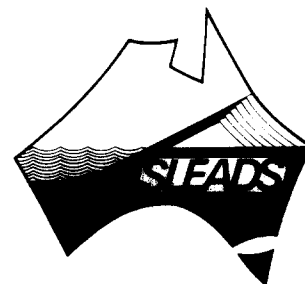


Sedimentological and stable-isotope evolution of lakes in the Vestfold Hills, Antarctica



Michael I. Bird^a, Allan R. Chivas^a, Christopher J. Radnell^a and Harry R. Burton^b

^aResearch School of Earth Sciences, The Australian National University, GPO Box 4, Canberra, ACT 2601, Australia

^bAntarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia

(Received May 27, 1988; revised and accepted July 6, 1990)

ABSTRACT

Bird, M.I., Chivas, A.R., Radnell, C.J. and Burton, H.R., 1991. Sedimentological and stable-isotope evolution of lakes in the Vestfold Hills, Antarctica. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 84: 109–130.

The sedimentological, chemical and isotopic characteristics of sediment cores from three slightly saline to hypersaline lakes (Highway, Ace and Organic Lakes) and two marine inlets (Ellis Fjord and Tainaya Bay) in the Vestfold Hills, Antarctica, have been examined.

Sections of the cores deposited in marine environments are characterized by uniform, regularly laminated, fine-grained, organic-rich sediments, with uniform organic $\delta^{13}\text{C}$ values (-18.0 to -19.4‰ vs. PDB) and sulfur contents. In contrast, sediments deposited in lacustrine environments are extremely heterogeneous, varying from finely laminated mat-like sequences to poorly sorted clastic-rich sediments. Authigenic monohydrocalcite and aragonite occur in some lake sediments.

The $\delta^{13}\text{C}$ values of organic matter in the lacustrine sediments exhibit an extremely wide range (-10.5 to -25.3‰) that can be related to variations in physico-chemical conditions in the lake waters. Strongly negative organic- $\delta^{13}\text{C}$ values coupled with high sulfur contents are indicative of an anoxic zone in the overlying lake waters, whereas less negative organic- $\delta^{13}\text{C}$ values coupled with low sulfur contents are indicative of well-mixed oxic conditions. Particularly high organic- $\delta^{13}\text{C}$ values result during high levels of microbial activity in the lakes, due to high rates of photosynthetic CO_2 fixation. The large shifts in organic- $\delta^{13}\text{C}$ are not necessarily accompanied by any change in macroscopic sedimentological characteristics, illustrating the utility of isotopic investigations in these environments. The $\delta^{13}\text{C}$ composition of authigenic carbonate in hypersaline Organic Lake sediments provides a record of changes in palaeoproductivity, while the $\delta^{18}\text{O}$ of the carbonate provides information on rates of meltwater input and evaporation in the lake.

^{14}C -dating suggests that Highway Lake was isolated from the sea by isostatic uplift at least 4600 yr before present (B.P.) whereas Organic Lake was isolated at approximately 2700 yr B.P. Apparent emergence rates calculated from the ^{14}C ages range from 1.0 to 2.1 mm yr^{-1} . The 'reservoir effect' in the lacustrine and marine environments is variable, but probably does not exceed ~ 1000 yr in any of the lakes examined.

Introduction

The Vestfold Hills, Princess Elizabeth Land, form one of a number of rocky, ice-free 'oases' which occur at intervals along the margin of the East Antarctic ice-sheet (Fig.1). Following the retreat of the continental ice-sheet from the region approximately 8000 yr B.P. (Adamson and Pickard, 1986b), isostatic rebound led to the gradual

emergence of the land from beneath the encroaching ocean. As a result, seawater became trapped in many of the depressions which occur across the Hills (McLeod, 1964; Burton, 1981). Today, some of these trapped and now highly evaporated water bodies form hypersaline lakes, while flushing out of the relict seawater by glacial meltwaters in other cases has led to the formation of lakes of very low salinity (Pickard et al., 1986). Fjords still penetrate

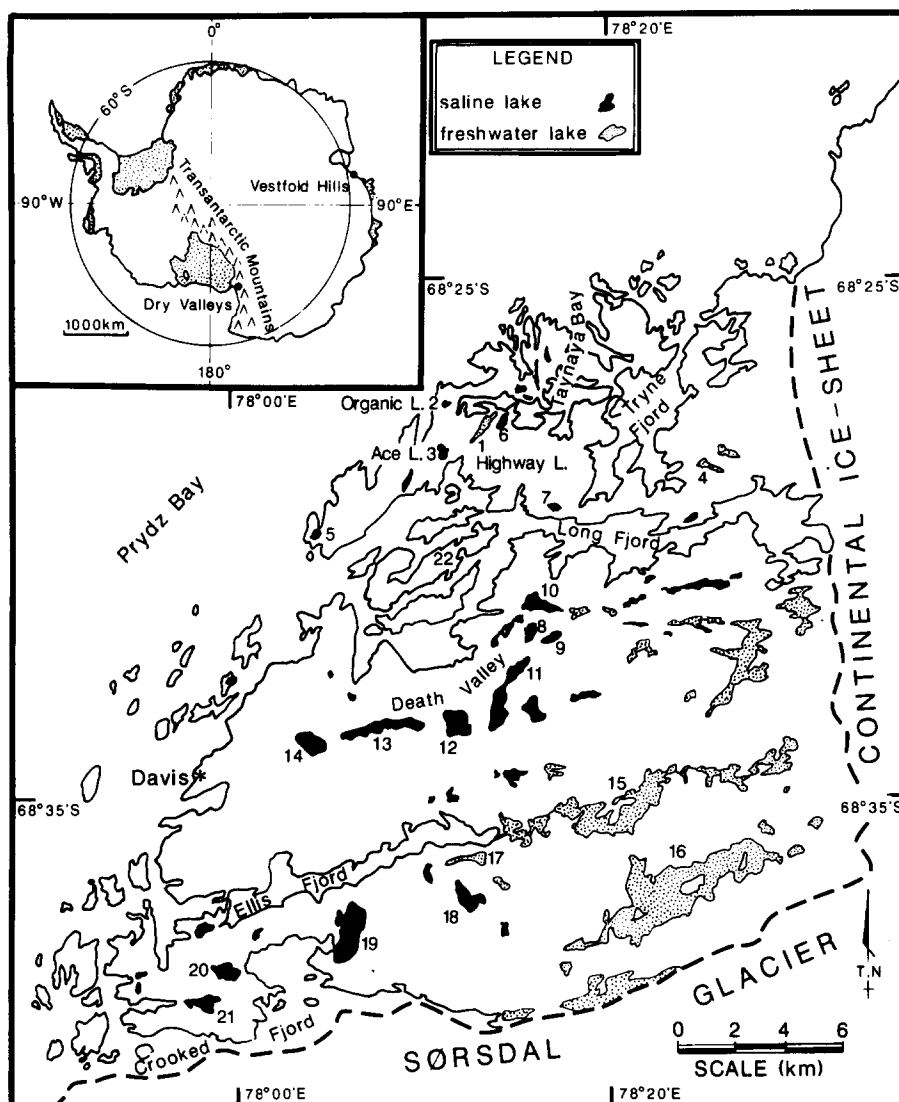


Fig.1. Location diagram for the Vestfold Hills, eastern Antarctica, indicating major topographic features. 1= Highway L., 2= Organic L., 3= Ace L., 4= Lichen Valley, 5= Rookery L., 6= Pendant L., 7= L. Abraxas, 8= Shield L., 9= Oval L., 10= Ekho L., 11= Club L., 12= Deep L., 13= L. Stinear, 14= L. Dingle, 15= Druzhby L., 16= Crooked L., 17= Watts L., 18= Lebed' L., 19= Burton L., 20= Clear L., 21= Laternula L., 22= Partizan Island.

deeply into the area, and as isostatic rebound continues, these will gradually be isolated from the sea to form new lakes.

Bedrock in the region consists of Archaean amphibolite to granulite facies gneisses, cut by Proterozoic basaltic dykes (Oliver et al., 1982; Collerson and Sheraton, 1986). The basement rocks, which are sparsely vegetated by algae, mosses and lichens, form a low-lying, rugged topography with a maximum elevation of 157 m

a.s.l. (Adamson and Pickard, 1986a). Glacial landforms dominate the geomorphology of the Vestfold Hills (Adamson and Pickard, 1986a) and prominent relict marine terraces, most approximately 6000 yr B.P. in age and now at about 6 m a.s.l., testify to the marine conditions prevailing in the Vestfold Hills following the retreat of the ice-sheet in the early Holocene (Peterson et al., 1988). The climate of the region is arid and relatively mild (mean annual temperature of -10.2°C), due to

warming of the region by the large area of exposed low-albedo bedrock (Burton and Campbell, 1980; Streten, 1986).

More than 150 lakes dot the 400 km² of the Vestfold Hills, exhibiting a wide range of sizes, depths, salinities and histories. Burton (1981) provides a review of the chemistry, physics and evolution of Antarctic lakes, including those of the Vestfold Hills. Conditions in the lakes, except in hypersaline lakes such as Deep Lake (salinity ~270 g l⁻¹), are less harsh than on land and as a result many lakes support an abundant flora and invertebrate fauna, although species diversity is lower than in comparable temperate lakes (Wright and Burton, 1981). Algae, cyanobacteria, bacteria and mosses form the bulk of the biomass in most lakes.

Studies of individual lakes and fjords in the Vestfold hills have focused particularly on the saline and hypersaline lakes. Detailed published chemical and physical data are available from Deep Lake (Barker, 1981), Ace Lake (Burton, 1980; Hand and Burton, 1981), Organic Lake (Franzmann et al., 1987) and Ellis Fjord (Gallagher and Burton, 1988). Surveys of species diversities, primary production rates, microbial sulfate-reduction rates, methane production, pigment and lipid compositions and annual cycles of biological activity have also been carried out in some of the above lakes (Burton and Barker, 1978; Burton, 1980; Hand, 1980; Hand and Burton, 1981; Volkman et al., 1986, 1988; Bayly and Burton, 1987; Franzmann et al., 1987; Burch, 1988).

In contrast to the volume of data available for the modern lacustrine environment, there has been comparatively little attention paid to the sedimentary record of the lakes which will contain a record of biological and chemical changes. Pickard et al. (1986) have documented the evolution of Watts Lake from a marine inlet about 4700–8000 yr B.P. to a freshwater lake using geomorphological evidence and the sedimentary record now exposed in the lake catchment area; however, no lake bottom sediments were examined. Volkman et al. (1986) present the only published study of a sediment core from a lake in the Vestfold Hills. The core, from Ace Lake, was analysed for bacterial and algal hydrocarbons, and the existence of

several changes from oxic to anoxic conditions in the lake in the past inferred from the hydrocarbon distributions down the core.

In this paper we present data from five sediment cores on the sedimentological and isotopic histories of three lakes (Organic, Ace and Highway Lakes) and two marine inlets (Ellis Fjord and Taynaya Bay) in the Vestfold Hills. The lakes are located within a few kilometres of each other on Long Peninsula (Fig. 1) and vary in salinity from slightly saline (Highway) to saline (Ace) to hypersaline (Organic). Constraints on the timing of major events in the evolution of the lakes are provided by the ¹⁴C-dating of organic matter and authigenic calcium carbonate in the cores. The dates can also be used to infer sedimentation rates in the lakes and the rate of emergence of the region.

Experimental techniques

Cores were collected by members of the Australian Antarctic Division, through the ice cover, using a Zullig corer, and stored at -18°C in their PVC core tube until extruded for sampling. Cores were cut in half lengthwise for inspection and then into 5–10 cm lengths, in a cold-room at -4°C. A quarter of each sample was weighed then dried at 105°C, and the weight loss accompanying drying used to calculate the water content.

An amount of 0.5–1.0 g of the dried material was repeatedly washed with de-ionized water, redried, and the soluble salt content calculated by weight loss. A sample of this material was treated with 1 M HCl in-vacuo to remove carbonates, and the CO₂ yield accompanying combustion for isotopic analysis was used to calculate the organic carbon content. A further sample of the washed and dried material was treated with 5% sodium hypochlorite solution to remove organic material, and the CO₂ yield accompanying reaction with phosphoric acid for isotopic analysis used to calculate carbonate content.

Sulfur analyses were performed on washed samples using a semi-automated Leco[®] iodometric sulfur titrator. Reproducibility of results using this technique is better than ±1% (E. Kiss, pers. comm.). No special care was taken to ensure that

easily oxidized or volatilized sulfur species, if present, were not lost during the washing and drying process undertaken to remove soluble sulfate derived from porewaters. However, as all samples were treated in the same manner, the results are comparable with each other. Mineralogy was determined, where necessary, by X-ray diffraction, and some specimens were examined using a Cambridge S-360 scanning electron microscope.

Isotopic analyses

The $\delta^{13}\text{C}$ composition of organic matter in acid-treated, washed and dried samples was determined by combustion of the sample with excess CuO and Ag-wire at 900°C , in evacuated and sealed silica tubes (Sofer, 1980), with subsequent cryogenic purification of the liberated CO_2 . The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ composition of the carbonate fraction was determined by reaction of sodium hypochlorite treated, washed and dried samples with 100% H_3PO_4 (McCrea, 1950). The stable-isotope composition of the CO_2 resulting from both these treatments was determined using a modified dual-inlet triple-collecting MS-12[®] mass spectrometer. All results are reported in parts per thousand (‰) and the overall precision of the analyses is estimated to be $\pm 0.1\text{‰}$ for organic carbon $\delta^{13}\text{C}$ (relative to PDB), and $\pm 0.2\text{‰}$ for carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (relative to V-SMOW).

^{14}C age determinations are quoted as conventional years before present (yr B.P.), the present being defined as 1950. Carbonates were removed by treatment with excess 6 M HCl and the neutralized residual organic material was combusted in a stream of oxygen. The CO_2 thus produced underwent reaction with molten Li to produce Li_2C_2 . This was then hydrolysed to produce acetylene and subsequently converted to benzene by catalytic trimerization. The ^{14}C activity of the benzene was determined by liquid scintillometry.

Results

A summary of the general features of the lakes and marine inlets examined in this study is given

in Table 1. Isotopic and chemical results from the sediment cores are provided in Table 2.

Ace Lake

This core was sectioned into 5-cm blocks at the time of collection, in 1978, and since that time has been partially melted and refrozen at least once. In spite of this drawback, three units can be visually identified in the core.

Unit 1: 0–35 cm. Black and reddish black, laminated algal material with occasional light < 0.5 mm carbonate-rich bands. An abrupt transition to:

Unit 2: 35–130 cm. Watery, diffusely banded green sediment changing gradually over the lower 5 cm to:

Unit 3: 130–185 cm. Black in the upper portion, laminated algal material similar to zone 1, with occasional carbonate-rich bands. Changing gradually over ~ 15 cm to grey laminated algal material with progressively fewer algal laminations and more fine clastic material down the core. From 170 to 180 cm there is very little macroscopic algal material and the sediment is predominantly composed of grey silt-sized clastic material.

Sand-sized material and occasional pebbles occur sporadically throughout the core. Treatment of samples from units 1 and 3 with acid led to the production of H_2S indicating the presence of acid-reactive sulfide. None of the units is unequivocally of marine origin, although the general appearance of unit 2 is very similar to that of sediments in the marine inlets. As the core had been melted and refrozen at some time, no attempt was made to examine porewaters. The laminated algal material of Units 1 and 3 bears a strong resemblance to descriptions of aerobic and anaerobic prostrate algal mats from Antarctic dry valley lakes (Wharton et al., 1983).

Highway Lake

The core smelt strongly of H_2S when extruded from its core-tube. Two distinct units could be readily identified on sectioning the core.

Unit 1: 0–212 cm. A monotonous sequence of black, finely laminated algal material, with a high water content, and very little clastic sediment.

TABLE 1

Description of lakes and fjords sampled for this study

Locality	Latitude (°S)	Longitude (°E)	Salinity (gl ⁻¹)	Depth (m)	Description and references (see Fig.1 for locations)
Organic Lake	68°27.4'	78°11.3'	176–250	7.5	Meromictic hypersaline lake; major ion chemistry similar to seawater; waters below 3.5 m anoxic with high conc. of DMS and low H ₂ S; upper water temperatures variable (–14 to +15°C); bottom water temp. constant –6°C; low species diversity — unicellular algae and bacteria; lake surface 2.7 m a.s.l.; saddle between lake and Taynaya Bay ~3.5 m a.s.l. References: Franzmann et al. (1987); Gibson et al. (1991), Burke and Burton (1988); 0.96 m core taken 20 m from the WSW shoreline beneath 1.8 m of ice and 2.8 m of water, Dec. 1987.
Ace Lake	68°24.8'	78°11.1'	28–40	25	Meromictic saline lake; major ion chemistry similar to seawater; waters anoxic below ~9 m with high conc. of CH ₄ ; upper water temperatures variable (–1 to +5°C); bottom water temperatures 0 to +1°C; supports benthic cyanobacterial mats, bacteria, planktic algal communities and a copepod crustacean. Lake surface 8.7 m a.s.l., saddle between lake and Long Fjord 8.8 m a.s.l. References: Burton and Barker (1979), Burton (1980), Hand (1980), Hand and Burton (1981), Volkman et al. (1986, 1988), Burch (1988). 1.85 m core collected from the deepest part of the lake beneath 1.8 m of ice and ~21 m of water, Sept. 1978.
Highway Lake	68°27.9'	78°11.3'	8–10	~15	Elongate slightly saline lake. Bottom waters possibly anoxic for part of the year. No biological information is available for this lake. Lake surface 7.7 m a.s.l., saddle between lake and Taynaya Bay ~7.7 m a.s.l. 3.6 m core collected from the centre of the lake beneath 1.8 m of ice and 15 m of water, Dec. 1987.
Ellis Fjord	68°35.5'	78°12.0'	34–48	117	Ellis Fjord is approximately 11 km long and averages ~1 km in width. Communication with the ocean is restricted by two shallow sills. Several of the basins in the fjord are permanently stratified. The deepest meromictic basin (110 m deep) is anoxic below 45 m and temperatures vary from –1 to –2°C at the surface to +1 to +2°C at the seafloor. References: Gallagher and Burton (1988), Gallagher et al. (1989). 4.1 m core collected from the Deep Meromictic Basin, below 70 m water depth.
Taynaya Bay	68°27.4'	78°14.8'	34–80	78	Taynaya Bay is shallower than Ellis Fjord (averaging approx. 30 m depth) and is connected to the sea via a narrow channel. The bay has 6 basins of which 3 are permanently stratified. The deepest basin (80 m depth) is anoxic below ~45 m. Reference: Burke and Burton (1988). 2.0 m core collected from the deepest basin in 78 m water depth, Dec. 1987.

Melting of the core caused the algal material to break up into large flakes (~0.5–1 cm across) and 'books' of stacked flakes. One area, from approximately 80–100 cm, was lighter in colour with a slightly greater proportion of fine-grained clastic material. Coarse sand-sized clastic material occurs in small amounts throughout the unit. This unit

bears a strong resemblance to descriptions of aerobic and anaerobic prostrate algal mats from Antarctic dry valley lakes (Wharton et al., 1983). A sharp boundary separates unit 1 from:

Unit 2: 212–361 cm. Very fine-grained, organic-rich sediment. The colour of this material was initially dark green to green-black, with diffuse

TABLE 2

Chemical and isotopic composition of some Antarctic lake sediments

Depth (cm)	Water (wt. %)	Salt (wt. %)	Sulfur (wt. %)	Carbonate (wt. %)	Org.-C (wt. %)	$\delta^{13}\text{C}_{\text{org}}$ (‰-PDB)	$\delta^{13}\text{C}_{\text{carb}}$ (‰-PDB)	$\delta^{18}\text{O}_{\text{carb}}$ (‰-SMOW)
<i>Organic Lake</i>								
0–5	61.0	24.6	0.11	3.5	0.66	–19.4	+1.8	+20.0
5–10	52.5	17.2	0.16	5.2	0.86	–19.0	+4.5	+20.5
10–15	43.8	12.1	0.16	3.4	0.79	–19.1	+6.8	+21.0
15–20	33.3	7.8	0.16	3.9	0.62	–18.5	+6.1	+22.0
20–24.5	33.7	8.1	0.23	3.4	0.94	–18.5	+4.6	+20.8
24.5–25.5	31.5	7.3	0.14	4.6	0.89	–19.7	+3.9	+19.0
25.5–27.5	29.8	6.7	0.20	2.4	0.75	–18.7	+5.0	+21.9
27.5–28.0	30.8	7.0	0.15	3.0	1.29	–17.9	+5.6	+18.8
28–30	28.7	6.2	0.20	2.4	0.62	–17.6	+5.4	+22.7
30–35	30.2	7.5	0.29	3.0	1.89	–19.1	+5.6	+22.6
35–40	47.0	15.4	0.45	9.6	1.64	–16.6	+7.3	+26.8
40–45	54.0	20.4	0.64	1.0	3.27	–17.6	+3.9	+27.1
45–50	54.8	21.1	0.99	0.2	3.02	–15.8	n.d.	n.d.
50–54	53.9	20.3	0.92	0.3	2.63	–15.6	–6.0	+24.5
54–60	57.6	23.6	0.75	2.9	1.92	–15.9	+5.2	+20.0
60–65	65.3	33.3	0.75	1.9	1.55	–16.4	n.d.	n.d.
65–70	66.9	35.6	n.d.	1.6	1.47	–16.4	–7.3	+26.2
70–75.5	63.7	30.8	n.d.	1.4	1.75	–17.3	n.d.	n.d.
75.5–80	63.6	30.9	n.d.	6.1	1.34	–17.1	–2.7	+31.2
80–85	56.3	22.8	n.d.	1.0	1.92	–18.9	–4.5	+29.3
85–90	53.6	20.5	n.d.	1.5	1.52	–18.9	–5.3	+28.8
90–96	51.0	18.4	0.70	1.5	1.77	–19.4	–3.0	+29.3
mollusc (50–60 cm)							+1.6	+35.9
mollusc (70–75 cm)							+4.7	+35.7
organic lump (37 cm)						–10.5		
feather (40 cm)						–22.1		
<i>Ace Lake</i>								
0–5	71.8	17.9	2.70		4.5	–24.9		
5–10	65.5	11.8	2.88		5.5	–24.0		
10–15	63.2	11.1	2.25		5.4	–22.2		
15–20	66.1	12.0	2.37		8.0	–23.7		
20–25	66.5	12.2	2.65		7.8	–25.3		
25–30	64.6	11.6	2.59		10.1	–24.9		
30–35	72.2	19.2	1.99		4.8	–22.4		
35–40	90.0	52.3	1.29		4.3	–22.1		
40–45	80.9	56.9	1.37		3.4	–21.7		
45–50	89.0	65.6	1.32		2.9	–21.9		
60–65	92.2	67.8	1.33		2.9	–21.5		
75–80	92.3	59.8	1.18		2.6	–21.4		
85–90	91.3	63.8	1.36		2.3	–21.5		
95–100	92.3	64.7	1.16		2.9	–20.9		
105–110	90.1	54.8	1.35		3.3	–22.1		
115–120	92.3	50.2	1.21		2.4	–21.8		
125–130	84.5	59.0	1.54		4.0	–22.3		
130–135	59.0	13.5	2.38		2.7	–23.4		
135–140	58.0	10.2	2.02		4.2	–25.3		
145–150	55.6	10.3	1.72		2.8	–25.9		
155–160	64.7	11.7	1.92		4.6	–25.3		
165–170	66.8	13.6	1.97		3.6	–24.6		
170–175	64.5	12.4	2.15		2.5	–24.4		
175–180	52.5	9.9	2.53		1.6	–24.1		
180–185	43.3	6.6	1.11		1.1	–24.0		

TABLE 2 (continued)

Depth (cm)	Water (wt.%)	Salt (wt.%)	Sulfur (wt.%)	Carbonate (wt.%)	Org.-C (wt.%)	$\delta^{13}\text{C}_{\text{org}}$ (‰-PDB)	$\delta^{13}\text{C}_{\text{carb}}$ (‰-PDB)	$\delta^{18}\text{O}_{\text{carb}}$ (‰-SMOW)
<i>Highway Lake</i>								
0–11.5	95.8				11.8	–18.0		
11.5–27.0	95.8				12.5	–19.9		
27–40	94.7				14.3	–21.3		
40–53	89.4		2.49		11.1	–21.4		
53–63	90.5				15.4	–22.0		
63–73	89.2		3.80		9.9	–23.0		
73–83	89.7				11.6	–21.6		
83–93	92.3				12.5	–20.0		
93–103	92.4				13.8	–16.2		
103–113	89.9				13.2	–18.3		
113–123	91.9				9.8	–18.1		
123–133	91.8				14.7	–16.3		
133–141	90.8				14.4	–15.0		
141–149	91.6				12.3	–14.5		
149–159								
159–169	91.6		1.91		12.9	–15.6		
169–179	91.5				9.0	–16.5		
179–189	91.4		1.45		12.2	–13.3		
189–199	90.6				10.7	–17.4		
199–209	86.3				12.6	–20.2		
209–219	86.3				9.2	–19.9		
219–229	92.4				5.4	–19.8		
229–239	94.3				6.2	–19.3		
239–247	92.8				4.2	–19.6		
273–283	93.6				4.7	–19.5		
303–313	95.0				5.1	–19.7		
333–343	92.8		1.62		4.5	–19.4		
<i>Ellis Fjord</i>								
63–73	85.9	38.1	1.46	3.3	3.92	–18.1	+1.64	+32.6
172–182	89.3	43.1		1.9	2.64	–18.0	–4.80	+30.1
260–270	89.9	47.6		1.8	2.12	–17.9	–4.81	+31.0
370–380	90.1	43.9			2.21	–18.0		
sea urchin (68 cm)							–1.55	+32.6
<i>Taynaya Bay</i>								
60–70	90.9	68.5	0.65		2.32	–19.3		
126–136	86.7	42.5		2.1	4.18	–19.4	–9.97	+27.6
<i>Burton "Lake"</i>								
0–15						–17.8		
15–30						–17.4		
60–75						–18.4		
365–380						–18.5		

n.d. = not determined.

lighter bands, however, upon drying, the colour of the sediment changed to light green, possibly indicating the oxidation of reduced sulfur species. As in unit 1, sand-sized clastic material occurs in

small amounts throughout. The discovery of fish remains in the lower part of this unit, coupled with the general similarity to Taynaya Bay sediments, suggests that it is marine in origin.

Organic Lake

No H_2S could be detected by smell at the time core extrusion, and three units could be visually identified when the core was sectioned.

Unit 1: 0–47 cm. The upper 5 cm of this unit was watery, grading into compact black, laminated, fine-grained sediment. X-ray photography indicates that the laminations vary in width from approximately 0.1 to 1 cm. Distinct white bands of aragonite (~ 1 mm in width) occur irregularly in the upper part of the unit, particularly from 24 to 28 cm. More diffuse light-coloured banding, attributable to monohydrocalcite and aragonite, occurs in the lower part of the unit. On drying, the colour of the sediment changed from black to brown. Well preserved feathers occur throughout the unit, and at 37 cm a single 1 cm wide rubbery mucilaginous lump of organic material was found. R. Garrick and J. Gibson (pers. comm.) report fungal remains from the same interval in another Organic Lake core. Laminated algal material, similar to that found in Ace and Highway Lake cores, was not present. An SEM study of the sediments indicated the occasional presence of diatom frustules, identified as *Cocconeis fasciolata* (D. Thomas, pers. comm.) however, the marine habitat of this species indicates that they were washed or blown into the lake. Treatment of the sediment with dilute HCl produced copious effervescence from carbonate phases and a strong odour of H_2S , indicating the presence of sulfides. The material turned light brown-green in colour after this treatment. Small pebbles (up to 1 cm across) and sand-sized clastic material increase in abundance toward the top of the unit.

Unit 2: 47–60 cm. This unit represents a transition zone. Four to five black bands (~ 0.5 mm in width) of sediment similar to unit 1 material occur from 47 to 60 cm, separated by greenish sediment similar to unit 3. Diffuse banding continues to approximately 58 cm. A large mollusc valve (2–3 cm across) was present in the interval 54–57 cm. The percentage of clastic material is low, similar to that at the base of unit 1.

Unit 3: 60–96 cm. Watery, dark green, diffusely banded sediment, progressively more compact with depth. Pieces of mollusc valve up to 4 cm in length

(probably *Laternula elliptica*) occur abundantly from 71 to 78 cm, and smaller fragments were found to the bottom of the core. Gastropods, sea urchin spines and diatoms are also abundant in the samples. The diatom species *Cocconeis fasciolata*, *Paralia sol* and *Gomphonema* sp. were identified from the core (D. Thomas, pers. comm.) all being of marine origin. The diatom genera *Nitzschia*, *Amphora*, *Cocconeis* and *Coscinodiscus*, most if not all of marine origin have been identified from an adjacent core (R. Garrick and J. Gibson, pers. comm.) Upon drying, the material turned light green in colour. The percentage of coarse clastic material increases toward the bottom of the unit, and X-ray imaging of the core indicates that the banding becomes more pronounced. This unit is considered to be marine in origin.

The Organic Lake core differs from the other cores in that it was collected from a relatively shallow depth (2.8 m), close to the edge of the lake and above the present oxic–anoxic interface.

Marine inlets

The Ellis Fjord core consists entirely of dark and pale green diffusely banded watery sediment. An X-ray photograph of the core indicates that the scale of banding varies irregularly down the core from 0.5 cm thick, well defined layers, to 1–2 cm thick, very diffuse bands. Dark green organic-rich bands are thought to represent the accumulation of algal remains from summer blooms, while pale green bands represent the accumulation of fine clastic detritus under quiescent conditions during winter. Small amounts of sand-sized clastic material occur throughout the core, as do sea-urchin plates. The sediment changes to light green in colour on drying. The marine diatom *Thalassiosira australis* was identified from one sample at 50 cm depth (D. Thomas, pers. comm.).

As with the Ellis Fjord core, the Taynaya Bay core is homogeneous along its length. The most striking difference between the two cores is that the latter smelt strongly of H_2S and the sediments were black in colour upon extrusion of the core. However, on drying, the colour of the sediments changed to light green, indistinguishable visually from the Ellis Fjord material. The marine diatoms

Thalassiosira australis, *Nitzschia curta*, *Pinnularia quadrantanea* and *Coscinodiscus bouvet* were identified from one sample at 35 cm depth (D. Thomas, pers. comm.).

Interpretation

¹⁴C chronology, uplift and sedimentation rates

Radiocarbon (¹⁴C) ages from carbonaceous material in Antarctica are difficult to interpret due to the variability in the so-called 'reservoir effect' of that region. Surface ocean waters and living marine organisms yield ¹⁴C ages older than terrestrial materials due to the depletion of ¹⁴C in the Antarctic water mass. This depletion with respect to the surrounding atmosphere exists for other oceanic masses but the depletion in the Antarctic is larger than elsewhere and also exhibits

regional variability. This is due to processes such as the release of ¹⁴C-depleted CO₂ from iceberg and glacial melt-waters (Ohmoto, 1983) and the slow equilibration of the oceanic carbon reservoir with atmospheric CO₂ in these cold waters.

Although measurements on Antarctic atmospheric CO₂ and live terrestrial mosses have yielded ¹⁴C levels consistent with values expected at more northern latitudes, the levels of surface lake waters and living lacustrine organisms vary from 'modern' to about 1300 yr B.P. (Ohmoto, 1983; Adamson and Pickard, 1986b). Typically though, the majority of reported ¹⁴C ages in Antarctica for living lacustrine and marine organisms are about 850–1300 yr B.P. (e.g. Harkness, 1979; Yoshida and Moriawaki, 1979; Adamson and Pickard, 1983, 1986a).

Irrespective of this variation, ¹⁴C ages obtained during this study (Table 3) can be used to place

TABLE 3

Radiocarbon dating results

ANU No.	Depth (cm)	Wt. depth (cm) ^a	Type	δ ¹³ C (‰)	¹⁴ C age ^b
<i>Highway Lake</i>					
6409	27–63	48	organic sediment	–21.6	1580 ± 90
6416	83–113	100	organic sediment	–18.1	3250 ± 90
6412	123–149	136	organic sediment	–15.4	3180 ± 90
6213	179–209	203	organic sediment	–18.0	4120 ± 70
6406	209–249	218	organic sediment	–19.8	6060 ± 150
6413	273–313	293	organic sediment	–19.6	6160 ± 200
6411	323–361	342	organic sediment	–19.4	6890 ± 200
<i>Organic Lake</i>					
6418	0–30	18	organic sediment	–18.6	1020 ± 140
6212	15–47	29	authigenic CaCO ₃	+10.2	830 ± 90
6214	30–47	40	organic sediment	–18.6	2440 ± 90
6407	47–60	52	organic sediment	–15.8	4770 ± 180
6410	60–96	86	organic sediment	–18.0	5820 ± 190
<i>Ace Lake</i>					
6414	20–35	27	organic sediment	–24.6	5310 ± 90
6419	35–75	48	organic sediment	–21.7	6110 ± 180
<i>Ellis Fjord</i>					
6405	43–83	63	organic sediment	–18.0	3090 ± 160
6408	152–192	172	organic sediment	–18.1	3330 ± 120
6417	260–300	280	organic sediment	–18.0	4230 ± 170
6415	370–410	390	organic sediment	–17.9	4540 ± 200

^aWeighted depth calculated from % carbon and % water data given in Table 2.

^b¹⁴C years quoted conventionally as yr B.P. (before 1950) and uncorrected for any reservoir effects.

constraints on sedimentation and uplift rates, and on the magnitude of reservoir effects in both marine and lacustrine systems. The ages obtained from Ellis Fjord (Fig.2) form a linear array, and least-squares regression yields an 'age' at the sediment–water interface of approximately 2600 yr B.P. This compares favourably with the ^{14}C age of the overlying bottom-water (2370 ± 75 yr B.P.; Gallagher et al., 1989), and suggests that a large proportion of the biomass must utilize ancient $\text{CO}_2/\text{HCO}_3^-$ derived from the deep meromictic basin waters. The 410 cm core represents about 2000 years of sediment accumulation at a rate of approximately 2 mm yr^{-1} . This is consistent with the approximately 2-mm width banding observed in much of the core being due to annual influences. Some additional uncertainty may be introduced into the sedimentation rate calculations by compaction of the sediment during coring and/or loss of the uppermost portion of the core. Either of

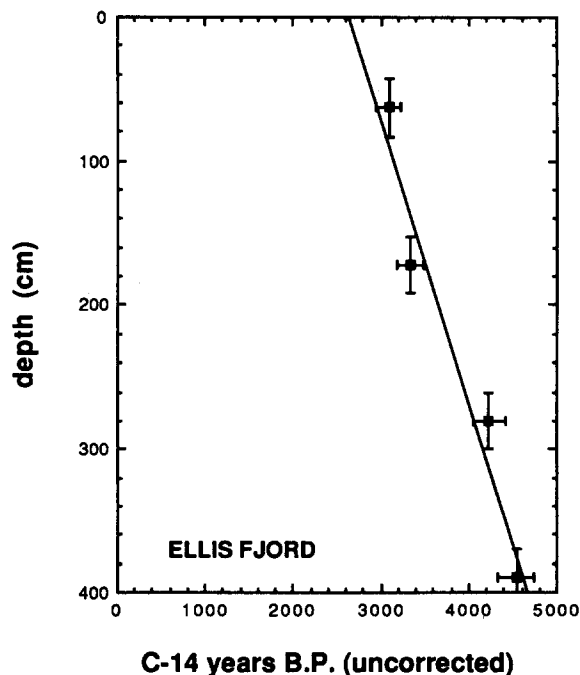


Fig.2. ^{14}C age as a function of depth in Ellis Fjord sediments, quoted as conventional yr B.P. (defined as 1950), and uncorrected for reservoir effects. Error bars for ^{14}C age determinations are $\pm 1\sigma$, the assigned depth is a weighted depth based on % carbon variations within the sample interval, and error bars for depth represent the length of the sampled interval.

these possibilities will decrease the apparent sedimentation rate.

The data for Highway Lake (Fig.3) could be interpreted either as a single linear array, or as a marine and a lacustrine group. Given that the sedimentation rate is unlikely to have remained constant in both environments, and that the degree of equilibration between atmospheric CO_2 in the lacustrine environment is likely to have been greater than in the marine environment, the latter interpretation is preferred. This is supported by the ~ 1200 year 'step' to lower ^{14}C ages associated with the marine to lacustrine transition.

Regression of the lacustrine data yields a reservoir effect at the sediment–water interface of approximately 1000 years. (This is similar to unpublished data for Deep Lake where a similar regression yields a 1000-year reservoir effect; Ferris and Radnell, pers. comm.). The total reservoir effect for the marine environment would thus be ~ 2200 years. Thus the sedimentation rate in the lacustrine part of the core above 211cm is $\sim 0.6 \text{ mm yr}^{-1}$, and in the marine part of the core the sedimentation rate is $\sim 1.2 \text{ mm yr}^{-1}$. Banding in the marine part of the core (particularly the

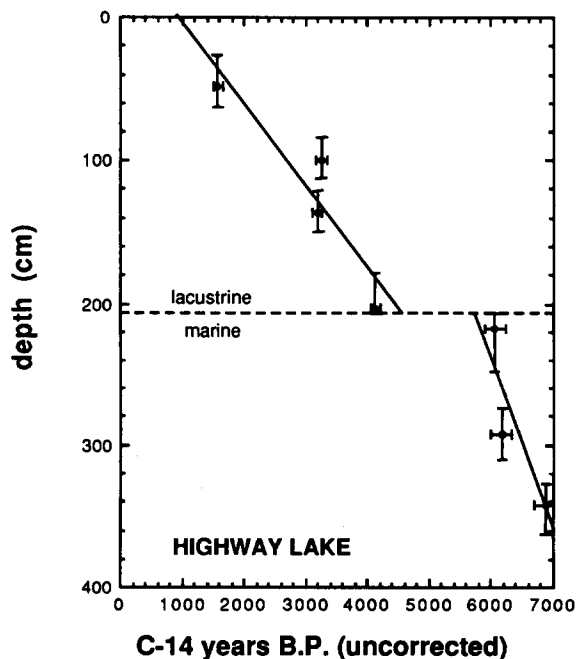


Fig.3. ^{14}C age as a function of depth in Highway Lake sediments (details as in Fig.2).

lower half) is on a finer scale than in the Ellis Fjord sediments, and the size here is also consistent with the banding being an annual phenomenon.

Interpretation of the Organic Lake data (Fig.4) is more difficult because the low organic content of the sediment precluded the analysis of more than two samples from either the marine or lacustrine portions of the core. As in the Highway Lake core there is evidence for a ~ 1300 year step across the marine to lacustrine transition, but no evidence for a reservoir correction in the lacustrine environment. If this were indeed the case then it could be due to the small lake-size and shallow water depth, c.f. others in this study, leading to a greater degree of equilibration with atmospheric CO_2 during the lacustrine phase. However, this result is more likely to be due to the large error involved in an extrapolation using only two data points. Irrespective, any reservoir effect must be less than about 1000 years, the age of the youngest sample. The sedimentation rates are $\sim 0.16 \text{ mm yr}^{-1}$ in the lacustrine portion of the core and $\sim 0.26 \text{ mm yr}^{-1}$ in the marine section of the core, although these can only be considered crude estimates.

The single ^{14}C date for carbonate in Organic

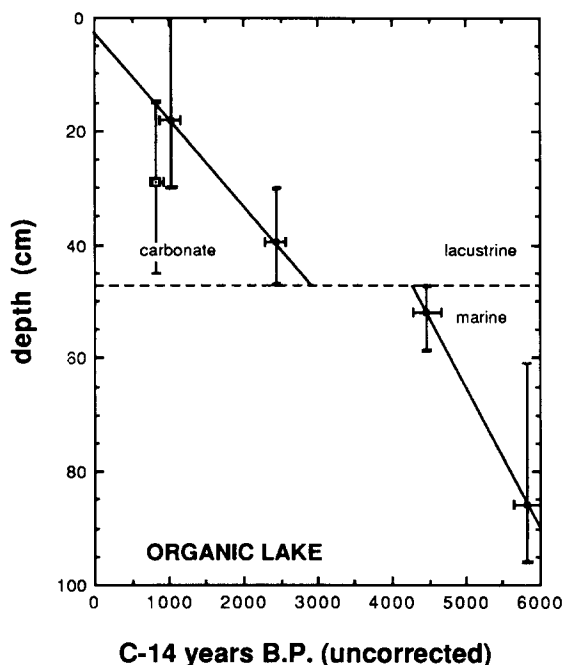


Fig.4. ^{14}C age as a function of depth in Organic Lake (details as in Fig.2).

Lake seems anomalously young compared to the organic matter ^{14}C dates, suggesting post-sedimentation re-mobilization/precipitation of carbonate within the sediments.

Only two ages are available from the Ace Lake core (Table 3), which indicate that a change from oxic (unit 2) to anoxic conditions (unit 1) occurred between about 5310 and 6110 yr B.P. (Fig.9). The sedimentation rate in the upper 35 cm of the core is approximately $0.06\text{--}0.08 \text{ mm yr}^{-1}$, assuming a reservoir correction between 0 and 1000 years.

The date of the transition from marine to lacustrine conditions in the lakes can be used to calculate the apparent uplift rates (relative to mean sea level) in the Organic and Highway Lake regions. In Highway Lake the connection with the sea was severed abruptly approximately 4600 yr B.P., and the present altitude of the lowest sill separating the lake from the sea is 7.7 m a.s.l. (Table 1). This suggests an apparent rate of emergence of $1.7\text{--}2.1 \text{ mm yr}^{-1}$, again using a 0–1000 yr reservoir effect.

In Organic Lake (sill altitude 3.5 m a.s.l.), where lacustrine conditions were established about 2700 yr B.P., similar calculations yield an apparent emergence rate of $1.0\text{--}1.6 \text{ mm yr}^{-1}$. Evidence supporting a possible lower rate of emergence at Organic Lake compared with Highway Lake is provided by the very rapid change from marine to lacustrine conditions in the latter core compared with a 13 cm-wide transition zone in the Organic Lake sediments, suggesting that Organic Lake existed for several hundred years in a form similar to modern Burton or Rookery Lakes, i.e. intermittently connected to the ocean. This indicates a low rate of emergence at that time possibly due to a concomitant rise in sea level. An extended period of episodic connection with the ocean may partially explain the present hypersalinity in Organic Lake, as the influx of seawater, followed by evaporation, has raised the salinity of Rookery Lake, for example, to four times that of seawater (Burton, 1981).

If the transition from unit 2 to unit 1 in Ace Lake, 8.7 m a.s.l. (~ 5400 yr B.P.) corresponds to a change from marine to lacustrine conditions then a rate of emergence of $1.6\text{--}2.0 \text{ mm yr}^{-1}$ (0–1000 yr reservoir effect) is indicated; if not, the calculated rates are minimum values.

The emergence rates calculated above are similar to those reported by Zhang et al. (1983) and Peterson et al. (1988) but are considerably higher than rates calculated for the northern Vestfold Hills by Adamson and Pickard (1986b). The rates of emergence decrease with decreasing age, consistent with the likely response of the crust to unloading during the retreat of the ice-cap (e.g. England, 1983), but again the opposite of findings by Adamson and Pickard (1986b).

Although the number of radiocarbon results reported here are not sufficient to calculate a single 'Antarctic reservoir effect', they do indicate that the effect would be between 0 and 1000 years. This is similar to the results in the other works cited above. However, the magnitude of the effect appears to be largely dependent on the size of, and degree of mixing within, the waterbody from which the biomass is extracting carbon.

Salinity and stable-isotope composition of lake and pore-waters

Previous studies have established a broad database of salinity and stable-isotope measurements

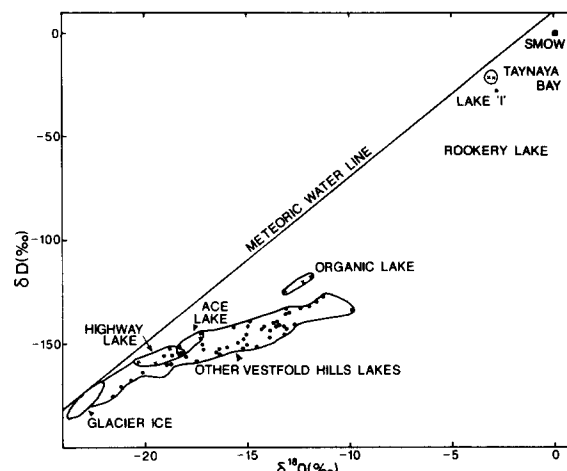


Fig.5. Stable-isotope composition of waters from lakes and sediments in the Vestfold Hills. Additional data from Matsubaya et al. (1979).

from lake waters in the Vestfold Hills (Matsubaya et al., 1979). Published data pertinent to the localities under investigation, and additional new data are provided in Table 4.

Figure 5 indicates that Ace and Highway Lake waters plot relatively close to the meteoric water

TABLE 4

Stable-isotope composition of waters from the lakes and marine inlets sampled during this study

Sample location	Type	Depth (m)	$\delta^{18}\text{O}$ (‰)	δD (‰)	Density (g cm^{-3})
Organic Lake	SW	2	-13.1	-125	1.040
	SW	5	-11.9	-118	1.150
	PW	1	-12.3	-120	1.123
Ace Lake	SW	5 ^a	-18.3	-154	—
	SW	10 ^a	-17.3	-147	—
	SW	15 ^a	-17.3	-145	—
Highway Lake	SW	15	—	—	1.007
	PW	0.19	-18.8	-152	1.004
	PW	0.88	-18.1	-154	1.006
	PW	1.84	-20.4	-158	1.006
	PW	3.48	-19.5	-160	1.007
Taynaya Bay	SW	70	—	—	1.060
	PW	0.35	-3.2	-22	1.062
	PW	1.31	-3.0	-22	1.048
Ellis Fjord	SW	10 ^b	-1.0	—	—
	SW	50 ^b	-3.0	—	—

SW = surface water; PW = porewater.

^aMatsubaya et al. (1979); ^bGallagher et al. (1989).

line, within the field described by other lakes in the Vestfold Hills, suggesting that the modern lake and pore waters are partly evaporated glacial meltwaters. Even in the marine portion of the Highway Lake core there is no evidence of higher salinity marine pore waters although a small increase in salinity does occur down the core. This indicates that effective flushing of the sediments by meltwaters has taken place to a depth of at least 3.5 m below the modern sediment–water interface.

In contrast, the Organic Lake surface and pore waters are strongly evaporated, highly saline and plot significantly above the field for lakes in the Vestfold Hills on Fig.5. Lake water at 2 m depth is less saline and less evaporated than water at 5 m depth indicating some dilution of the upper waters by meltwaters, with an attendant decrease in salinity. The stable-isotope composition of the waters suggest that the modern waters contain 10–20% of the original seawater, assuming a meltwater $\delta^{18}\text{O}$ value of -20 to -22‰ and fjord water with a $\delta^{18}\text{O}$ value of -1 to -3‰ . Lakes retaining some seawater isotopic signature are also known from elsewhere in Antarctica (Matsubaya et al., 1979). Incomplete flushing of the original seawater by later meltwaters is probably the result of a small catchment area and comparatively late severance of the lake's marine connection. As in Highway Lake, pore water salinities are comparable to that of the overlying lake water.

The stable-isotope composition of Taynaya Bay sediment pore-waters are similar to Ellis Fjord waters. This suggests that the same process of brine exclusion by freezing, with attendant isotopic fractionation between ice and brine (Gallagher et al., 1989), was an important process in the formation of the deep, saline Taynaya Bay waters. As pore waters at 130 cm depth are significantly less saline than pore waters near the sediment–water interface, it is likely that brine production is a continuing process.

Organic carbon and sulfur

The carbon-isotope composition ($\delta^{13}\text{C}$) of organic matter in the sediments is characterized by extremely uniform values in marine sediments, and

widely but regularly varying values in sediments of lacustrine origin, spanning a total range from -25.9 to -10.5‰ .

In Ellis Fjord, four samples representing approximately 1800 years of sediment accumulation all yielded values within experimental error of -18.0‰ , and in Taynaya Bay two samples both yielded values of -19.3‰ . These values are considerably higher than published analyses of organic carbon in high-latitude open marine sediments which exhibit a range from approximately -22 to -28‰ (Sackett et al., 1973; Rau et al., 1982; Sackett, 1986a, b).

The organic matter flux to the sediments will comprise contributions from planktonic communities (living both in surface and bottom waters), and benthic communities, minus material decomposed in the water column during settling. Differences in the open marine and marine-inlet environments which might have led to the comparatively high marine-inlet $\delta^{13}\text{C}$ values include (1) poor circulation in the inlets, coupled with abundant plankton populations in summer resulting in a low pCO_2 in surface waters, and decrease in the isotopic fractionation exerted by the microbial population during photosynthesis (Calder and Parker, 1973; Pardue et al., 1976). (2) comparatively warm bottom-water temperatures in the inlets (up to 2°C) resulting in a decrease in the magnitude of fractionation. This could only account for a small fraction of the difference ($<1\text{‰}$). (3) anaerobic bacterial fermentation resulting in the production of isotopically heavy CO_2 which was then utilized by the planktic microbial population in the bottom waters. The last hypothesis is supported by the constancy of the $\delta^{13}\text{C}$ and by the high levels of CO_2 which have been reported from the bottom-waters of Ellis Fjord (Gallagher et al., 1989).

There is likewise very little variation in the $\delta^{13}\text{C}$ values of organic matter in the 1.3-m thick (~ 1000 year) marine section of Highway Lake sediments (Fig.6), and the values are identical to those obtained from Taynaya Bay sediments. In the Organic Lake marine section, $\delta^{13}\text{C}$ values increase over 40 cm from values identical to Taynaya Bay samples towards the top of Unit 2, reflecting increasing isolation from Taynaya Bay prior to the formation of the lake (Fig.7). A similar excursion

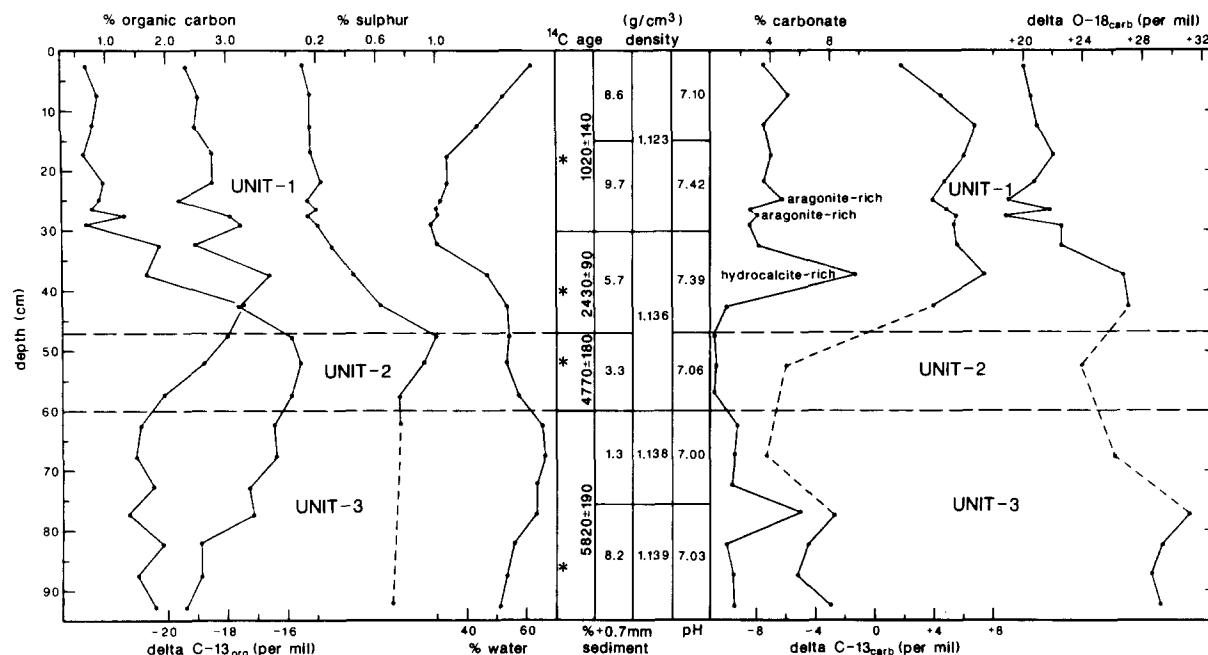


Fig.7. Chemical and isotopic compositions of Organic Lake sediments and porewaters (asterisk in ^{14}C column indicates weighted depth of sample).

of the lake, and changes in the physico-chemical conditions (salinity, temperature, light intensity, nutrient availability etc.) within the lake. Large modifications to the $\delta^{13}\text{C}$ of organic matter as a result of decomposition and microbial degradation following sedimentation are unlikely due to the very low temperatures occurring in the sediments (Volkman et al., 1986).

To test whether there is a strong dependence on the relative proportions of the various organisms (algae, cyanobacteria, bacteria etc.) contributing to the sedimentary organic carbon pool, samples from Highway and Ace Lakes were ultrasonically disaggregated in an attempt to separate a fine fraction containing predominantly free-living organisms from a coarse mat-like fraction containing colonial benthic organisms. Table 5 shows that there are small differences in $\delta^{13}\text{C}$ (up to 2.7‰), with the fine fraction tending to be isotopically lighter than the coarse fraction. This is probably due to higher abundances of bacteria in the fine fraction, which tend to have low $\delta^{13}\text{C}$ values (Schidlowski et al., 1983).

The observed differences are not large enough to explain the large shifts in $\delta^{13}\text{C}$ observed in the

lake sediments, and the fact that if the bulk-sediment $\delta^{13}\text{C}$ value is low then both the fine and coarse fractions have low $\delta^{13}\text{C}$ values, and vice versa, indicates that the $\delta^{13}\text{C}$ composition of the

TABLE 5

$\delta^{13}\text{C}$ values in fine and coarse organic fractions from selected samples

Sample (cm)	Fraction ^a	$\delta^{13}\text{C}_{\text{PDB}}$ (‰)
<i>Highway Lake</i>		
68	fine	-23.3
	coarse	-20.6
145	fine	-16.6
	coarse	-17.7
174	fine	-17.0
	coarse	-15.7
<i>Ace Lake</i>		
3	fine	-24.0
	coarse	-23.6
22	fine	-26.3
	coarse	-24.5

^afine = organic material easily suspended by ultrasonic agitation in water. coarse = coherent flakes of organic material not disaggregated by ~10 min ultrasonic agitation in water.

microbial population as a whole varies with changes in environmental conditions. This conclusion is supported by the range of values obtained from surface sediment samples from Organic Lake (Table 6; Figs. 7 and 8). The $\delta^{13}\text{C}$ values of organic matter in the sediments decrease dramatically with depth, from -10.8‰ in a small stream draining into the lake, to -14.8‰ in the shallowest lake sample to -20.4‰ in the deepest part of the lake.

The only quantitatively important organisms currently present in the lake are two species of unicellular algae and three species of bacteria (Gibson et al., 1991), and the observed decrease in $\delta^{13}\text{C}$ appears to be related to decreasing rates of photosynthesis with depth, in response to increasing salinity, and decreasing temperature and

light levels. The annual ice-cover and meromictic nature of the lake will limit the availability of CO_2 in the lake waters for photosynthesis. Gibson et al. (1990) report the highest populations of algae in a sample taken from 2 m depth, where the highest lake-sediment $\delta^{13}\text{C}$ value was obtained. The low $\delta^{13}\text{C}$ values in the deepest lake sediments are probably also due to an increasing contribution of bacterial material derived from the anoxic zone of the lake.

The particularly high $\delta^{13}\text{C}$ values obtained from organic matter in a meltwater stream draining into the lake is a result of extreme competition for available CO_2 by a blooming algal population, as is frequently reported from microbial mat communities (Behrens and Frishnan, 1971; Aizenshtat et al., 1984; Schidlowski et al., 1985; Schidlowski, 1986). The analysed sample is composed of several cyanobacteria and diatom species as well as unicellular and filamentous green algae (R. Garrick, pers. comm.). The only common, externally derived organic material identified in the sediment core were penguin feathers blown in from a nearby rookery, and these have a $\delta^{13}\text{C}$ value of -22.1‰ , although their contribution to the total organic content and $\delta^{13}\text{C}$ of the sediments is small. A solitary lump of mucilaginous organic material which occurred at 37 cm depth had a similar $\delta^{13}\text{C}$ value (-10.5‰) to that obtained from the meltwater stream (Table 5) and significantly higher than the bulk of the organic material, suggesting that it may also have actually been washed into the lake.

The transition from marine to lacustrine condi-

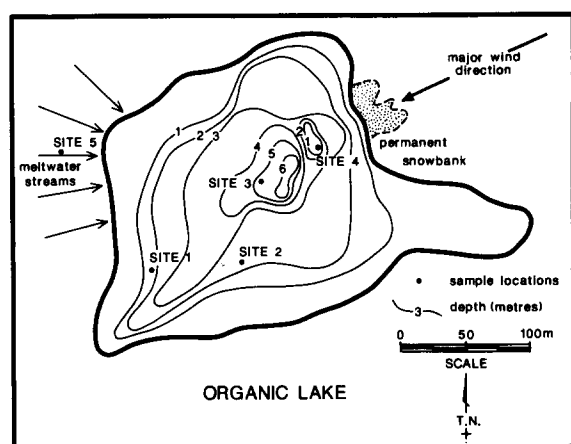


Fig. 8. Bathymetric map of Organic Lake showing the location of grab samples collected for analysis (adapted from Franzmann et al., 1987).

TABLE 6

$\delta^{13}\text{C}$ values in organic matter from lake and stream surface sediment samples, Organic Lake

Sample	Water depth ^a (m)	$\delta^{13}\text{C}_{\text{PDB}}$ (‰)	1 N HCl treatment
Site 5	0.05	-10.8	no effervescence, no H_2S
Site 4	1.5	-14.8	mild effervescence, no H_2S
Site 1	3.0	-18.5	strong effervescence, H_2S
Site 2	4.0	-18.6	mild effervescence, no H_2S
Site 3	6.7	-20.4	no effervescence, no H_2S

^aDepths were measured at the time of collection, and differ from those on Fig. 8 due to a rise in lake level since the last bathymetric survey (as reported in Franzmann et al., 1987) was undertaken.

tions in Organic Lake is accompanied by an increase in organic carbon content, $\delta^{13}\text{C}$ values and sulfur contents. This is consistent with increasing light and nutrient levels as the land emerged from the sea and a flourishing microbial community. Following isolation from the sea, increasing salinity led to a fall-off in microbial activity, with a consequent decrease in organic carbon content, $\delta^{13}\text{C}$ values and sulfur content of the sediments. The very low sulfur contents in the lacustrine section of the core suggest that the core locality has been above the oxic–anoxic interface in the lake since soon after its formation and that bacterial sulfate-reduction is now negligible (although the H_2S odour of the sediments indicates that sulfate reduction must have been occurring at some time).

The marine–lacustrine transition in Highway Lake is also marked by a rapid increase in organic carbon content and $\delta^{13}\text{C}$ values, although neither is exactly coincident with the sedimentological transition (Fig.6). Again these increases are interpreted as due to an increase in biological activity accompanying the emergence of the land and isolation of the lake from the sea. Organic carbon content remains erratically high, however the $\delta^{13}\text{C}$ value decreases from -13.3‰ at 185 cm to a low of -23‰ at 70 cm depth, before rising again to -18.0‰ at the sediment–water interface. The decrease in $\delta^{13}\text{C}$ value is accompanied by a doubling in sulfur content, suggesting that the low $\delta^{13}\text{C}$ values may be the result of the formation of an anoxic zone in the lake, coupled with a decrease in microbial activity in the overlying water column. As the core was taken from the deepest part of the lake, the presence of an anoxic zone in the lake in the past, would have been recorded by the sediments in the core.

The interpretation of the Ace Lake data (Fig.9) is again hampered by a lack of unequivocal evidence as to the marine or lacustrine origin of units 2 and 3. Unlike Highway and Organic Lakes, the increase in organic carbon content accompanying the transition between Units 1 and 2 is not accompanied by an increase in $\delta^{13}\text{C}$ value, which decreases to low values between -22 and -25‰ . The sulfur content increases dramatically and is inversely related to $\delta^{13}\text{C}$ values, suggesting the

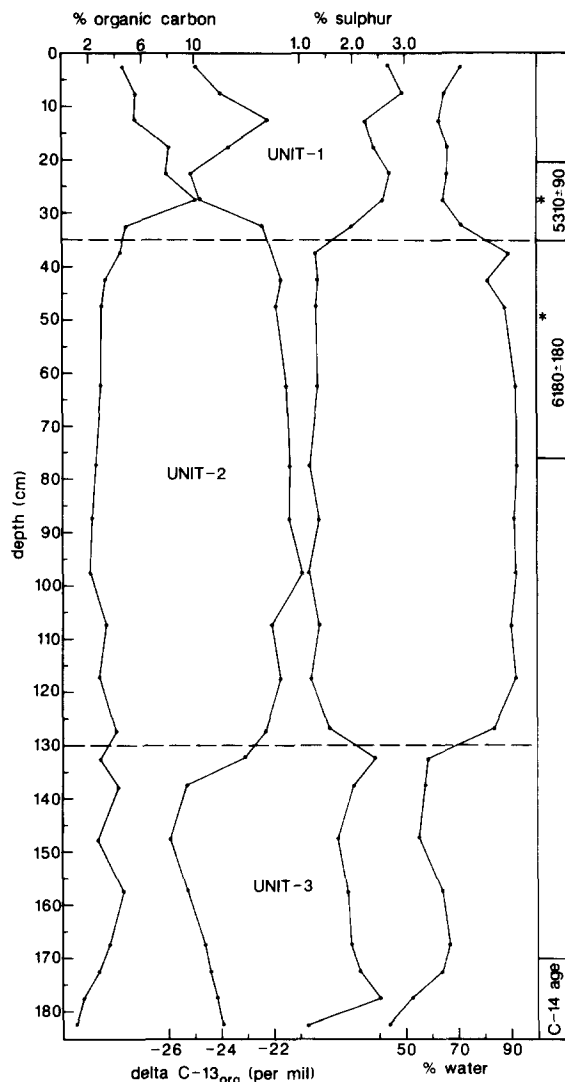


Fig.9. Chemical and isotopic composition of Ace Lake sediments (asterisk in ^{14}C column indicates weighted depth of sample).

deposition of Unit 1 sediments under anoxic conditions, as are presently observed in the lake.

The old ^{14}C age obtained for the Unit 1–Unit 2 transition (Table 3) coupled with sedimentological characteristics and constant $\delta^{13}\text{C}$ values suggest that Unit 2 is of marine origin. However, if this interpretation is accepted then it becomes difficult to interpret the characteristics of Unit 3, which must also then be of marine origin. Sedimentological characteristics, low $\delta^{13}\text{C}$ value, high sulfur and organic carbon contents, all suggest accumulation

of the Unit 3 sediments under anoxic lacustrine conditions, in the same manner as Unit 1. The alternative is that no marine sediments were penetrated by the core, and that Unit 2 represents a period when the lake was well mixed, separating two periods of meromixis. This interpretation is consistent with the sulfur-isotope results of Burton and Barker (1978) which indicate at least two periods of meromixis in the lake, separated by a holomictic phase. However, the probable age of the sediments at the bottom of the core is then inconsistent with the likely timing of isolation of the lake (assuming emergence rates similar to those calculated for Organic and Highway Lakes). Further work is required to resolve this disparity.

The $\delta^{13}\text{C}$ and sulfur profiles for Ace Lake are remarkably well correlated with the algal and bacterial hydrocarbon profiles obtained by Volkman et al. (1986). The hydrocarbon profiles were obtained from a core taken from the centre of the lake, and the results were interpreted by Volkman et al. (1986) as indicating an upper 40 cm of anoxic sediments, followed by 60 cm of oxic sediments and a lower 50 cm of oxic/anoxic sediments.

Carbonates

Regular light-coloured laminations separated by dark organic and clastic material are a conspicuous feature of both the Organic Lake and Ace Lake sediments. The laminations are generally less than 2 mm thick and are composed of authigenic calcium carbonate. Calcium carbonate is also a minor component of the Ellis Fjord and Taynaya Bay sediments.

The precipitation of carbonate minerals in lacustrine and semi-isolated marine environments has been widely reported (Kelts and Hsü, 1978; Last and Schweyen, 1985; Anderson and Dyrssen, 1987) and numerous examples have been recorded from Antarctic lakes (Burton, 1981; Wharton et al., 1982, 1983). Such calcium carbonate can be precipitated biogenically, as a result of photosynthesizing organisms (algae, cyanobacteria and bacteria) depleting the water column in CO_2 (Krumbein, 1979) or inorganically through solute concentration changes or the warming of frigid brines (Thompson and Nelson, 1956). As rates of organic matter

degradation and sulfate reduction in the sediments are low (Volkman et al., 1986) it is unlikely that the oxidation of organic material in the sediments by anaerobic bacteria is a significant calcification process, as has been suggested for other areas (Lyons et al., 1984).

A detailed study of authigenic carbonates in the Organic Lake sediments indicates a major peak in abundance at the base of unit 1 (Fig. 7), due primarily to the presence of monohydrocalcite (identified by XRD), with minor aragonite. Monohydrocalcite has been only rarely reported from lacustrine environments, the best documented occurrence being that at Lake Fellmongery, south-eastern South Australia, where the mineral forms a tufa-like beachrock around the margins of the lake. Taylor (1975) cited a high Mg/Ca ratio, high pH and microbial activity as requirements for the formation of the mineral in the lake. As the Mg/Ca ratio in Organic Lake is currently 6.5–7.3 (~ 1.5 times seawater) and as the $\delta^{13}\text{C}$ data discussed in the preceding section suggest a peak in microbial activity at the base of Unit 1, it is likely that the same factors were responsible for the formation of monohydrocalcite in Organic Lake. In contrast to the pelletal morphology exhibited by the Lake Fellmongery examples, SEM examination of the Organic Lake material revealed that the monohydrocalcite occurs as platy aggregates up to 10 μm across.

Pronounced carbonate bands which are particularly well developed from 24 to 28 cm depth in the Organic Lake sediments are composed exclusively of aragonite. The aragonite occurs as regularly sized pelloids 5 μm long and 2 μm in diameter, occasionally with several pelloids cemented together to form irregularly branching clusters.

At the top of the core, the aragonite pelloids could not be identified by SEM, although carbonate content of the sediments remains relatively high and it is likely that inorganic carbonate precipitation gradually replaced biogenic precipitation as the lake became hypersaline and microbial activity decreased. Temperatures at higher levels in the lake fluctuate widely on an annual basis (Franzmann et al., 1987) and this would provide a suitable mechanism for carbonate precipitation in the modern lake environment.

Variations in the $\delta^{13}\text{C}$ values of carbonate formed in lacustrine environments can be related to fluctuations in productivity within the lake, due to the preferential removal of ^{12}C by photosynthesizing organisms (Pearson and Coplen, 1978; Last and Slezak, 1986). The incorporation of isotopically light CO_2 derived from the microbial degradation of organic matter or isotopically heavy CO_2 formed as a by-product of methanogenesis may also affect the $\delta^{13}\text{C}$ values of precipitated carbonate.

The $\delta^{13}\text{C}$ values of carbonates from Organic Lake sediments range from -7.3‰ to $+7.3\text{‰}$. Values in the marine section of the core are lighter as a result of the incorporation of isotopically light CO_2 derived from the microbial degradation of organic matter. The values are similar to values obtained from Ellis Fjord and Taynaya Bay, which range as low as -10.0‰ , and in Ellis Fjord at least, high levels of microbially-generated CO_2 have been reported from the anoxic portion of the water column (Gallagher et al., 1989). The low values are in contrast to the comparatively high values ($+1.6$ to $+4.6\text{‰}$) obtained from mollusc shells within the Organic Lake sediments.

A large increase in $\delta^{13}\text{C}$ accompanies the transition from marine to lacustrine conditions, indicating a substantial increase in productivity within the lake, and values fluctuate between $+4.5$ and $+7.3\text{‰}$ until the top ~ 10 cm of the sediments whereupon the values decrease. The uppermost carbonate sample has a $\delta^{13}\text{C}$ value of $+1.8\text{‰}$, roughly in equilibrium with atmospheric CO_2 , attesting to the presently observed very low microbial populations.

The $\delta^{18}\text{O}$ composition of authigenic carbonate is determined by the temperature and isotopic composition of the water from which the mineral has formed and can trace the isotopic history of the watermass from which the carbonate precipitated. A study of authigenic carbonates in Lake Vanda sediments, in the Antarctic Dry Valleys area, has been reported by Nakai et al. (1975).

Two carbonate samples from Ellis Fjord sediments have $\delta^{18}\text{O}$ values of $+30.1$ and $+31.0\text{‰}$ (excluding a third carbonate sample from 63 to 73 cm which is primarily derived from sea-urchin platelets, see Table 2). Assuming modern temper-

atures (0 – 2°C) yields $\delta^{18}\text{O}$ values for the water of approximately -3 to -4‰ (calcite–water isotopic fractionation curve of Friedman and O'Neil, 1977), similar to measured bottom-water isotopic values (Gallagher et al., 1989). The low $\delta^{18}\text{O}$ value obtained from carbonate in Taynaya Bay sediments ($+27.6\text{‰}$) indicates a component of meteoric water in the waters from which the carbonate precipitated, and indeed, modern shallow Taynaya Bay waters are substantially depleted in ^{18}O due to mixing with meltwaters (H.R. Burton, unpubl. data).

The $\delta^{18}\text{O}$ record provided by carbonate in Organic Lake sediments shows a steady decline in $\delta^{18}\text{O}$ from the deeper marine section of the core, where values are similar to those obtained from carbonate in marine inlet sediments, to the youngest lacustrine sediments. An initial rise in $\delta^{18}\text{O}$ at the base of Unit 1 suggests strong evaporation at that time, after which, input of meteoric waters progressively lowered the $\delta^{18}\text{O}$ of the lake waters, even though the lake was, and still is undergoing evaporative concentration. The aragonite-rich bands in the middle of Unit 1 have lower $\delta^{18}\text{O}$ values than the surrounding carbonate, suggesting high meltwater input and hence lower salinity in the lake at those times.

Carbonate in the uppermost sediments ($\delta^{18}\text{O} = +20\text{‰}$) would be in equilibrium with modern lake waters ($\delta^{18}\text{O} = -12$ to -13‰) at temperatures of $+5$ to $+10^\circ\text{C}$. Such temperatures are attained on a seasonal basis in the upper levels of the water column (Franzman et al., 1987), supporting the conclusion above, that carbonate precipitation in the modern lake environment is largely the result of seasonal warming of the lake waters and not related to biological activity.

Conclusions

Sedimentological, chemical and isotopic data from sediment cores provide information on the evolution of lakes and marine inlets in the Vestfold Hills. The $\delta^{13}\text{C}$ values of organic matter in the sediments appears to be particularly sensitive to changes in physico-chemical conditions in the overlying water-column, which in turn are partly depen-

dent on the bulk and composition of the microbial population in the lake.

Antarctic lakes are one of the few modern environments where microbial mat communities can flourish, due to the absence of a significant grazing fauna. The major factor controlling the $\delta^{13}\text{C}$ values of Antarctic-lake mat communities (e.g. Unit 1 — Highway Lake) appears to be CO_2 availability. This factor is also thought to control the $\delta^{13}\text{C}$ composition of microbial mats from highly saline lakes and sabkhas elsewhere in the world (Schidlowski et al., 1985; Schidlowski, 1986), in spite of the very large temperature and (in some cases) salinity differences between the environments. As CO_2 solubility increases at low temperatures, and therefore should be readily available, it is likely that the almost year-round ice-cover on the Antarctic lakes is responsible for limiting CO_2 availability. A study of modern Antarctic lake communities would add greatly to our understanding of the factors controlling carbon-isotope fractionation in microbial mat communities, particularly the effect of secondary factors such as light availability (both with depth and seasonal fluctuations), temperature and salinity.

The evolution of the lakes examined in this study, which have been emerging from the ocean at rates of about $1.0\text{--}2.1\text{ mm yr}^{-1}$, can be summarized as follows:

Organic Lake: Approximately 6000 yr B.P. the Organic Lake area was an arm of Taynaya Bay, and shallow marine sediments, including mollusc valves, were being deposited in the basin. As the land gradually emerged from the sea, productivity increased, and somewhere around 2700 yr B.P. the lake was episodically isolated from the marine inlet (Unit 2). This episodic isolation from the sea may have led to an increase in salinity at this time, and when the lake's marine connection was finally severed evaporation continued to increase the salinity of the lake. The amount of microbial activity peaked soon after the isolation of the lake (Unit 1) and thereafter began to decline to the presently observed low levels. No mat material is evident in the core, possibly because the higher input of terrigenous material at the core site, relative to the other lakes examined, was unfavourable for mat development. A small peak in sulfur abundance in

Unit 2 may indicate that the core locality was beneath the oxic/anoxic interface in the lake waters at this time. Monohydrocalcite and aragonite were periodically precipitated from the lake waters by both biological and chemical means.

Highway Lake: This area initially connected Long Fjord with Taynaya Bay at approximately 6000 yr B.P. (Peterson et al., 1988), and the uplift of the region would first have severed the lake's connection with Long Fjord. The oldest sediments penetrated by the core are approximately 6900 years old and regularly laminated marine sediments (Unit 2) were deposited until approximately 4700 yr B.P. when the connection with Taynaya Bay was abruptly severed and a microbial mat community established itself on the lake bottom (Unit 1). Productivity increased dramatically and meltwaters gradually replaced the original seawater. An anoxic zone developed in the lake at ~ 2000 yr B.P. and although this has now largely disappeared a remnant of it may still remain. A monotonous sequence of laminated algal mat material has been deposited throughout the history of the lake, and chemical/isotopic techniques were required to infer the several stages in the evolution of the lake.

Ace Lake: As discussed in preceding sections the interpretation of the data from this lake is ambiguous, however, the balance of evidence suggests that no marine sediments were penetrated by the core. The oldest sediments in the core were deposited under anoxic conditions, with limited mat development at the top of Unit 3. The anoxic zone then disappeared and throughout the deposition of Unit 2, the lake was well mixed with a sequence of fine-grained algal muds being deposited which are macroscopically similar to the marine-inlet sediments. Anoxic conditions and mat communities were re-established in the lake at approximately 5400 yr B.P. and have remained until the present.

^{14}C -dating has provided a useful framework against which to examine the evolution of the lakes and to calculate sedimentation and relative emergence rates. However, the interpretation of ^{14}C data is hampered by the large variation in reservoir effects, dependent upon whether the sediments are marine or lacustrine in origin, and in the lacustrine environment on the degree of mixing of the lake

waters and the degree of equilibration of the lake's carbon pool with the atmospheric CO₂ reservoir.

Acknowledgements

We wish to acknowledge J. Ferris, J. Gibson, R. Garrick, J. Bauld, D. Thomas, E. Laing, J. Cali, D. Adamson and J. Pickard for their various assistance and/or advice during the course of this project. Stable-isotope analyses of lake waters were provided by J. Olley and C. Barnes of the CSIRO Division of Water Resources. The study was made possible by an ASAC grant (Project No. AUS/05/88) from the Australian Antarctic Division.

References

- Adamson, D. A. and Pickard, J., 1983. Late Quaternary ice movement across the Vestfold Hills, Antarctica. In: R. L. Oliver, P. R. James and J. B. Jago (Editors), *Antarctic Earth Science*. Aust. Acad. Sci., Canberra, pp. 465–469.
- Adamson, D. A. and Pickard, J., 1986a. Physiography and geomorphology of the Vestfold Hills. In: J. Pickard (Editor), *Antarctic Oasis*. Academic Press, Sydney, pp. 99–139.
- Adamson, D. A. and Pickard, J., 1986b. Cainozoic history of the Vestfold Hills. In: J. Pickard (Editor), *Antarctic Oasis*. Academic Press, Sydney, pp. 63–97.
- Aizenshtat, Z., Lipiner, G. and Cohen, Y., 1984. Biogeochemistry of carbon and sulfur in the microbial mats of the solar lake (Sinai). In: Y. Cohen, R. W. Castenholz and H. O. Halverson (Editors), *Microbial Mats: Stromatolites*. Liss, New York, N. Y., pp. 281–312.
- Anderson, L. G. and Dyrssen, D., 1987. Formation of chemogenic calcite in super-anoxic seawater — Framvaren, southern Norway. *Mar. Chem.*, 20: 361–376.
- Barker, R. J., 1981. Physical and chemical parameters of Deep Lake, Vestfold Hills, Antarctica. *ANARE Sci. Rep.*, B130, 73 pp.
- Bayly, I. A. E. and Burton, H. R., 1987. Vertical distribution of *Paralabidocera antarctica* (Copepoda: Calanoida) in Ace Lake, Antarctica, in summer. *Aust. J. Mar. Freshw. Res.*, 38: 537–543.
- Behrens, E. W. and Frishnan, S. A., 1971. Stable carbon isotopes in blue-green algal mats. *J. Geol.*, 79: 94–100.
- Burch, M. D., 1988. Annual cycle of phytoplankton in Ace Lake, an ice covered, saline meromictic lake. *Hydrobiologia*, 165: 59–76.
- Burke, C. M. and Burton, H. R. 1988. Photosynthetic bacteria in meromictic lakes and stratified fjords of the Vestfold Hills, Antarctica. *Hydrobiologia*, 165: 13–24.
- Burton, H. R., 1980. Methane in a saline Antarctic Lake. In: P. A. Trudinger and M. R. Walter (Editors), *Biogeochemistry of Ancient and Modern environments*. Aust. Acad. Sci., Canberra, pp. 243–250.
- Burton, H. R., 1981. Chemistry, physics and evolution of Antarctic saline lakes: a review. *Hydrobiologia*, 82: 339–362.
- Burton, H. R. and Barker, R. J., 1978. Sulfur chemistry and microbiological fractionation of sulfur isotopes in a saline Antarctic lake. *Geomicrobiol. J.*, 1: 329–340.
- Burton, H. R. and Campbell, P. J., 1980. The climate of the Vestfold Hills, Davis station, Antarctica, with a note on its effect on the hydrology of hypersaline Deep Lake. *ANARE Sci. Rep.*, D129, 50 pp.
- Calder, J. A. and Parker, P. L., 1973. Geochemical implications of induced changes in C¹³ fractionation in blue-green algae. *Geochim. Cosmochim. Acta*, 37: 133–140.
- Collerson, K. D. and Sheraton, J. W., 1986. Bedrock geology and crustal evolution of the Vestfold Hills. In: J. Pickard (Editor), *Antarctic Oasis*. Academic Press, Sydney, pp. 21–62.
- England, J., 1983. Isostatic adjustments in a full glacial sea. *Can. J. Earth Sci.*, 20: 895–917.
- Franzmann, P. D., Deprez, P. P., Burton, H. R. and Van den Hoff, J., 1987. Limnology of Organic Lake, Antarctica, a meromictic lake that contains high concentrations of dimethyl sulphide. *Aust. J. Mar. Freshw. Res.*, 38: 409–417.
- Friedman, I. and O'Neil, J. R., 1977. Compilation of stable-isotope fractionation factors of geochemical interest. In: M. Fleischer (Editor), *Data of Geochemistry* (6th ed.). U. S. Geol. Surv. Prof. Pap., 440-KK, 12 pp.
- Gallagher, J. B. and Burton, H. R., 1988. Seasonal mixing of Ellis Fjord, Vestfold Hills, East Antarctica. *Estuarine, Coastal Shelf Sci.*, 27: 363–380.
- Gallagher, J. B., Burton, H. R. and Calf, G., 1989. Meromixis in an Antarctic fjord: a precursor to meromictic lakes on an isostatically rising coastline. *Hydrobiologia*, 172: 235–255.
- Gibson, J. A. E., Garrick, R. C., Franzmann, P. D., Deprez, P. P. and Burton, H. R., 1991. Reduced sulfur gases in saline lakes of the Vestfold Hills, Antarctica. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 84: 131–140.
- Hand, R. M., 1980. Bacterial populations of two saline Antarctic lakes. In: P. A. Trudinger and M. R. Walter (Editors), *Biogeochemistry of Ancient and Modern Environments*. Aust. Acad. Sci., Canberra, pp. 123–129.
- Hand, R. M. and Burton, H. R., 1981. Microbial ecology of an Antarctic saline meromictic lake. *Hydrobiologia*, 82: 363–374.
- Harkness, D. D., 1979. Radiocarbon dates from Antarctica. *Br. Antarct. Surv. Bull.*, 47: 43–59.
- Kelts, K. and Hsü, K. J., 1978. Freshwater carbonate sedimentation. In: A. Lerman (Editor), *Lakes — Chemistry, Geology, Physics*. Springer, New York, N. Y., pp. 295–323.
- Krumbein, W. E., 1979. Calcification by bacteria and algae. In: P. A. Trudinger and D. J. Swaine (Editors), *Biogeochemical Cycling of Mineral-forming Elements*. Elsevier, New York, N. Y., pp. 47–68.
- Last, W. M. and Schweyen, T. H., 1985. Late Holocene history of Waldsea Lake, Saskatchewan, Canada. *Quat. Res.*, 24: 219–234.
- Last, W. M. and Slezak, L. A., 1986. Paleohydrology, sedimentology, and geochemistry of two meromictic saline lakes in southern Saskatchewan. *Géogr. Phys. Quat.*, 40: 5–15.
- Lyons, W. B., Long, D. T., Hines, M. E., Gaudette, H. E. and

- Armstrong, P. B., 1984. Calcification of cyanobacterial mats in Solar Lake, Sinai. *Geology*, 12: 623–626.
- Matsubaya, O., Sakai, H., Torii, T., Burton, H. R. and Kerry, K., 1979. Antarctic saline lakes — stable-isotope ratios, chemical compositions and evolution. *Geochim. Cosmochim. Acta*, 43: 7–23.
- McLeod, I. R., 1964. The saline lakes of the Vestfold Hills, Princess Elizabeth Land. In: R. J. Adie (Editor), *Antarctic Geology*. North-Holland, Amsterdam, pp. 65–72.
- McCrea, J. M., 1950. The isotopic chemistry of carbonates and the paleotemperature scale. *J. Chem. Phys.*, 18: 849–857.
- Nakai, N., Wada, H., Kiyosu, Y. and Takimoto, M., 1975. Stable isotope studies on the origin and geological history of water and salts in the Lake Vanda area, Antarctica. *Geochem. J.*, 9: 7–24.
- Ohmoto, K., 1983. The problem and significance of radiocarbon geochronology in Antarctica. In: R. L. Oliver, P. R. James and J. B. Jago (Editors), *Antarctic Earth Science*. Aust. Acad. Sci., Canberra, pp. 450–452.
- Oliver, R. L., James, P. R., Collerson, K. D. and Ryan, A. B., 1982. Precambrian geologic relations in the Vestfold Hills, Antarctica. In: C. Craddock (Editor), *Antarctic Geoscience*. Univ. Wisconsin Press, Madison, pp. 435–444.
- Pardue, J. W., Scalani, R. S., Van Baalen, C. and Parker, P. L., 1976. Maximum carbon isotope fractionation in photosynthesis by blue-green algae and a green alga. *Geochim. Cosmochim. Acta*, 40: 309–312.
- Pearson Jr., F. J. and Coplen, T. B., 1978. Stable-isotope studies of lakes. In: A. Lerman (Editor), *Lakes — Chemistry, Geology, Physics*. Springer, New York, N. Y., pp. 325–339.
- Peterson, J. A., Findlayson, B. L. and Qingsong, Z., 1988. Changing distribution of late Quaternary lacustrine and littoral environments in the Vestfold Hills, Antarctica. *Hydrobiologia*, 165: 221–226.
- Pickard, J., Adamson, D. A. and Heath, C. W., 1986. The evolution of Watts Lake, Vestfold Hills, East Antarctica, from marine inlet to freshwater lake. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 53: 271–288.
- Rau, G. H., Sweeney, R. E. and Kaplan, I. R., 1982. Plankton $^{13}\text{C}/^{12}\text{C}$ ratio changes with latitude: differences between northern and southern oceans. *Deep-Sea Res.*, 29: 1035–1039.
- Sackett, W. M., 1986a. $\delta^{13}\text{C}$ signatures of organic carbon in southern high latitude deep sea sediments: paleotemperature implications. *Org. Geochem.*, 9: 63–68.
- Sackett, W. M., 1986b. Organic carbon in sediments underlying the Ross ice shelf. *Org. Geochem.*, 9: 135–137.
- Sackett, W. M., Eadie, B. J. and Exner, M. E., 1973. Stable isotope composition of organic carbon in recent Antarctic sediments. In: B. Tissot and F. Biennier (Editors), *Proc. 6th Int. Meet. Org. Geochem. Rueil-Malmaison*, pp. 661–671.
- Schidlowski, M., 1986. Isotopic geochemistry of microbial mat formation. *Abstr. 12th Int. Assoc. Sedimentol. Congr.*, Canberra, pp. 269.
- Schidlowski, M., Hayes, J. M. and Kaplan, I. R., 1983. Isotopic inferences of ancient biochemistries: carbon, sulfur, hydrogen and nitrogen. In: J. W. Schopf (Editor), *Earth's Earliest Biosphere: Its Origin and Evolution*. Princeton Univ. Press, Princeton, N. J., pp. 149–186.
- Schidlowski, M., Matzigkeit, U., Mook, W. G. and Krumbein, W. E., 1985. Carbon isotope geochemistry and ^{14}C ages of microbial mats from the Gavish Sabkha and the Solar Lake. In: G. M. Friedman and W. E. Krumbein (Editors), *The Gavish Sabkha*. Springer, New York, N. Y., pp. 381–401.
- Sofer, Z., 1980. Preparation of carbon dioxide for stable carbon isotope analysis of petroleum fractions. *Anal. Chem.*, 52: 1389–1391.
- Streten, N. A., 1986. Climate of the Vestfold Hills. In: J. Pickard (Editor), *Antarctic Oasis*. Academic Press, Sydney, pp. 141–164.
- Taylor, G. F., 1975. The occurrence of monohydrocalcite in two small lakes in the southeast of South Australia. *Am. Mineral.*, 60: 690–697.
- Thompson, T. G. and Nelson, K. H., 1956. Concentration of brines and deposition of salts from seawater under frigid conditions. *Am. J. Sci.*, 254: 227–238.
- Volkman, J. K., Allen, D. I., Stevenson, P. L. and Burton, H. R., 1986. Bacterial and algal hydrocarbons in sediments from a saline Antarctic lake, Ace Lake. *Org. Geochem.*, 10: 671–681.
- Volkman, J. K., Burton, H. R., Everitt, D. A. and Allen, D. I., 1988. Pigment and lipid compositions of algal and bacterial communities in Ace Lake, Vestfold Hills, Antarctica. *Hydrobiologia*, 165: 41–58.
- Wharton Jr., R. A., Parker, B. C., Simmons Jr., G. M., Seaburg, K. G. and Love, F. G., 1982. Biogenic calcite structures forming in Lake Fryxell, Antarctica. *Nature*, 295: 403–405.
- Wharton Jr., R. A., Parker, B. C. and Simmons Jr., G. M., 1983. Distribution, species composition and morphology of algal mats in Antarctic dry valley lakes. *Phycologia*, 22: 355–365.
- Wright, S. W. and Burton, H. R., 1981. The biology of Antarctic saline lakes. *Hydrobiologia*, 82: 319–338.
- Yoshida, Y. and Moriwaki, K., 1979. Some considerations on elevated coastal features and their dates around Syowa Station, Antarctica. *Mem. Nat. Inst. Polar Res. Jap. Spec. Issue*, 13: 220–226.
- Zhang, Q., Xie, Y. and Li, Y., 1983. A preliminary study of the evolution of the post late Pleistocene Vestfold Hills environment, East Antarctica. In: R. L. Oliver, P. R. James and J. B. Jago (Editors), *Antarctic Earth Science*. Aust. Acad. Sci., Canberra, pp. 473–477.