2 + y^2)
a - b	(a-b)	+/-	SQRT(x^2 + y^2)
a . b	(ab)	+/-	((ab)(SQRT{[x/a]^2 + [y/b]^2}))
a / b	(a/b)	+/-	((ab)(SQRT{[x/a]^2 + [y/b]^2}))

Beaker Mass Error (g)	Beaker & wet sample error (g)	Beaker & dry sample error (g)	Wet sample error (g)	Dry sample error (g)	Water mass error (g)	Moisture content error
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	5.97E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	3.03E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.48E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.68E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.55E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.19E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.32E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.28E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.06E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.25E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.19E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	2.03E-06
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!
0.00002	0.00002	0.00002	2.83E-05	2.83E-05	0.00004	#DIV/0!

Moisture Content Data

Typically it is found that at the sediment-water interface the moisture content will approach 100% (ie. 1.00 on the graph) At increasing depths the soil is subjected to a higher rate of compaction which will result in lower moisture contents



DETERMINATION OF SEDIMENT SPECIFIC GRAVITY

Client: Andrew McMinn
Project: Ace Lake

Volumetric flask capacity (ml) = 100
Mean slice density (g/cm^3) = 2.500

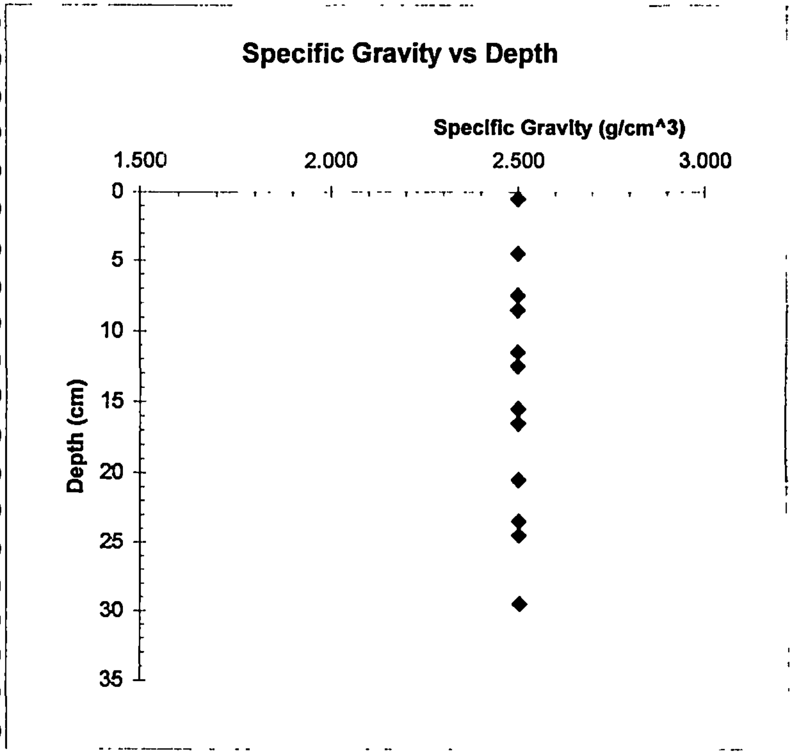
M_{soil} = ($M_{flask\&soil}$ - M_{flask})

M_{water} = ($M_{flask,soil\&water}$ - $M_{flask\&soil}$)

V_{water} = M_{water} [because density = 1g/ml]

V_{soil} = (100 - V_{water})
[ie. flask volume = 100 ml]

LH Number	M_{flask} Mass of dry flask (g)	$M_{flask\&soil}$ Mass of flask + soil (g)	$M_{flask,soil\&water}$ Mass of flask, soil + water (g)	M_{soil} Mass of soil (g)	M_{water} Mass of water (g)	V_{soil} Volume of soil (cm^3)	ρ Dry mass / wet volume ratio (g/cm^3)
4404	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4408	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4411	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4412	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4415	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4416	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4419	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4420	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4424(2)	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4427	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4428	100.00	350.00	350.00	250.00	0.00	100.00	2.500
4432(2)	100.00	350.00	350.00	250.00	0.00	100.00	2.500
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000
0				0.00	0.00	100.00	0.000

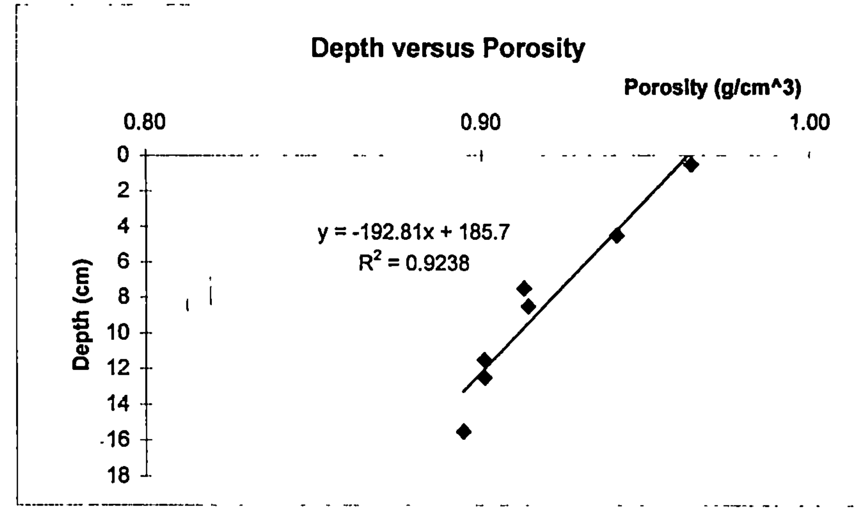


DETERMINATION OF POROSITY AND BULK DRY DENSITY

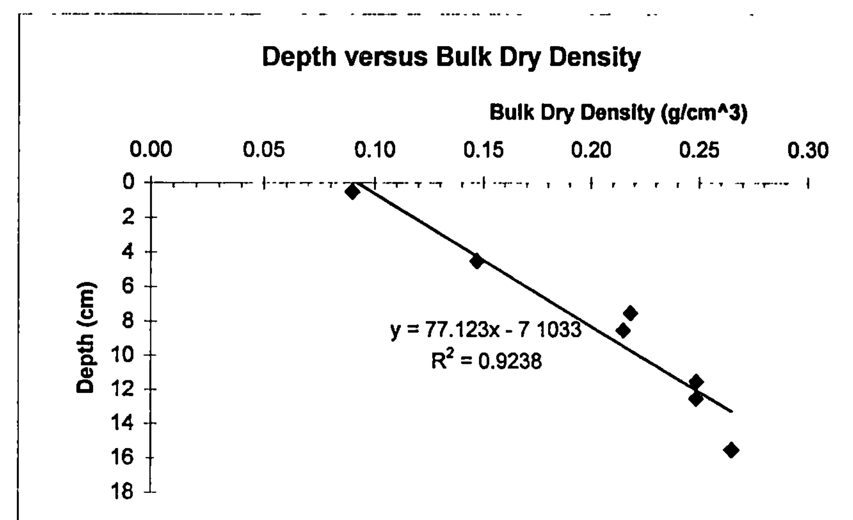
Client: Andrew McMinn

Project: Ace Lake

LH Number	Depth (cm)	w Moisture Content (%) (as decimal)	(1-w)/ρ cm^3/g	w+(1-w)/ρ cm^3/g	w/[w+(1-w)/ρ] Porosity Φ (g/cm^3)	ρ (1-Φ) Bulk Dry Density (g/cm^3)	Bulk Dry Density error
4404	0.5	0.9148	0.0341	0.9489	0.96407	0.08983	
4408	4.5	0.8649	0.0540	0.9189	0.94119	0.14703	
4411	7.5	0.8073	0.0771	0.8844	0.91284	0.21791	
4412	8.5	0.8100	0.0760	0.8860	0.91421	0.21446	
4415	11.5	0.7841	0.0864	0.8704	0.90077	0.24807	
4416	12.5	0.7842	0.0863	0.8705	0.90084	0.24790	
4419	15.5	0.7721	0.0912	0.8633	0.89440	0.26399	
4420	16.5	0.7336	0.1066	0.8402	0.87317	0.31707	
4424(2)	20.5	0.7578	0.0969	0.8547	0.88663	0.28344	
4427	23.5	0.7247	0.1101	0.8348	0.86809	0.32977	
4428	24.5	0.7281	0.1088	0.8369	0.87004	0.32490	
4432(2)	29.5	0.7088	0.1165	0.8253	0.85886	0.35285	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	
0	0	0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.00000	



Typically a graph of Porosity data will show a region of linear decline of Porosity with depth over the 'Pb-210 sediment ranges followed by a region of essentially co Porosity (ie. independent of depth)



ty (g/cm^3)
1.00

atable'
stant

:m^3)
25 0.30

Notes on how the regression function works

This function uses the "least squares" method to calculate a straight line that best fits the data and returns an array that describes the line. The equation of the line is in the form of:

$$y = m_1x_1 + m_2x_2 + \ldots\ldots\ldots\ldots + b \quad \text{or} \quad y = mx + b$$

The syntax of the function is:

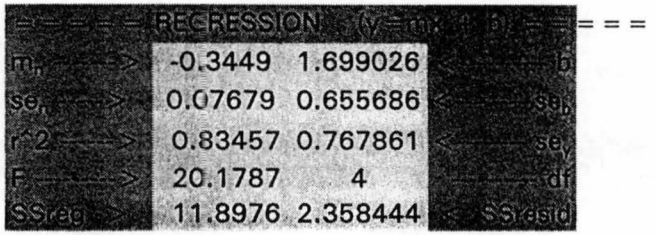
LINEST(known_y's, known_x's, const, stats)

Where **known_y's** are the set of values which we already know in the relationship y = mx + b. In our case this refers to the values for Ln(unsupported Pb-210). The **known_x's** in our case refer to either the depth of the sediment (CRS & CIC model) or the cumulative dry-mass (CF:CS model). **const** is a logical value specifying whether to force the constant b to equal zero. If the value for **const** is true (ie. 1) then b is calculated normally.
stats is a logical value specifying whether to return additional regression statistics. If the value for **const** is true then the following regression statistics are returned:

$se_1, se_2, \ldots\ldots, se_n$	The standard error values for the coefficients $m_1, m_2, \ldots\ldots, m_n$
se_b	The standard error value for the constant b
r^2	Correlation coefficient (1 = perfect correlation, 0 = no correlation)
se_y	The standard error of the y estimate
F	The F statistic is used to determine whether th observed relationship between the dependent a and independent variables occurs by chance
dF	The degrees of freedom
SSreg	The regression sum of squares
SSresid	The resisual sum of squares

The following is the regression function used in the CIC model

{=LINEST(BY$9:BY14,BZ$9:BZ14,1,1)}



It is important to note that the regression range must be adjusted to include only those values of ln(unsupported Pb-210) which are above the baseline of supported Pb-210. Note that this is usually NOT the full data set but rather the data range which includes the values of ln(unsupported Pb-210) which are non constant. The best way to determine this is to look at the graph of ln(unsopported Pb-210) vs D

Remember that to FIX the equation into the array box you need to highlight all of the yellow cells and then hold down the SHIFT and CONTROL keys and then press ENTER

Other Comments

Sedimentation Rate Units

nd

It took me a while to come to terms with the fact that you don't need to adust the sedimentation rate (g/cm^2/year) to take into account the surface area of the core (= πr^2) .

In the CRC Model the sedimentation rate is derived in part from:

d	ρ	C	ρC	Σ ρC from	Σ ρC from
Depth	Dry bulk density	Excess Pb-210 Corrected Activity		depth (d) to the bottom Ax	surface to the bottom Ao
(cm)	(g/cm^3)	(dpm/g)	(dpm/cm^3)	(dpm/cm^2)	(dpm/cm^2)

A simple explanation is that because both ρ and C are variables that are not dependent on the size of the sample, the product ρC will also be independent of sample size. When ρC is summed from depth (d) to the bottom of the profile the units change to (dpm/cm^2) because we have (cm)(dpm/cm^3) where the cm cancels to cm^2 on the denominator. The resulting units for Ax and Ao, which are expressed as activity per unit area (dpm/cm^2), are consequently not related to the surface area of the core and thus it would be incorrect to try and adjust the sedimentation rate to take into account this parameter.

epth

Sediment Specific Gravity Determinations

A simple Pycnometer is used to measure the dry mass to wet volume ratio for each slice of the core.

The method involves the following steps:

1. Weigh accurately a clean **dry** 100ml volumetric flask.
2. Weigh accurately approximately 5 to 10 g of oven dried ground soil into the 100ml volumetric flask.
3. Add 1 or 2 drops of non-foaming wetting agent to the flask and make up the volume to 100ml with distilled water. Re-weigh the flask.

Porosity Calculations

There are two possibilities namely a constant sediment Porosity or a variable sediment Porosity

Case (1) For a constant sediment Porosity the following equation will hold:

$$W = (1 - \Phi) \cdot V_{tot} \cdot \rho$$

where W = dry weight of sediment (g)
ρ = density of dry sediment (g/cm^3)
V_{tot} = total volume of sediment (cm^3)

Note that $V_{tot} = s \cdot z$ where s is the surface area (usually 1 cm^2) and z is the length of the core

Case (2) For a variable sediment Porosity where Φ is some function of d the above function becomes:

$$dW = (1 - \Phi_d) \cdot s \cdot \rho \, dz$$

or over any depth interval z_1 to z_2