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Dry Valleys
J.W.G.

A SEDIMENTOLOGICAL STUDY OF THREE SALINE LAKES IN THE DRY VALLEYS OF VICTORIA LAND, ANTARCTICA

A thesis
submitted in partial fulfilment of the requirements
for the Degree
of
Master of Science in Earth Science
at the
University of Waikato
by

JOHN WATSON GUMBLEY

University of Waikato
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ABSTRACT

The Dry Valley region of Victoria Land is the largest ice-free area in Antarctica. Within the frigid arid environment of the Dry Valleys, where the mean annual air temperature is -20°C, there are several permanently ice-covered, amictic, saline lakes occupying undrained bedrock depressions. Three of these lakes, namely Lakes Vanda, Bonney and Joyce, have been studied with the aim of determining the nature of their bottom sediments and relating the stratigraphy of bottom sediment cores to Holocene climatic fluctuations. These lakes have an area of 0.8 to 5.2 km^2, are from 35 to 68m in maximum depth and have an ice-cover 3 to 4m thick. The lakes are chemically and thermally stratified and receive their water from meltwater streams draining the local glaciers.

The bottom sediments consist of detrital sands and silts, chemical precipitates and organic material. The detrital sediments consist of feldspar and quartz with smaller quantities of hornblende, augite, hypersthene and mica that are derived locally from the rocks exposed on the adjacent valley sides. These sediments are mainly wind-transported or, to a lesser extent, river-transported into the lakes. The wind derived sediments are either blown onto the lake-ice, where they eventually sink to the lake-floor, or they are blown into the moat developed about the shores of the lake in summer. The chemical precipitates consist mainly of gypsum, halite, aragonite and calcite whose constituent elements were derived from meltwater streams discharging into the lakes; however Lake Bonney also received dissolved

solids of marine origin about 300,000 years B.P. and 1,200 years B.P.

From the sequence of chemical precipitate - rich bands and grain-size cycles in cores from Lakes Vanda and Joyce, together with the stratigraphy in the Lake Bonney cores, a sequence of climatic fluctuations is inferred. Colder climatic phases are most probably associated with periods of low lake-level during which chemical precipitates formed following the concentration of brines under frigid evaporitic conditions. At these times the sediment input from meltwater streams was low because of the locking-up of water in valley glaciers, and the main source of sediment would probably then be wind-derived.

U/Th dating of the chemical precipitates has provided an absolute record of past climatic changes which indicate that the major glacier systems in the Dry Valley region were nonsynchronous. Low lake levels occurred in Lake Vanda some 2,000 and 5,500 years B.P. and on at least four earlier occasions. Sediment cores from Lake Joyce indicate a period of low lake-level about 3,000 years B.P. The Lake Bonney cores suggest periods of low lake-level occurred following each of the marine incursions into the valley (300,000 and 1,200 years B.P.) and that the advance of the Taylor Glacier into the Bonney Basin at least 10,000 years B.P. probably coincided with the Taylor I Glaciation. Frigid evaporitic conditions have continued to operate in Lake Bonney since 1,200 years B.P. with halite crystals forming on the lake-floor. However, the lake-level has been steadily rising over the last 500 years.

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CHAPTER I

INTRODUCTION

The Victoria, Wright and Taylor Valleys, often referred to as the Dry Valleys, together cover about 2,500 km^2 of the Victoria Land region of Antarctica. The ice-free valleys lie about 70 km north-west of Scott Base and are bounded by the Polar Plateau on the west and the Wilson Piedmont Glacier on the east (Fig. 1.1). The lakes studied are amictic, permanently ice-covered, and include Lake Vanda in the Wright Valley and Lakes Bonney and Joyce in the Taylor Valley.

Lake Vanda, which has a length of 5.64 km and a width of 1.51 km, occupies an undrained bedrock depression in the lowest part of the Wright Valley. Lake Bonney is situated at the terminal snout of the Taylor Glacier and is split into two lobes by a bedrock protuberance known as the Bonney Reigel. The western lobe, which adjoins the Taylor Glacier snout, is a lobate depression 1.8 km long, while the eastern lobe is elongate and about 4 km long. Lake Joyce occupies a near-circular basin, approximately 700 m in diameter, the south-eastern boundary of which is formed by the Taylor Glacier.

1.1 PURPOSE OF STUDY.

The objective of this study was to present a detailed description of the sedimentology of Lakes Vanda, Bonney and Joyce. The texture and mineralogy of the detrital bottom sediments has been studied so as to determine the mechanisms of transport and deposition of these sediments and to elucidate their provenance. The composition of the chemical precipitates

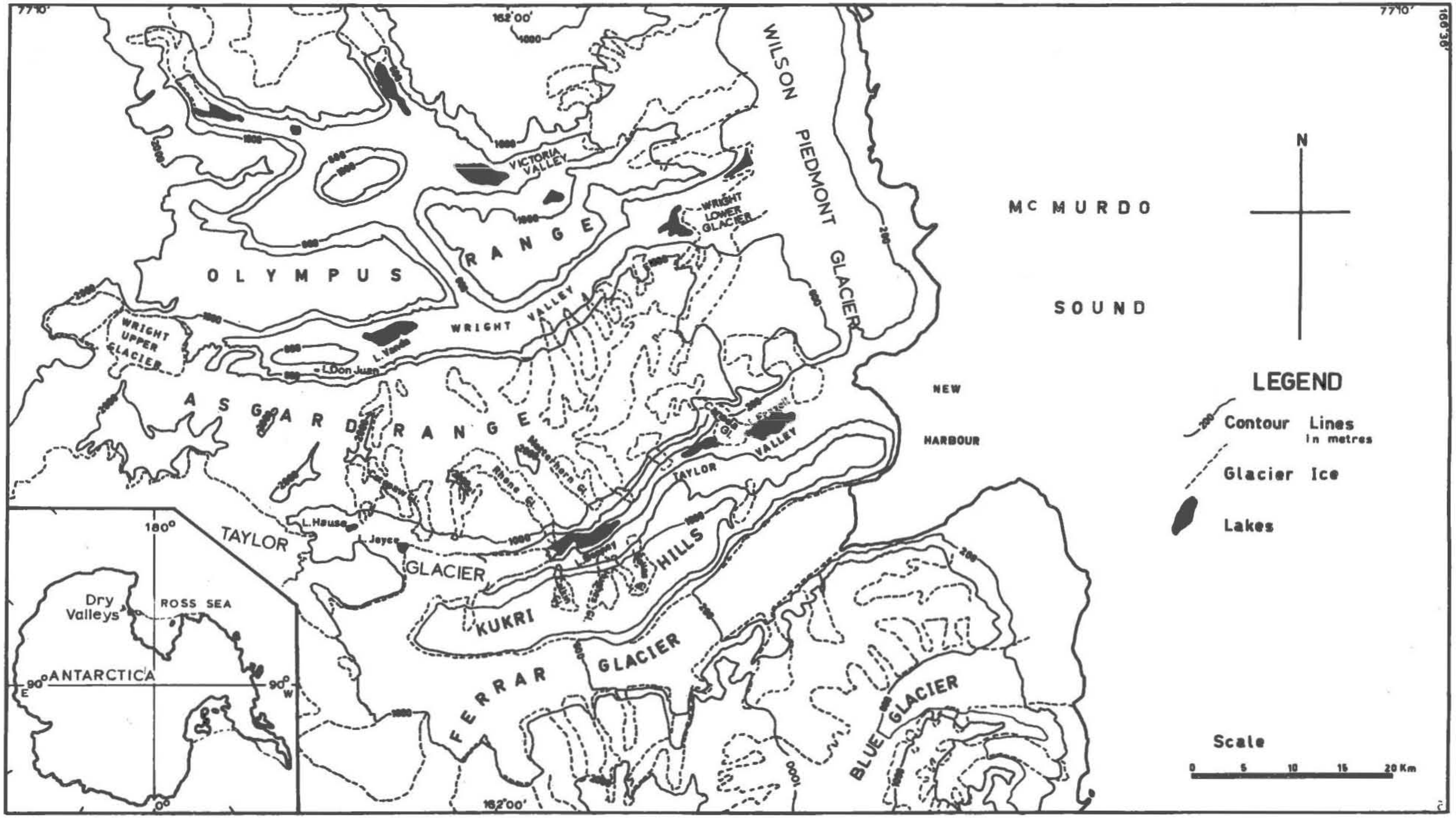


Fig. 1.1 Locality map of the Dry Valley region, Antarctica.

in the sediments was investigated with the aim of relating them to the chemical and physical composition of the lake waters.

From the study of the bottom sediments and the stratigraphy preserved in deep cores, a sequence of Holocene climatic fluctuations has been inferred.

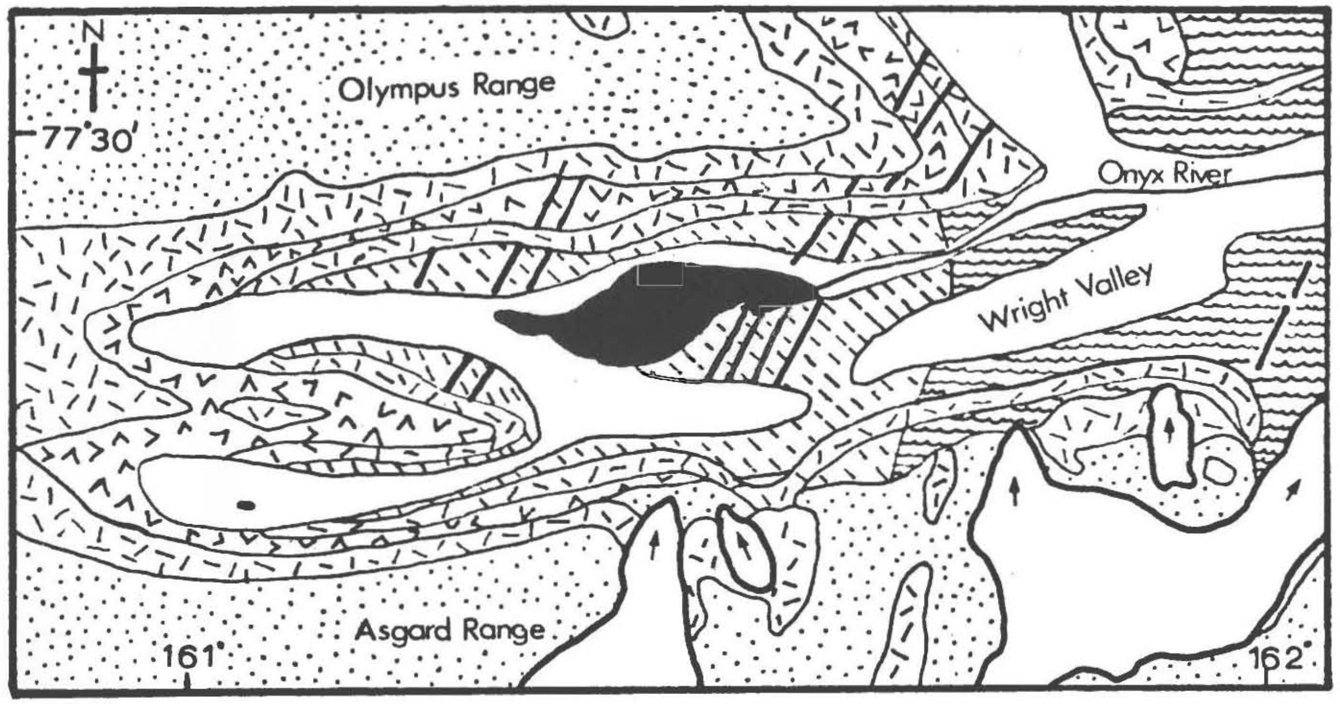
1.2 PREVIOUS WORKERS.

The literature concerning the geology of the Dry Valleys and the unique chemical structure of the waters in the lakes of this region is quite extensive (eg. Angino and Armitage, 1962; McKelvey and Webb, 1962; Haskell et al., 1965; Wilson, 1967; Boswell et al., 1967; Denton et al., 1971). Sedimentological data on the lakes of the Dry Valley region have been outlined only by Goldman et al. (1967), Nelson and Wilson (1972), the Dry Valley Drilling Project (1974), Craig et al. (1974) and McCabe (1974).

1.3 GEOLOGICAL SETTING.

The geology of the Dry Valleys (Fig. 1.2) consists of a basement of Precambrian to Cambrian metamorphic rocks of the Skelton Group and the Ordovician to Silurian granitic rocks of the Granite Harbour Intrusive Complex. The granites of the complex are intruded by a highly complex system of lamprophyre and porphyry dykes. The basement rocks are overlain by the Devonian to Jurassic sandstones of the Beacon Supergroup and the Jurassic to Cretaceous Ferrar Dolerites. The mineralogy of the above-mentioned rocks is summarised in Fig. 1.2. The geological record for the Lower Tertiary is as yet unknown (Neall and Smith, 1967). The Upper Tertiary however is represented in the geological record by moraine and by basalt flows and small scoria cones (McMurdo Volcanics).

WRIGHT VALLEY REGION



1 2 3 4 5 Km

TAYLOR VALLEY REGION

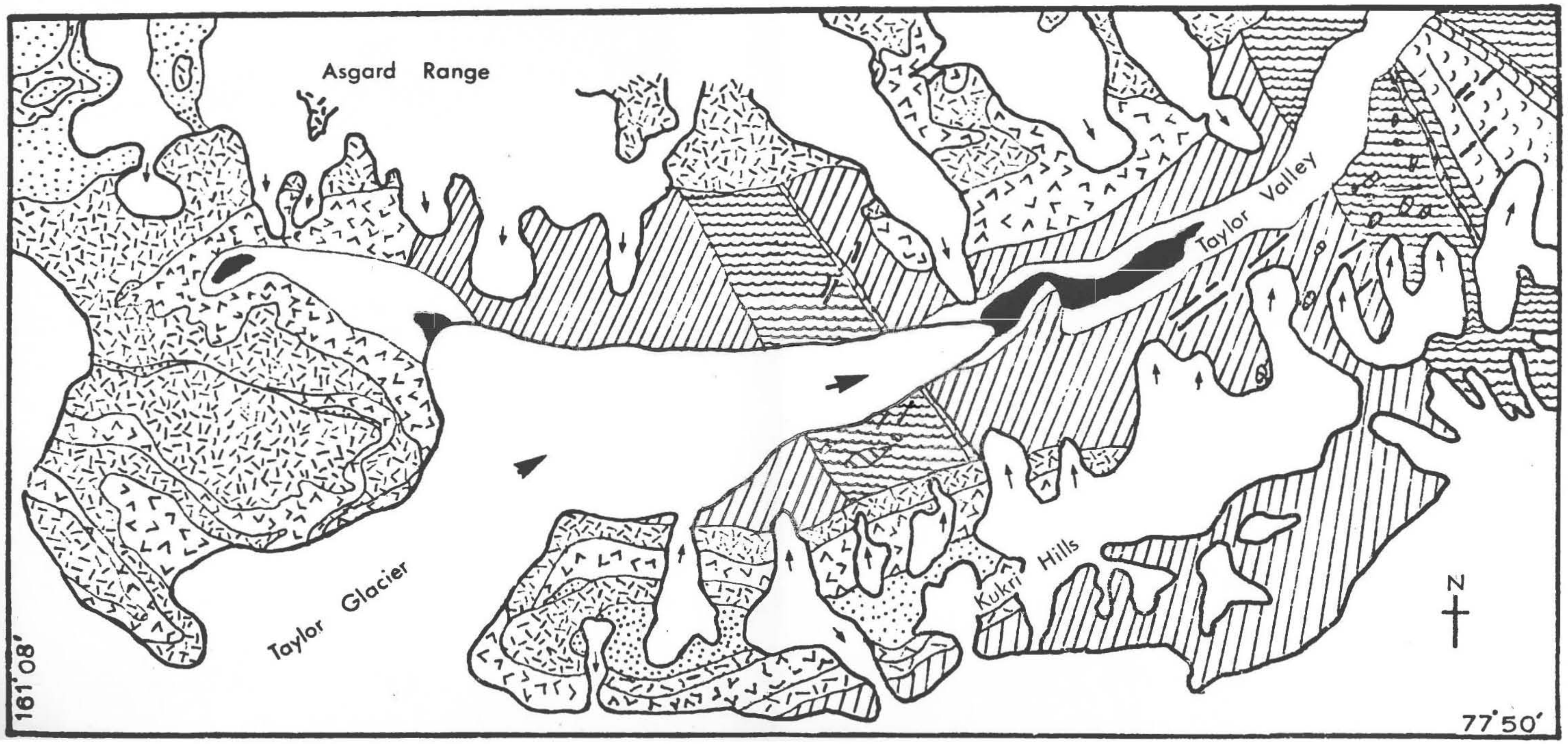


Fig. 1.2 Geological map of the Wright and Taylor Valley region, Antarctica.

L E G E N D

Lakes.			
Glaciers. (arrows show flow direction of glacier)			
Moraine and fluvioglacial deposits.			Recent to Upper Tertiary
Basalt flows and scoria with olivine and plagioclase.	McMurdo Volcanics		
Dolerite sills and dykes with pyroxenes and calcic plagioclase.	Ferrar Dolerite Formation		Jurassic
Quartzite siltstones and arkose of mainly quartz.	Beacon Sandstone Group		Triassic to Devonian
Lamprophyre dykes with augite, biotite and an andesine groundmass. Porphyry dykes with andesine-labradorite, hornblende, titano-augite, biotite and an orthoclase groundmass.			Silurian
Granite with quartz, oligoclase biotite and minor hornblende.	Irizar and Vida Granite	Granite Harbour Intrusive Complex	
Lamprophyre and porphyry dykes similar to above-mentioned dykes.			
Granitic rocks with quartz, plagioclase, biotite and minor. hornblende.	Larsen Granodiorite		Ordovician
	Olympus Granite Gneiss		
	Dias Granite		
Marble, schist and quartzite with calcite, quartz, feldspar, biotite, hornblende and garnet.	Skelton Group (Asgard Formation)		Cambrian to Pre Cambrian

Modified after McKelvey and Webb (1962) and Haskell *et al*. (1965).

The Late Cenozoic history of the Dry Valleys has been the subject of considerable investigation. That multiple glaciation has played a dominant role in shaping these valleys has been recognised by many workers (eg. Nichols, 1965; Denton et al., 1971; Calkin and Bull, 1974). Calkin and Bull (1974) grouped the main events in the history of the Dry Valleys, for the last several million years, into five sequential phases:

(1) alpine glaciation in the Tertiary; coalescence of glaciers flowing inland and formation of the ice sheet of Greater Antarctica;

(2) cutting and enlargement of the valleys by large outlet glaciers flowing from the ice sheet;

(3) final retreat of the through-valley outlet glaciers, accompanied by extensive meltwater erosion and followed, at least in the Wright and Taylor Valleys, by marine submergence;

(4) cooling, thinning of glaciers and valley emergence by late Pliocene to Pleistocence time, with 3 or 4 episodes of local alpine glaciation and glacial advances along the valleys from both ends; and

(5) the present (Holocene) phase, in which the local glaciers are nearly in equilibrium.

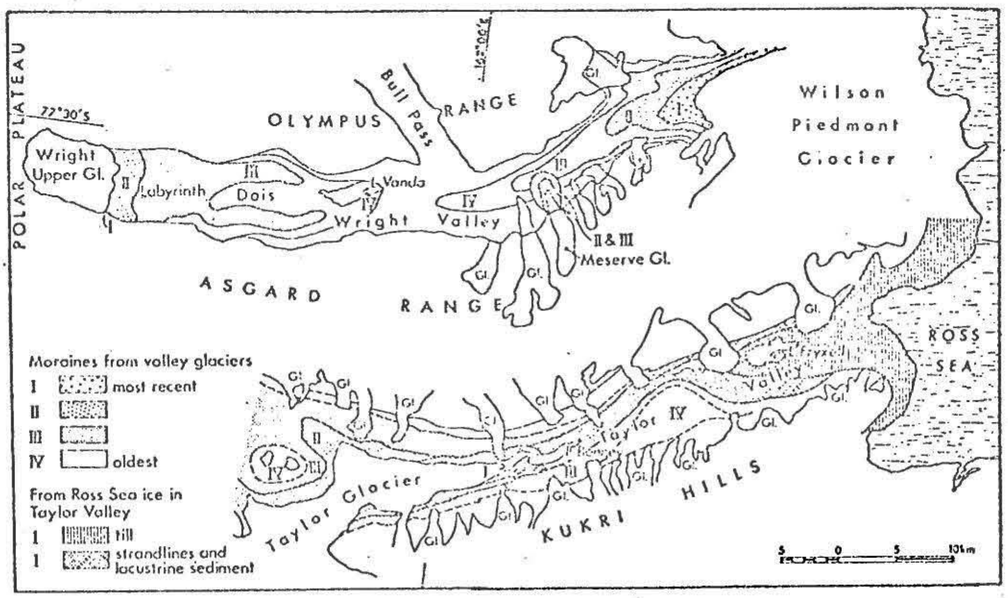
Past fluctuations of the three major glacier systems in the Dry Valleys were not synchronous. Therefore the history and chronology of each system must be considered independently, as indicated in Fig. 1.3. The first glacier system, the ice sheet of east Antarctica, is represented in the Dry Valleys by the Taylor and Wright Upper Glaciers. These two glaciers are small tongues of the ice sheet that spill over bedrock thresholds and occupy the western ends of the Taylor and Wright Valleys (Fig. 1.1). The second glacier system, the Ross Ice Shelf, has a number of ice tongues which extend westward up the

Dry Valleys from the Ross Sea. Finally, independent alpine glaciers occur throughout the Dry Valley region.

The Taylor Glacier drains the ice sheet in East Antarctica and on at least five occasions in the past (Fig. 1.3) increases in the surface level of the ice sheet have caused major advances in the Taylor Glacier. The present tongue of the Taylor Glacier is in physical contact with the deposits of Ross Sea I and Ross Sea II ages. Subsequent to the recession of Ross Sea I ice and concomitant draining of lake water from the Taylor Valley, the Taylor Glacier advanced across Ross Sea I strandlines, across moraines deposited by alpine glaciers during the Ross Sea II/I interval of ice recession and across Ross Sea II strandlines (Fig. 1.3). The data of Denton et al. (1970) indicate that the Taylor Glacier, the Wright Upper Glacier, and the adjoining ice sheet were smaller than at present during Ross Sea I and II times, and that they have since advanced.

Since the major valley-cutting period, the Wright Upper Glacier has invaded the west end of Wright Valley at least three times prior to the present (Fig. 1.3). The earliest of these advances, Wright Upper Glaciation IV, was the most extensive and extended to the east end of the depression now occupied by Lake Vanda.

The Dry Valleys have experienced possibly four west-flowing glacial invasions from the Ross Sea and McMurdo Sound areas. In the Wright Valley these advances have been recorded by movement of a lobe of the Wilson Piedmont Glacier, the Wright Lower Glacier. In the Taylor Valley during the Ross Sea II and Ross Sea I Glaciations, ice tongues from Ross Sea ice sheets pushed westward to the vicinity of the present Canada Glacier (Fig. 1.1). These tongues dammed large lakes in the Taylor Valley the strandlines



A

		VICTORIA VALLEY SYSTEM (Calkin, 1971a)	WRIGHT VALLEY (Modified after Nichols, 1971; Calkin and Bull, 1972; Behling, 1972): WRIGHT UPPER (INLAND ICE)	WRIGHT VALLEY: ALPINE	WRIGHT VALLEY: ROSS SEA (GROUNDED ROSS ICE SHELF)	McMURDO SOUND AND TAYLOR VALLEY (Denton and others, 1971): ROSS SEA (GROUNDED ROSS ICE SHELF)	McMURDO SOUND AND TAYLOR VALLEY: ALPINE	McMURDO SOUND AND TAYLOR VALLEY: TAYLOR (INLAND ICE)
PLEISTOCENE			I	I			I	I
	VICTORIA GLACIATION	PACKARD DRIFT EPISODE			WRIGHT LOWER	4 940 – I – 49 000	12 200	
			II				II 0.4 million	
		VIDA DRIFT EPISODE			TRILOGY	II		II
				II		III ↕ ?		
		BULL DRIFT			LOOP	IV 1.2 million		
			III ?	II a				III 1.6–2.1 million
—?— PLIOCENE			IV 4.2 million (↕ ?)	III			III 3.5 million	IV 2.7–3.5 million
		INSEL GLACIATION	VALLEY CUTTING EPISODE (S) (VANDA GLACIATION)		WRIGHT VALLEY FJORD STAGE			V etc

Figures represent years B.P.

B

Fig. 1.3 The extent of glacial advances (A) and the chronology and correlation of glacial episodes (B) in the Wright and Taylor Valleys. After Denton <u>et al</u>. (1970) and Calkin <u>et al</u>. (1970).

of which are common throughout the eastern half of the valley, those of Ross Sea I age occurring up to about 310 m in altitude and those of Ross Sea II age reaching 400 m (Denton et al. 1970).

The small alpine glaciers obviously respond more completely and quickly to changes in the local climate than do the axial glaciers considered above. In the Wright Valley, the alpine glaciers on the eastern part of the south side of the valley appear to be out of phase with the westward moving advances of the Wright Lower Glacier (Calkin et al., 1970). In the Taylor Valley, only minor fluctuations of alpine glaciers occurred, the youngest two alpine glaciations being opposite in phase to the Ross Sea Glaciations.

Evidence suggests that valley glaciation occurs when the ice sheet thickens, causing ice to pour over valley-head cols. The Ross Ice Shelf also thickens, perhaps as a result of surface-level changes in the East Antarctic ice sheet, and expands northwards, thus causing ice to intrude into the Dry Valleys. Wilson (1964) suggested the possibility that when the ice shelf advanced the supply of moisture to inland areas was reduced because incoming snow was forced to fall on the expanded ice shelf. This would have the effect of reducing alpine glaciation at that time when valley glaciation was at a maximum, and vice versa.

While the gross U-shaped cross-section of the Dry Valleys is undoubtedly the result of glacial action, the present frigid arid climate has greatly modified the terrain, largely through the influences of strong winds, fluvial action, frost riving and chemical weathering.

1.4 CLIMATE.

Features of the climate include low temperatures, low precipitation, low humidity and relatively low mean cloud cover.

At Lake Vanda the maximum and minimum mean monthly air temperature for 1970 was respectively + 2.4°C in January and - 36.9°C in July (Thompson et al., 1971). With the exception of January and December all months of the year have a mean air temperature below 0°C.

In the summer of 1969 and 1970 Vanda Station experienced a well developed sequence of up- and down-valley winds with velocities of generally 8 to 10 m/sec (Thompson et al., 1971). During the warmer part of the day easterly winds were recorded while "overnight", when the input of solar radiation was at a minimum westerlies occurred. Winter winds are generally light. In 1970 winds exceeded 17 m/sec (gale force or 33 knots) on 55 days, and the maximum gust recorded was 41 m/sec from the west on 6th August.

One can reasonably assume that the climate at Lake Bonney is similar to that at Lake Vanda. Lake Joyce, because of its higher altitude, experiences colder temperatures and predominantly westerly winds due to katabatic flow from the Polar Plateau.

The 1973/74 summer field season, in which the writer participated, was remarkably warm with temperatures above 0°C for two consecutive weeks.

1.5 DRAINAGE, BATHYMETRY AND LAKE-ICE THICKNESS.

Data obtained at Lake Vanda over the last five summers indicate little overland flow occurs into Lake Vanda except via the Onyx River (P.W. Anderton, pers. comm.). The supply of meltwater to the Onyx River is mainly from the Lower Wright Glacier. Hydrological data for the Onyx River for the 1971/72 (Hawes, unpublished) and 1973/74 summer season (P.W. Anderton, 1974, pers. comm.) are summarised in Table 1.1.

Table 1.1 Summary of Onyx River discharge characteristics.

1971 / 72	
Flow commenced on 29/1/71 and ceased on 9/2/72 (72 days)	
Mean daily discharge	23.29 (cusecs)
Maximum daily discharge	176.06 (cusecs)
Total volume	4.106×10^6 m^3
Daily sediment discharge	
Mean daily discharge	1.036 tons/day
Maximum daily discharge	15.298 tons/day
Total suspended sediment deposited into	
Lake Vanda for 1971 / 72 summer =	75.66 tons
1973 / 74	
(preliminary data)	
Flow commenced on 1/1/74 and ceased on 12/2/74 (43 days)	
Total volume	3.255×10^6 m^3

A generalised bathymetric map for Lake Vanda (Fig. 3.16) was constructed by Nelson and Wilson (1972). A maximum depth of 68.8m occurs near the centre of the western lobe of the lake within a 68m "depression" aligned roughly north-south across the general east-west trend shown by the shallower isobaths. The maximum depth zone appears to correspond to that position farthest removed from the influence of easterly and westerly sediment sources. The Lake Vanda ice-cover is about 1.7 to 3.2m thick (Cutfield, 1973).

Lake Bonney acts as a drainage trap for meltwater streams from the Rhone, Lacroix, Matterhorn, Calkin, Hughes and Sollas valley-side glaciers as well as the main Taylor Glacier (Fig. 1.1). The bathymetry of the west lobe (Fig. 4.23) indicates a lobate depression containing the deepest part of Lake Bonney (35m). The east lobe consists of a flat floored elongate basin some 33m deep. Prior to the 1973/74 summer thaw the Lake Bonney ice thickness was approximately uniform at 3 to 4m. Warm summer temperatures in the 1973/74 field season gave rise to considerable meltwater from the watershed glaciers which resulted in a rise in lake level of at least 1m. At the same time, the lake-ice thinned to 2 to 3m thickness.

Lake Joyce occupies a circular basin into which meltwater from the Taylor Glacier, Catspaw Glacier and an unnamed glacier to the west of Catspaw flow. The bathymetry of Lake Joyce (Fig. 5.5) is characterised by a narrow trough, 40m deep, trending south-east to north-west. The Taylor Glacier forms the 300m long south-east boundary of Lake Joyce with a moraine barrier separating the basin from the glacier for most of the lakes southern boundary. The average lake ice thickness is 3.5 to 4.2m although the ice is 7.2 m thick adjacent to the Taylor Glacier.

During the austral summer months a moat of water forms about most of the shores of all three lakes. The width of the moat varies although considerably greater melt-out occurs where meltwater streams enter the lakes. A moat up to 10m wide occurs where the Onyx River enters Lake Vanda and where the meltwater stream from the Lacroix and Sollas Glacier enters Lake Bonney.

The amount of meltwater flowing into the lakes, the thickness of the floating lake-ice and the width of the meltwater rim around the lakes varies considerably, both seasonally and annually.

1.6 PHYSICAL AND CHEMICAL DATA.

The lakes studied have unique temperature and chemical concentration gradients (Table 1.2 and Fig. 1.4). Chemical analyses of the lake water (Table 1.2) emphasise the highly saline nature of the lakes. The density of the Lake Vanda bottom water is 1.10 (Wilson, 1967) and 1.20 for Lake Bonney (Angino and Armitage, 1962). The salinity of Lakes Vanda, Bonney and Joyce is 138.2‰, 424.1‰ amd 2.3‰ respectively. The salinity values are calculated from chlorinity according to the empirical relationship : Salinity = 0.03 + 1.805 x chlorinity. The dense saline lake bottom waters appear to be conducive to the formation of the chemical precipitates listed in Table 1.3. Salt formation in Lakes Vanda and Bonney is probably aided by the relatively high concentrations of magnesium which has the effect of markedly decreasing the solubility of salts, particularly sodium chloride (Braitsch, 1971). The concentration of brines and deposition of salts under frigid conditions (Thompson and Nelson, 1956) is also a process that cannot be discounted in the formation of the Dry Valley lake chemical precipitates.

1.7 GENERAL SEDIMENT CHARACTERISTICS.

The lake-bottom detrital sediments consist of a varied assemblage of sands and silts whose mean size and sorting is related to proximity to meltwater stream outlets,

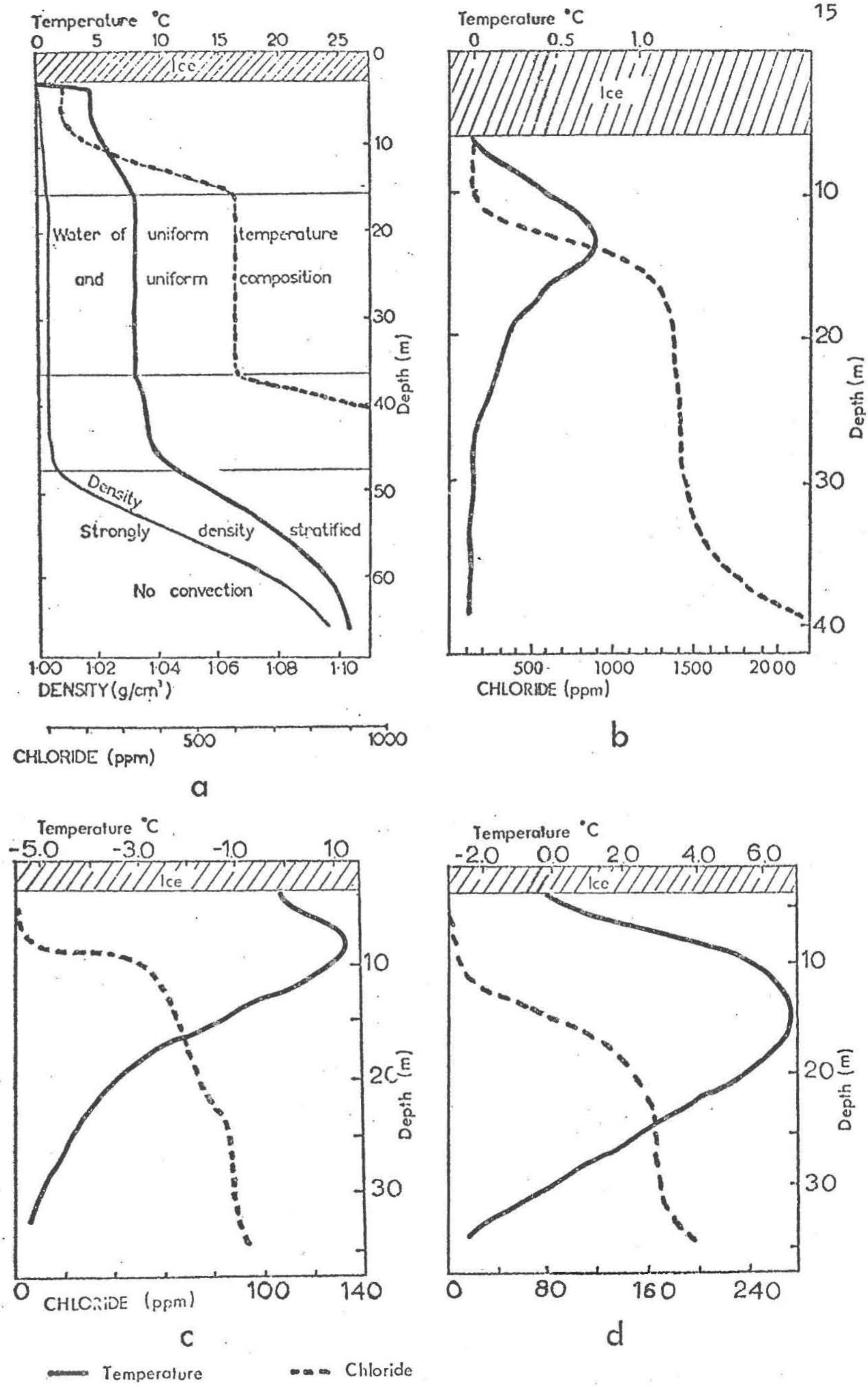
Table 1.2 Chemical analyses of the bottom water of the Dry Valley Lakes (after Boswell et al., 1967).

	Lake Vanda	Lake Bonney	Lake Joyce	Seawater
Na	11,300	94,200	1,250	10,500
K	350	3,900	95	380
Mg	35,300	43,000	215	1,350
Ca	1,600	1,200	35	400
Cl	127,400	248,000	2,150	19,000
Total Solids	176,500	390,900	5,000	35,000

Table 1.3 Approximate limiting density and salinity values within which various salts precipitate from solution (after Clarke, 1924).

Salt	Lower Limit		Upper Limit	
	Density	Salinity (ppt)	Density	Salinity (ppt)
$CaCO_3$	1.05	72	1.12	199
$CaSO_4$	1.12	199	1.20	332
$CaSO_4$ + NaCl	1.21	353	1.25	427
NaCl	1.27	457	1.30	523
Mg_2SO_4	1.21	353	1.30	523

Fig. 1.4 Temperature and chlorinity profiles for (a) Lake Vanda (b) Lake Joyce and the (c) west lobe and (d) east lobe of Lake Bonney. After Hoare et al. (1964), Wilson and Wellman (1962) and Hendy et al. (1973).


Temperature °C
0 5 10 15 20 25
Ice
Water of uniform temperature
and uniform composition
Density
Strongly density stratified
No convection
Depth (m)
1·00 1·02 1·04 1·06 1·08 1·10
DENSITY (g/cm³)
500 1000
CHLORIDE (ppm)
a
Temperature °C
0 0.5 1.0
Ice
Depth (m)
500 1000 1500 2000
CHLORIDE (ppm)
b
Temperature °C
-5.0 -3.0 -1.0 1.0
Ice
Depth (m)
0 100 140
CHLORIDE (ppm)
c
Temperature °C
-2.0 0.0 2.0 4.0 6.0
Ice
Depth (m)
0 80 160 240
d
Temperature
Chloride

wind-exposure and to lake water depth. The locally derived detrital sediments are either river-transported or wind-blown into the lakes. In Lakes Vanda and Joyce two broad sediment facies can be distinguished on the basis of sediment relationship to aerobic/anaerobic zones. The Lake Vanda aerobic sediments are generally medium grained sands often containing organic floc. The anaerobic sediments are generally fine to medium-grained sands that typically contain varve-like chemical precipitate and terrigenous silt bands. In Lake Joyce the aerobic sediments are fine-grained sands whereas the anaerobic sediments are fine to medium-grained sands that contain calcareous sand-silt bands. The highly saline bottom waters of the Lake Bonney east lobe have produced a sediment facies consisting almost entirely of halite. However, the Lake Bonney west lobe and remaining east lobe bottom sediments consist of detrital medium-grained sands and sandy silts that are intermixed with various chemical precipitates.

CHAPTER II

PROCEDURE

2.1 COLLECTING METHODS.

Sampling locations were planned so as to cover as fully as possible the various lake environments. Following augering with a Sipre Auger, lake bottom samples were collected using a 40cm - long gravity corer or a small cone-shaped gravity sampler. In addition eight longer cores were collected to elucidate the stratigraphy of Lakes Vanda and Bonney. In these cases the corer consisted of a steel pipe, 2m - long and 5cm in diameter, with a plastic liner (4cm in diameter). By lifting and dropping a lead sleeve on a second wire attached to the rig on the lake ice cover the core pipe was pounded into the sediment (Fig. 2.1).

At Lakes Vanda and Bonney sediment was also collected from the lake ice-cover and from the snout of the Taylor Glacier. Suspended sediment samples were collected at various levels in the water column at Lake Vanda using a Nansen water bottle.

The bottom sediments of Lake Vanda were collected by C.S. Nelson and A.T. Wilson in January, 1972. The Lake Vanda long cores and all the Lake Bonney samples were obtained by the writer in January, 1974. The Lake Joyce samples were

Fig. 2.1 Corer in use at Lake Vanda. Note strandlines on northern shore.

collected by the 1972/73 University of Waikato Expedition in January, 1973.

2.2. LABORATORY METHODS.

Cores were split longitudinally and described lithologically using the Wentworth grain size classification (Table 2.1) and the Revised (1967) Standard Soil Colour Charts (Oyama and Takehara, 1967). Figure 2.2 illustrates the procedure adopted for laboratory analyses.

Table 2.1 Grain size scale for sediments.

MILLIMETRES	PHI (Ø)	WENTWORTH SIZE CLASS	
		Boulder	GRAVEL
256	-8.0		
		Cobble	
64	-6.0		
		Pebble	
4	-2.0		
		Granule	
2	-1.0		
		Very coarse sand	SAND
1	0		
		Coarse sand	
0.5	1.0		
		Medium sand	
0.25	2.0		
		Fine sand	
0.125	3.0		
		Very fine sand	
0.063	4.0		
		Silt	MUD
0.0039	8.0		
		Clay	

Sediment textural classes (after Folk, 1968) were determined following analysis of the sand, silt and clay content. The textural parameters of mean grain size, standard deviation, Raw sediment

Reference sample

Total and inorganic carbon analyses

X-ray fluorescence (X R F) analyses

X-ray diffraction (X R D) analyses of chemical precipitates

Treat with dilute H_2O_2 for removal of organic matter Dry

Bulk sediment X R D analyses

Weigh. Treat with CH_3COOH to remove carbonate minerals. Dry, reweigh and calculate wt. % CO_3

Disperse with sodium metahexaphosphate (Calgon) and wet sievedwith a 4 ∅ (63 µ)sieve

Dry sand fraction and sieve at $\frac{1}{4}$ ∅ intervals for textural analyses

selected samples for heavy mineral separation using tetrabromoethane (S.G. = 2.7)

Microscopic analyses of light and heavy sand mineralogy

The %20 µ, 6 µ and 2 µ mud fractions determined using pipette methods

X R D analyses of clay fraction (<6 µ and <2 µ)

Fig. 2.2 Analytical procedure

skewness and kurtosis (Table 2.2) were calculated and compared using graphical methods.

Some attempt was made to calculate the percentages of minerals in samples using X-ray diffraction (X R D) techniques, although the inherent errors of the procedure in the presence of salts, and particularly carbonates (Runnells, 1970), is realised. The clay mineralogy was studied by X R D. Oriented particle mounts of the $< 6\ \mu$ and $< 2\ \mu$ fractions were prepared using the dropper-on-glass-slide technique. Identification of the clay minerals was based on the analyses of air-dry, glycolated, and heated (550°C) mounts (Carrol, 1970).

Selected gypsum, aragonite, calcite and halite samples from Lakes Vanda and Bonney were analysed with the University of Waikato Ortec X-ray fluorescent (X R F) analyser. Long-scan runs (2,000 seconds/sample) without standards were made to compare elemental peak intensity ratios between samples.

The mineralogy of the sand fraction was studied using a petrographic microscope with the distinction between glass ($\underline{n}$ = 1.50 - 1.51), quartz ($\underline{n}$ = 1.54) and feldspar ($\underline{n}$ = 1.52 - 1.58) being made by mounting sand grains in anisol ($\underline{n}$ = 1.518), an aromatic ester.

A Beckman Total Carbon Analyser was used to determine the inorganic and organic carbon content. Total carbon is determined by measuring the carbon dioxide produced in a

Graphic Mean

$$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Inclusive Graphic Standard Deviation

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Verbal Classification:

σ_I under 0.35ϕ	very well sorted (vws)
0.35 to 0.50ϕ	well sorted (ws)
0.50 to 0.71ϕ	moderately well sorted (mws)
0.71 to 1.0ϕ	moderately sorted (ms)
1.0 to 2.0ϕ	poorly sorted (ps)
2.0 to 4.0ϕ	very poorly sorted (vps)
over 4.0ϕ	extremely poorly sorted (eps)

Inclusive Graphic Skewness

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Verbal Classification:

Sk_I from +1.00 to +0.30	strongly fine-skewed (sfs)
+0.30 to +0.10	fine-skewed (fs)
+0.10 to -0.10	near-symmetrical (ns)
-0.10 to -0.30	coarse-skewed (cs)
-0.30 to -1.00	strongly coarse-skewed (scs)

Graphic Kurtosis

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

Verbal classification:

K_G under 0.67	very platykurtic (vpk)
0.67 to 0.90	platykurtic (pk)
0.90 to 1.11	mesokurtic (mk)
1.11 to 1.50	leptokurtic (lk)
1.50 to 3.00	very leptokurtic (vlk)
over 3.00	extremely leptokurtic (elk)

TABLE 2.1 Statistical Parameters (after Folk, 1968)

non-dispersant infra-red analyser after the sample has been subjected to a temperature of 950°C and passed on to a cobalt oxide catalyst. The total inorganic carbon content is measured similarly following the passage of the sample through a column (heated at 150°C) which contains quartz chips soaked in phosphoric acid. The difference between the two results gives the content of organic carbon.

Fig. 3.1 View of the Wright Valley from the west: Lake Vanda in foreground.

CHAPTER III

LAKE VANDA SEDIMENTS

3.1 INTRODUCTION.

The detrital sediment entering Lake Vanda is wind-blown or river-transported by the Onyx River (Table 1.1). Sample 13 is wind blown sediment obtained from the lake-ice at site 13. Sample 14 was collected by C. Hendy and R. Holdsworth from near site 6 (Fig. 3.16) during a storm lasting several days in late September, 1973. During gusts of at least sixty knots (R. Holdsworth, 1974, pers. comm.) the westerly to south-westerly winds blew sand in sheets that were generally no higher than 2m above the lake-ice surface although sheets were seen 10m above the lake, particularly in the area around site 1.

Sand grains settling on the lake ice begin to sink following the formation of an icy crust under the grains. Eventually the sand particle falls through the ice because of its insulating properties whereby melting takes place around and beneath the icy crust. The melting proceeds towards the surface of the ice resulting in the collapse of the unsupported crust.

Aerial photographs of Lake Vanda show a series of semi-parallel "dirtlines" on and within the lake-ice which are especially prominent along the southern side of the main lobe

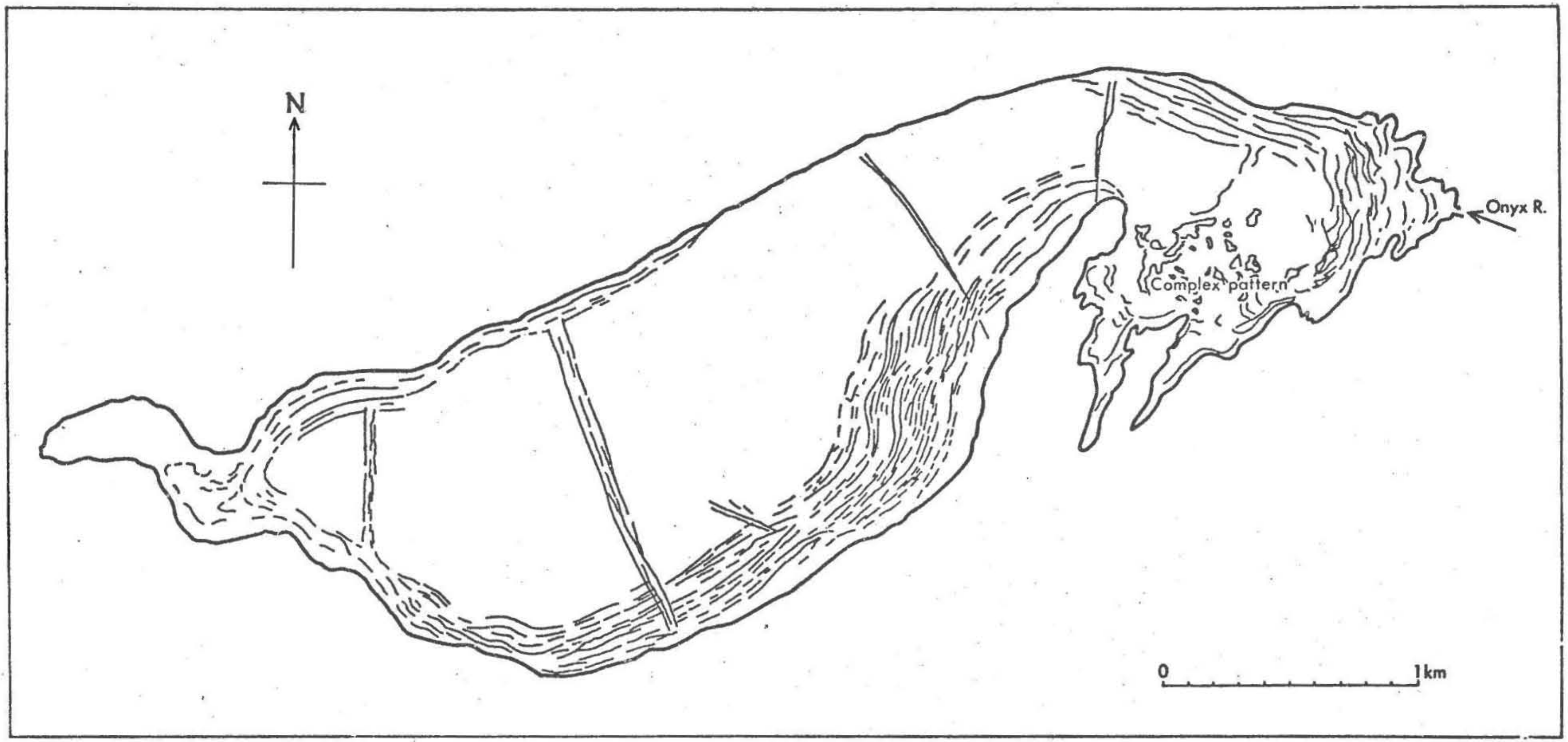


Fig. 3.2 "Dirt lines" on the Lake Vanda ice cover. The "dirt lines" appear as roughly aligned ablation pits and probably represent the inner edges of former moats.

of the lake (Fig. 3.2). On the ice surface the "dirtlines" appear as a series of roughly aligned ablation pits and probably represent the inner edges of former moats. The fact that the lines are not parallel to the depth contours suggests the ice cover, once free-floating is capable of lateral movement in strong winds.

3.2 GENERAL SEDIMENT CHARACTERISTICS.

The bottom sediments of Lake Vanda (Fig. 3.16) were shown by Nelson and Wilson (1972) to consist of a varied assemblage of organic rich, chemical precipitate-bearing, quartz and feldspar-rich sands. Broadly, two contrasting bottom sediment facies are present, each sharply separated by the 60m depth contour. Shallower than 60m the environment is aerobic and the sediments are mainly pale fawn, massive, medium quartz and feldspar-rich sands overlain by a lighter coloured layer of organic detritus up to 13cm thick (cores 1 and 3 - Fig. 3.3). In very shallow locations the sediments are difficult to core as they become increasingly gravelly and resemble those above the present shore of Lake Vanda.

In contrast, below 60m the environment is anaerobic, the sediments emit a strong hydrogen sulphide odour, and are grey and grey-green medium and fine-grained sands containing finely disseminated organic matter and variable, but significant

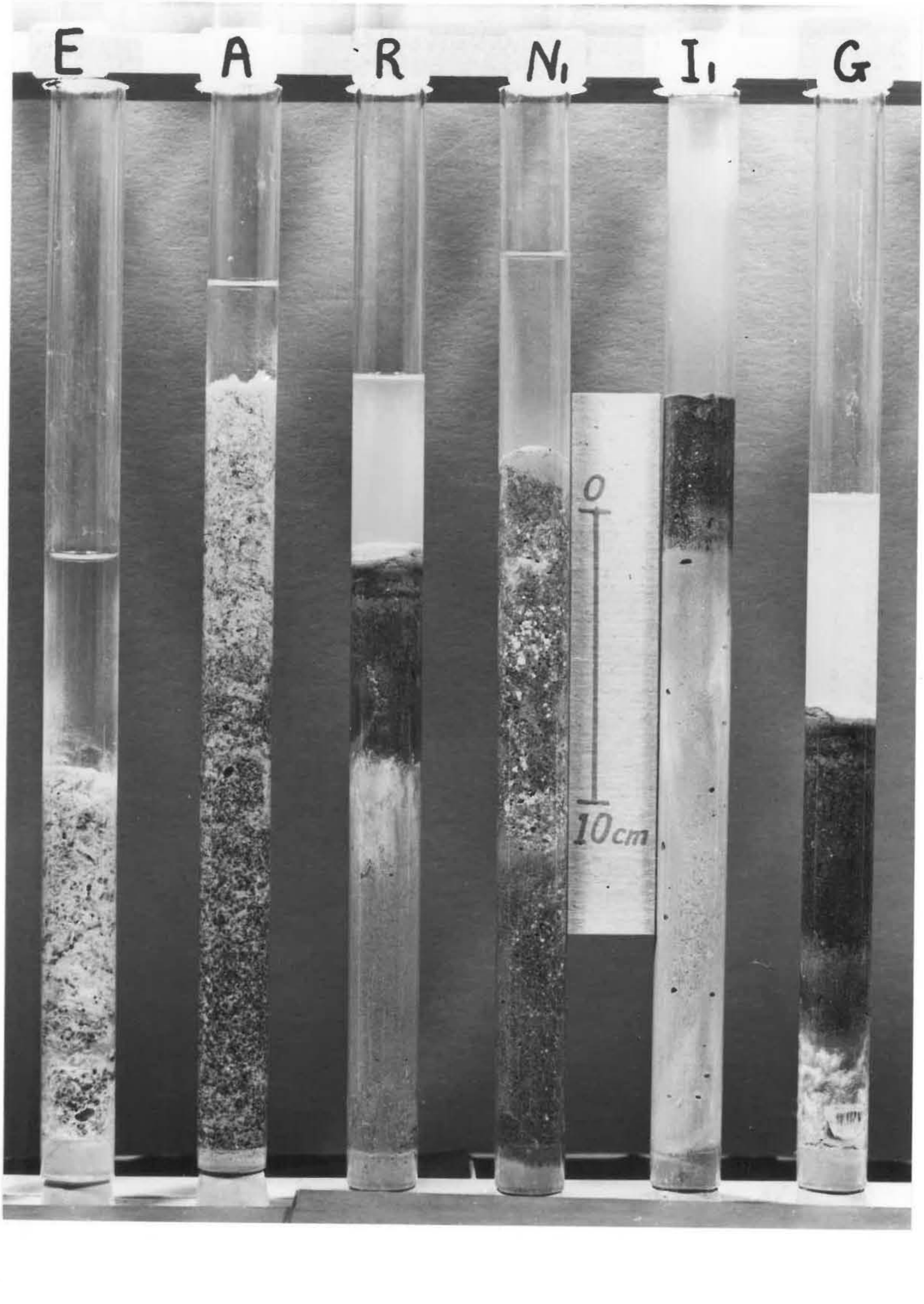


Fig. 3.3 Lake Vanda bottom sediment cores. Cores 1 (field notation A) and 3 (E) are aerobic sediments composed of medium grained sands overlain by lighter coloured organic floc. The anaerobic cores 15 (I), 16 (N) and 17 (R) consist of grey, medium to fine grained sands and chemical precipitates.

quantities of calcite and gypsum, often in the form of varve-like bands (cores 14, 15 and 16 - Fig. 3.3).

3.3 TEXTURE

The bottom sediments of Lake Vanda range from sand to silty sand only, which reflects the restricted range of variables acting on the sedimentary system (Fig. 3.4). Silty sand textures are restricted to bottom sediments at sites 6 and 7 which are located in the deepest part of the lake. Pure sand textures include the wind-blown samples 13 and 14 and the remaining samples whose water depths range from 14.0 to 67.8m. The stratigraphy of the site 6 deep core (Fig. 3.8) shows a series of chemical precipitate/terrigenous silt bands separated by detrital sand and silty sand (Fig. 3.5). The silty sands are generally located near the evaporitic bands and compared to the sandy samples, have higher organic carbon and chemical precipitate content.

The grain size parameters for the Lake Vanda bottom sediments are summarised in Table 3.1. Scatter plots of combinations of textural parameters are presented in an attempt to differentiate various lacustrine sub-environments (Fig. 3.7).

The mean grain size ranges from 2.9 ∅ (0.14mm) to 1.0 ∅ (0.50mm). Sediment sorting ranges from 0.6 ∅ (moderately well sorted) to 2.9 ∅ (very poorly sorted). The approximately north-south transect indicates that bottom sediments at depths of

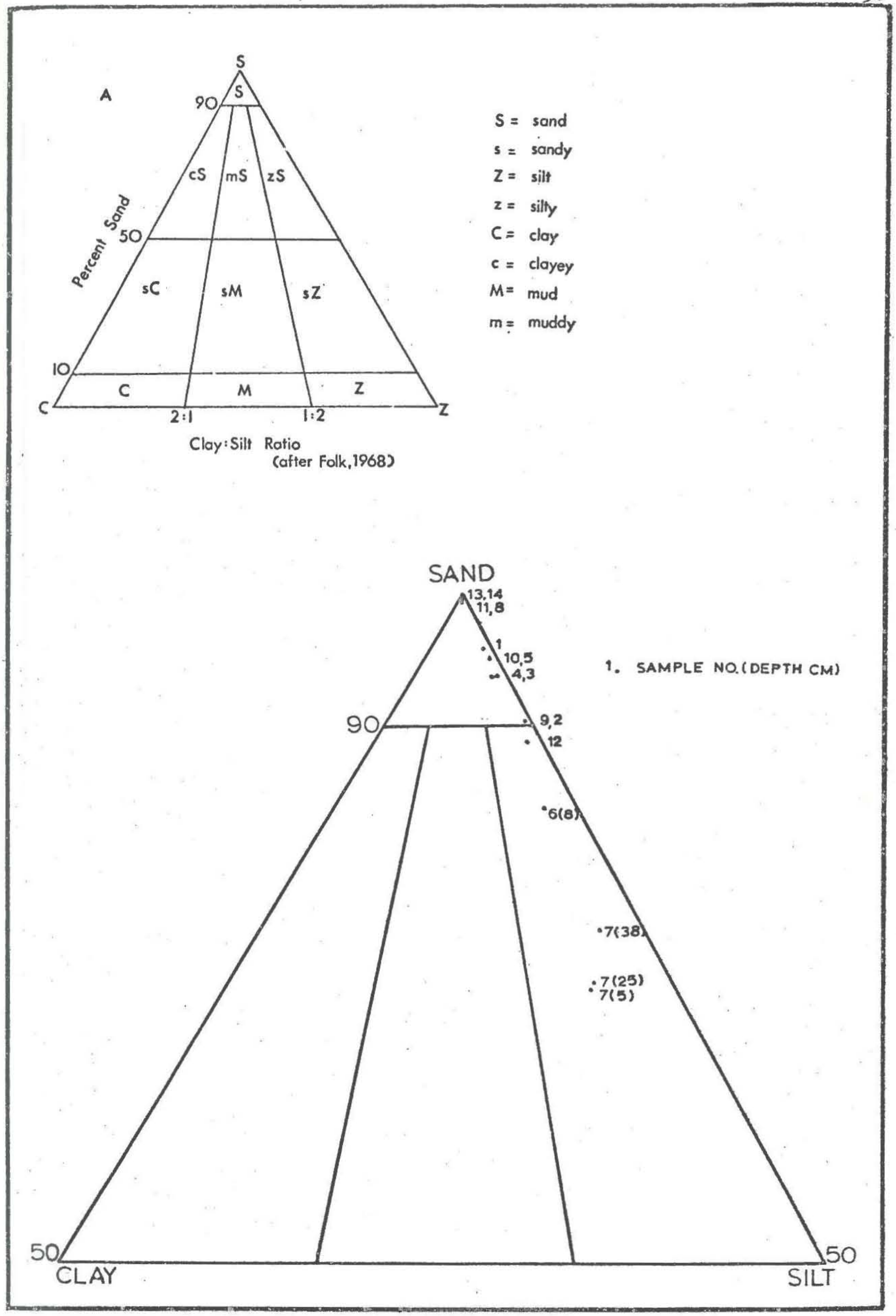


Fig. 3.4 Textural classes of detrital sediment of Lake Vanda.

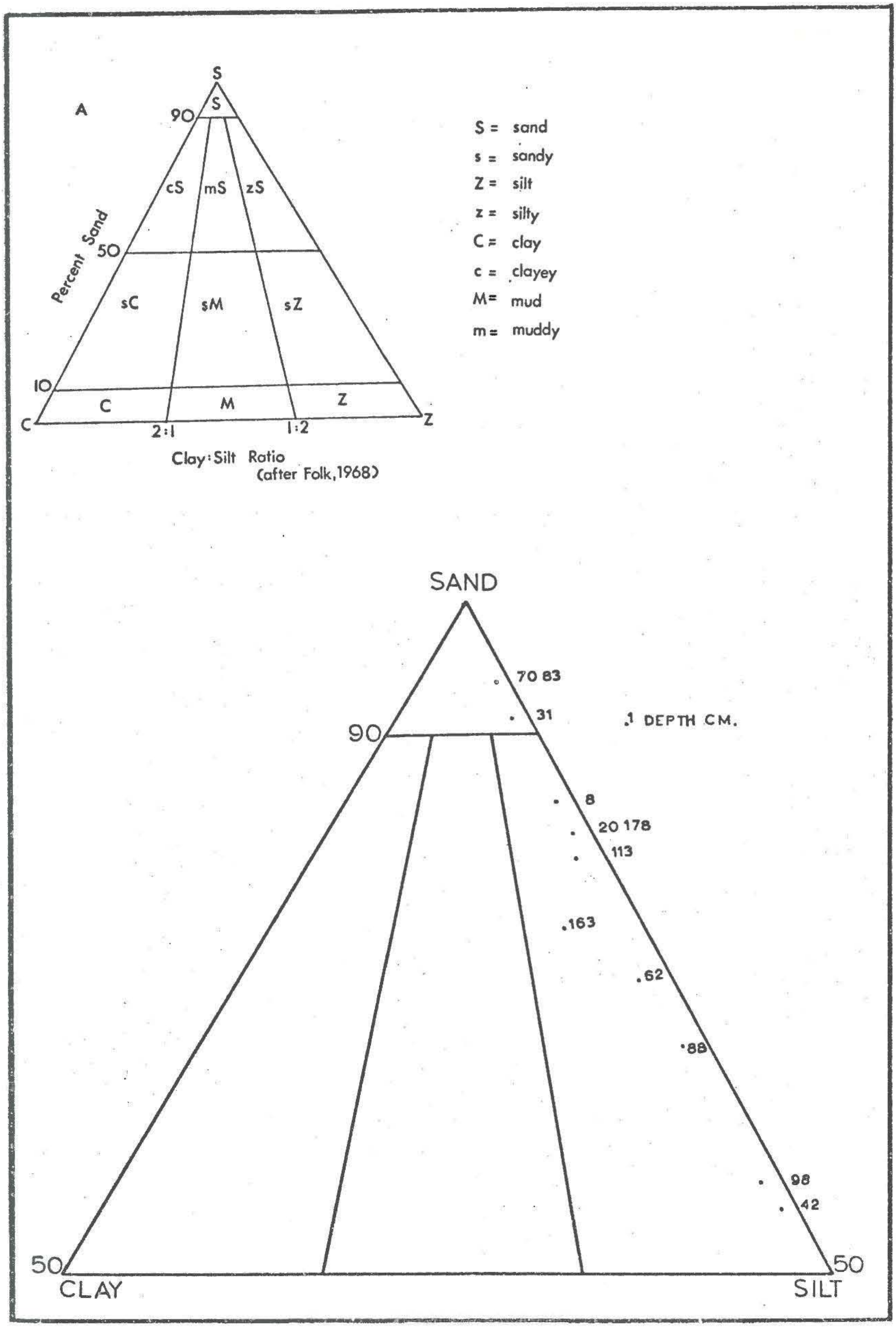


Fig. 3.5 Textural classes of detrital sediment in the site 6 core of Lake Vanda.

Table 3.1 Textural parameters of the Lake Vanda detrital bottom sediments.

Sample number (depth cm)	Mean size (Mz Ø)	Sorting (σ_IØ)	Skewness (Sk_I)	Kurtosis (K_G)
1	1.1	1.0	+0.1	1.3
2	1.7	1.2	+0.3	1.9
3	1.2	1.5	0.0	2.3
4	1.4	1.1	+0.2	1.9
5	1.6	0.9	+0.3	1.4
6 (8)	1.6	1.8	+0.3	1.7
7 (5)	2.9	1.8	+0.3	1.2
7 (25)	2.8	2.4	+0.1	1.0
7 (38)	2.7	2.3	+0.4	1.1
8	1.0	0.9	-0.2	1.2
9	1.6	1.8	+0.1	2.6
10	1.1	0.8	-0.1	1.0
11	1.3	0.9	-0.1	1.3
12	1.6	3.2	+0.1	1.0
13 (from lake - ice)	2.0	0.6	-0.1	0.8
14 (wind-blown)	1.4	0.6	0.0	1.1

less than 27m are poorly sorted and have a mean size of 1.65 Ø to 1.70 Ø (Fig. 3.6). At depths of between 40m and 52m the sediments are poorly to moderately sorted (σ_IØ from 0.9 to 1.5) and have a mean size range of 1.0 Ø to 1.2 Ø. The transect shows that below the 52m depth there is a general trend of decreasing mean size (1.44 Ø to 2.47 Ø). Sorting is better on the northern side of the lake compared to the southern transect

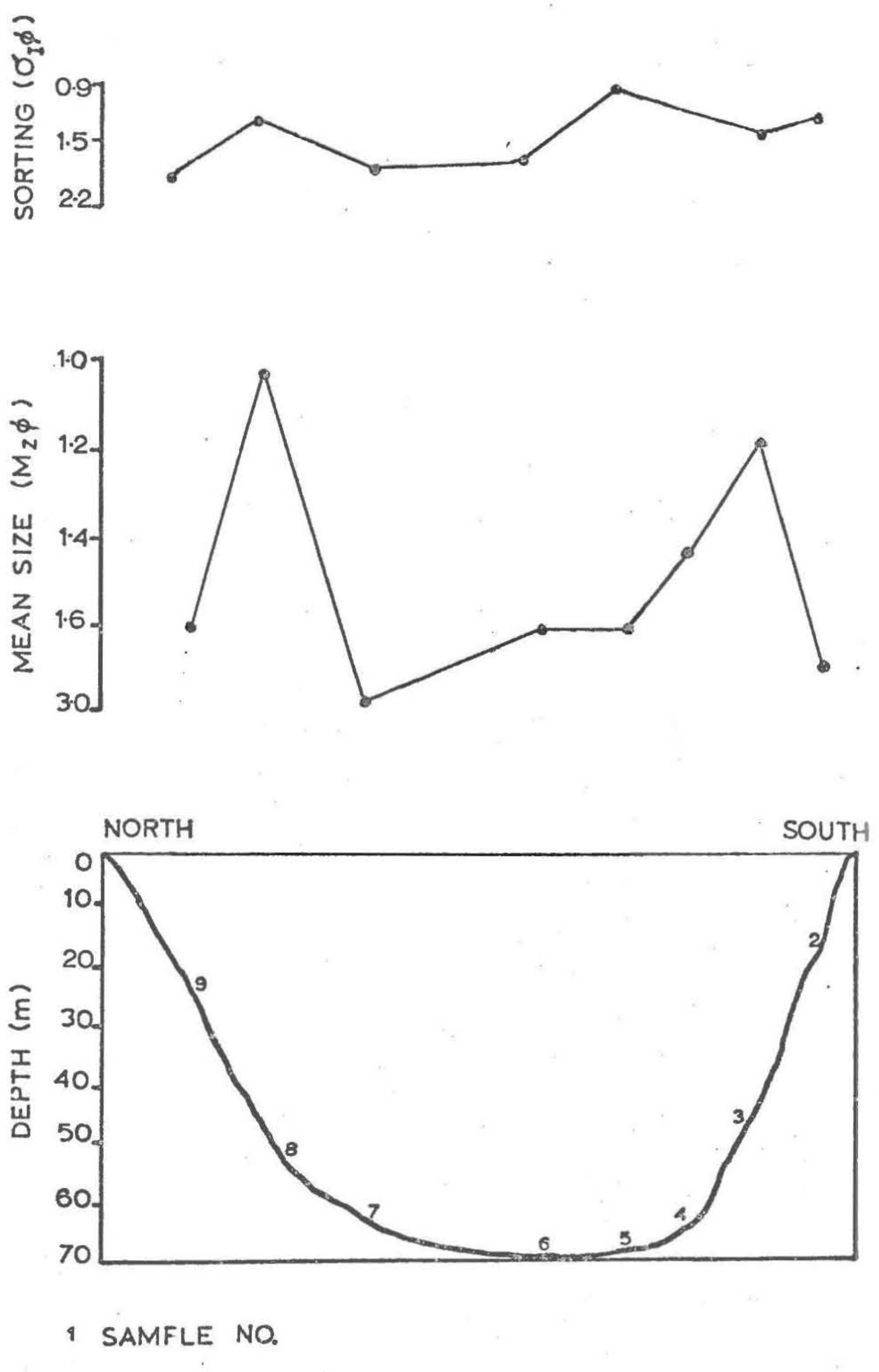


Fig. 3.6 Transect approximately north-south across Lake Vanda showing the mean size and sorting of detrital bottom sediments.

sites. Comparing the mean grain size to sorting (Fig. 3.7), the wind-blown samples 13 and 14 encompass a mean size (2.1 ø to 1.44 ø) which includes the mean for sediments from a wide range of depths but they are the only samples that are moderately well sorted.

Skewness values indicate that sediments at shallow depths are fine-skewed with a trend to near symmetrical values at 27 to 40m depth and coarse skewness at 52 to 57m depth. Sites deeper than 57m are fine - to strongly fine-skewed. Kurtosis values present a more complex picture, although sediments at shallow depths are typically very leptokurtic while those from the deeper parts of the lake are mesokurtic and leptokurtic.

Analyses of the site 6 deep core shows a broad association between the very poorly sorted fine sands (eg. 20 and 113cm depth) and high chemical precipitate and organic carbon contents (Figs. 3.8 and 3.9). Both medium sands and the fine to very fine sands are in the poorly to very poorly sorted range. Skewness and kurtosis values show no obvious relationship to these grain-size cycles although the fine-grained sands associated with the chemical precipitate/silt bands are often more finely skewed.

Textural analyses of Lake Vanda bottom sediments illustrate the importance of wind-derived detrital sediment in the total lake sediment budget. In strong winds sand would be expected

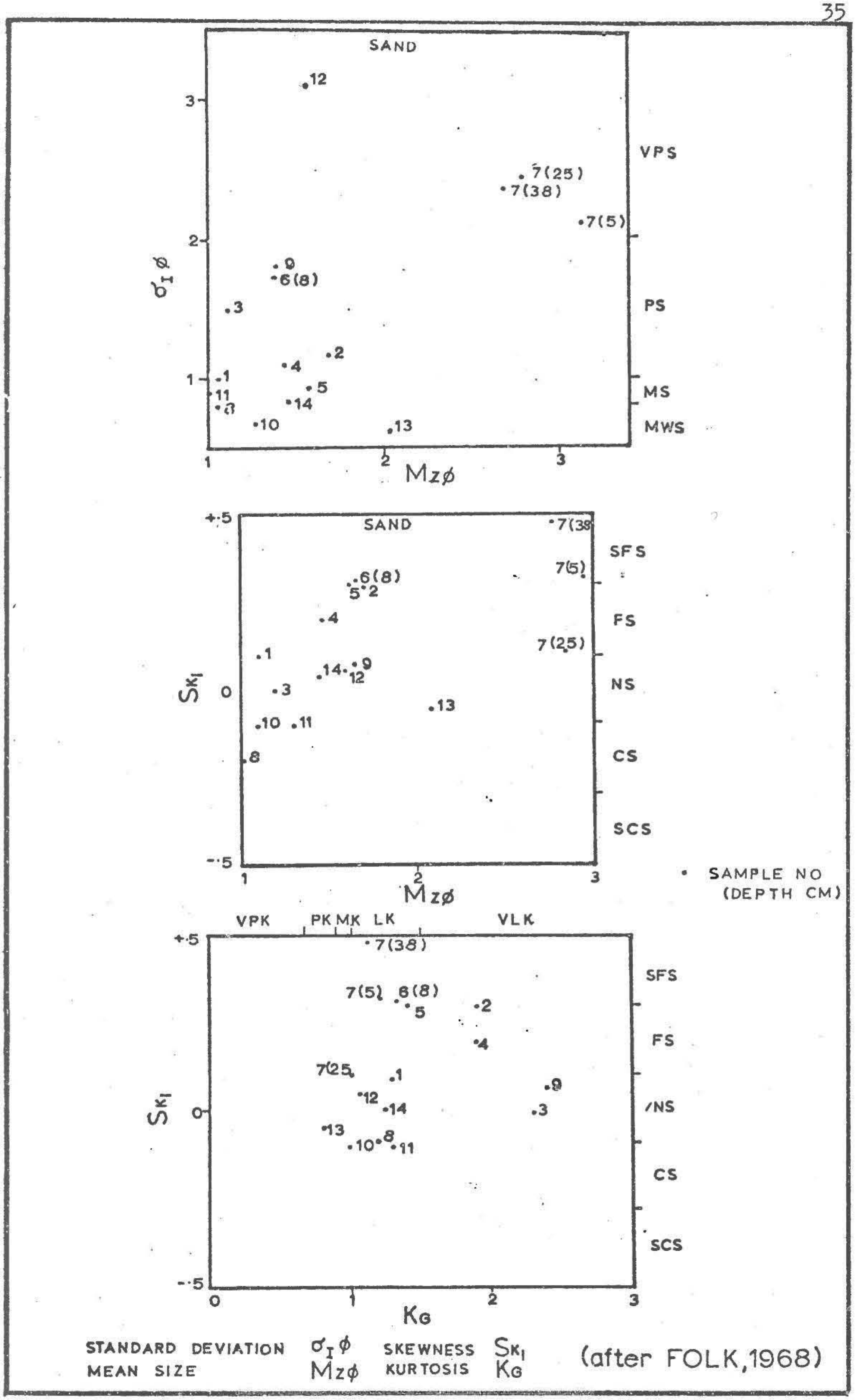


Fig. 3.7 Scatter plots of detrital bottom sediments of Lake Vanda.

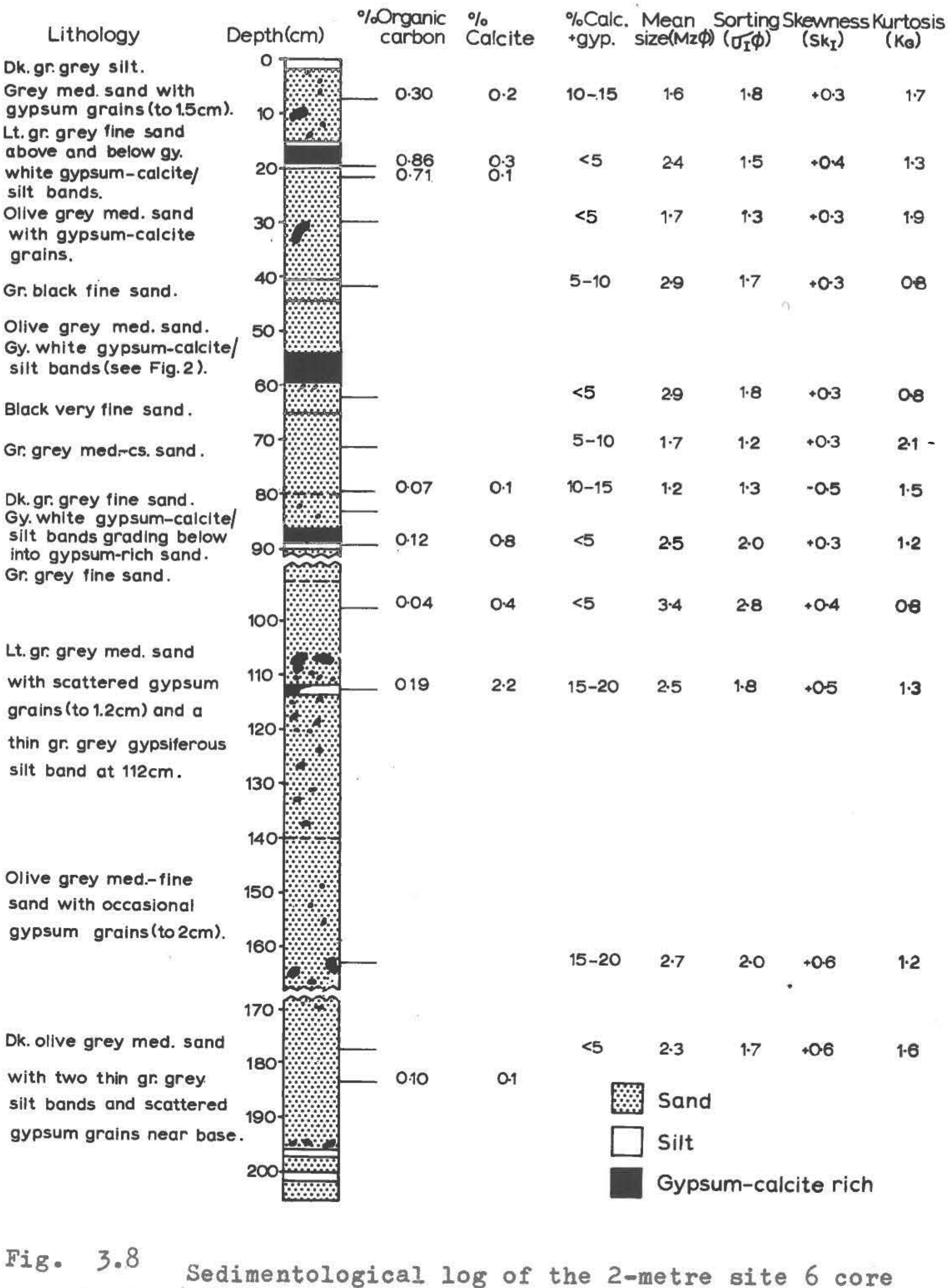


Fig. 3.8 Sedimentological log of the 2-metre site 6 core of Lake Vanda (dk.=dark; lt.=light; gr.=greenish; gy.=greyish; med.=medium; cs.=coarse). Calcite % based on inorganic C analyses, and calcite + gypsum % was determined using X R D. Textural parameters are after Folk (1968).

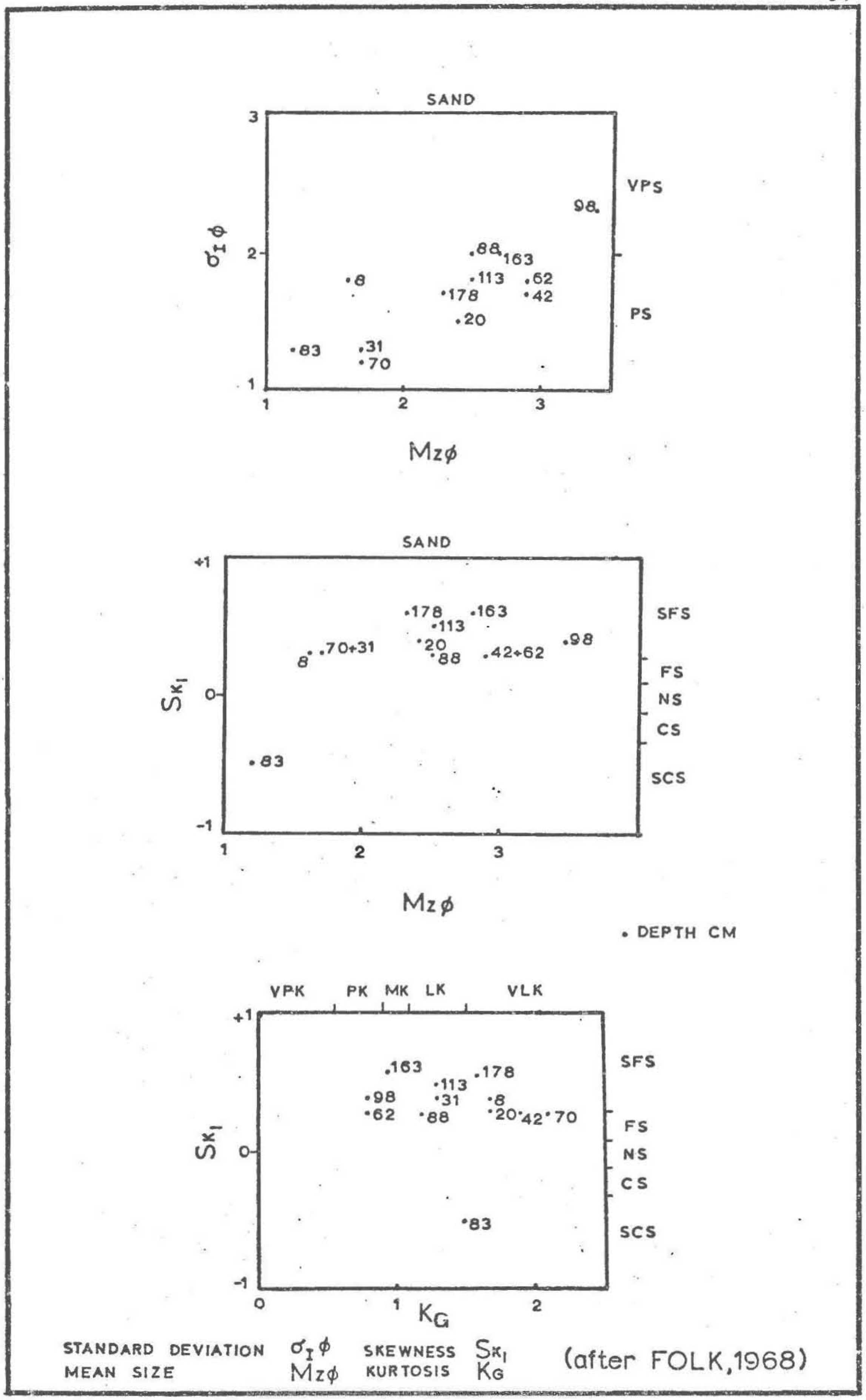


Fig. 3.9 Scatter plots of detrital sediments of the Lake Vanda site 6 core.

to move across the lake ice at a considerably faster rate than would occur over a loose rock/sand surface. According to Bagnold (1960) sand saltates in high speed wind whereas once fine particles (< 0.03mm) settle they cannot be swept up again individually because they sink into a surface layer of non-turbulent air. The lake-ice may act as a dust trap.

The lake bottom sediments are mainly wind-derived sands and silty sands. The detrital sediments entering the lake edge, particularly via the summer moat, are notably silty sands. The silt fraction is either deposited at this shallow depth or is kept in suspension until it is deposited in the less turbulent water in the deepest part of the lake. The transect across the width of the lake's mid-section shows the sand to be best sorted on the steeper 25 to 50m depth slope where water turbulence appears to be greatest. The western lobe of the lake consists of wind-derived detrital sediment whereas the eastern lobe sediment is siltier and may be primarily deposited by discharge from the Onyx River.

The site 6 deep core detrital sediments show the lake sedimentary environment has varied in its recent history (Fig. 3.8). The chemical precipitate/terrigenous silt bands are varve-like and suggest periods of low sedimentation rates. Variations in lake-level is inferred from the grain-size cycles.

3.4 DETRITAL MINERALOGY.

Bulk sediment analyses show the detrital constituents to consist almost entirely of quartz and feldspar. The quartz: feldspar ratio ranges from 0.7 to 3.1 in the bottom sediments (Table 3.2). Plagioclase is the dominant feldspar with the potash feldspar : plagioclase mean value being 0.9. In the site 6 deep core the quartz : feldspar ratio ranges from 0.7 to 4.3 (Fig. 3.2) with quartz generally the dominant mineral. In contrast to the bottom sediments potash feldspar dominates over plagioclase in the site 6 deep core.

The light mineral fraction (s.g. =<2.7) consists of quartz, feldspar, rock fragments, mica and volcanic glass. Notes on these constituents are presented below.

Quartz grains are subangular to subrounded and occasionally rounded. Grains are anhedral to subhedral and generally have frosted surface textures. Inclusions are common and often oriented in trains. About half of the inclusions are opaque minerals and include cubic magnetite.

Feldspars are generally subangular to angular and consist of oligoclase, microcline, orthoclase and labradorite.

Rock fragments are abundant in some samples and examination of the 2mm plus fraction shows a dominance of grey gneiss, granite, lamprophyre and dolerite lithologies. Many of the rock fragments are pitted and show evidence of physical weathering.

Table 3.2 Quartz and feldspar ratios of the bottom sediments of Lake Vanda (based on XRD analyses).

Sample number (depth cm)	Quartz/Feldspar	Potash feldspar/ plagioclase
1	0.7	0.3
2	1.3	2.5
4	2.3	0.5
7 (5)	3.1	0.5
7 (38)	2.7	1.2
8	1.3	0.5
12	1.1	1.0
6 (1)	2.4	2.0
(10)	0.7	50.0
(18)	1.2	1.3
(31)	0.8	2.9
(42)	1.5	0.7
(62)	2.1	2.7
(71)	1.8	3.0
(83)	1.3	1.3
(86)	2.1	1.8
(96)	2.3	13.0
(112)	2.6	1.5
(165)	1.1	1.3
(180)	4.3	11.0

Biotite, and to a less extent muscovite, occur in minor amounts in most samples. Mica is most common in the deepest part of the lake (eg. site 6) and is generally in the form of small subrounded plates.

Minor amounts of clear volcanic glass, in grains up to 1.0mm in size, occur in the upper 70cm of the site 6 deep core. The glass occurs either as spheres with gas vacuoles (Fig. 3.10) or as conchoidally fractured grains.

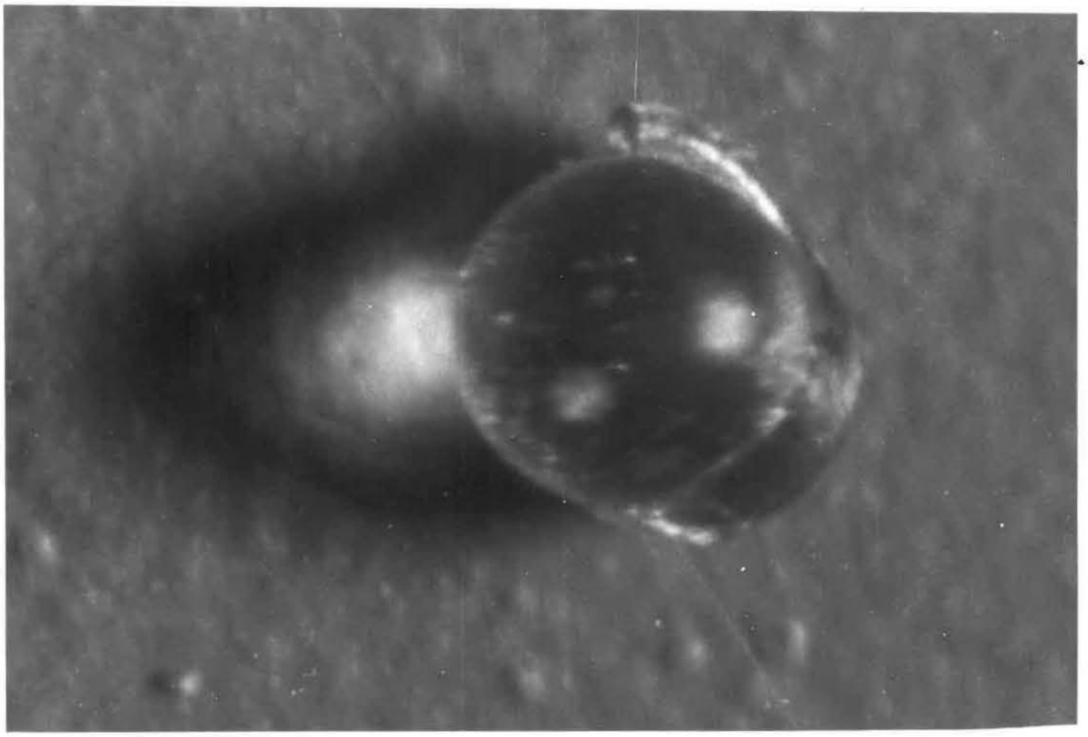


Fig. 3.10 Volcanic glass spheroid (0.8mm diameter) with gas vacuoles.

The quartz originates mainly from the Granite Harbour Intrusive Complex of which the Larsen Granodiorite forms the Lake Vanda bedrock. The rounded quartz grains, however, may be derived from the sandstone of the Beacon Supergroup. The source of the feldspar is complex, although the plagioclase is derived from the Granite Harbour Intrusive Complex and to a minor extent from the Ferrar Dolerite and lamprophyre and porphyry dykes in the Lake Vanda area. The main source of potash feldspar is probably the porphyry dykes, which are particularly common immediately south of Lake Vanda, and the Larsen Granodiorite, which has a variable feldspar composition (Dry Valley Drilling Project, 1974). The reason for the dominance of potash feldspar over plagioclase in the sediments from the deep part of the lake remains uncertain but may be related to the fine-grained nature of the orthoclase derived in abundance from the groundmass of the porphyry dykes (McKelvey and Webb, 1962).

Micaceous minerals are derived from the local granites (which contain $<10\%$ mica) and the lamprophyre (25 to 30% mica) and prophyry (minor amounts of mica) dykes.

The volcanic glass is derived either from the small basaltic cinder cones located in the lower Wright Valley or from Ross Island (Jones et al., 1973).

The heavy mineral (s.g. > 2.7) content of the lake bottom sediment ranges from 16.1 to 21.6 percent. Table 3.3 shows the influence of sediment sorting processes with heavy mineral content decreasing towards the deeper parts of the lake. The site 6 deep core heavy mineral content shows no clear relationship to grain-size cycles.

Table 3.3 Percentage of heavy minerals in the bottom sediments of Lake Vanda.

Sample number	% Heavy minerals
1	16.1
2	21.5
5	17.3
11	16.6
12	21.6
13 (from lake ice)	2.2
6 (depth cm)	
1	7.0
9	20.2
22	11.2
31	21.5
42	16.8
62	15.6
70	14.8
80	16.9
98	30.1
112	24.7
162	14.2
177	9.6

The heavy minerals are dominated by hornblende, hypersthene and augite with minor amounts of opaque minerals, zircon, apatite and chlorite (Table 3.4). According to their pleochroic tints, hornblende occurs in two varieties, namely a green to light brown hornblende and a light brown to dark reddish brown variety. The latter variety dominates. Inclusions are common and are mainly opaques, apatite and zircon. Grains are subangular to subrounded with occasional subrounded elongate forms. Hypersthene generally occurs as subangular elongate prisms. Inclusions of opaque minerals and apatite are occasionally present. The hypersthene is pleochroic from pale pinkish green to pinkish brown. Augite is generally pale green to brown and occurs mainly as subrounded grains. Inclusions are common and include mainly opaques and apatite. The opaque minerals in the sediments are mainly magnetite and are most abundant in the fine-sand grade.

Table 3.4 Percentages of individual heavy mineral species in the total sand fraction.

Sample number	Hornblende	Hypersthene	Augite	Opaques	Others
1	24	30	36	R	10
2	40	30	22	R	8
5	44	30	22	R	4
11	44	18	22	R	16
12	30	28	30	R	6

R = rare

The hornblende is derived from the Granite Harbour Intrusive Complex (Fig. 1.2). The lamprophyre and porphyry dykes contain up to 40% brown hornblende while the granites contain up to 5% hornblende. It is concluded that the lamprophyre and porphyry dykes are the main source of hornblende. The pyroxenes are largely derived from the Ferrar Dolerites which contain augite, pigeonite and hypersthene. The porphyry dykes contain minor amounts of titano-augite.

The clay mineralogy is dominated by illite with lesser amounts of montmorillonite, chlorite and mixed-layer illite-montmorillonite (Fig. 3.11). Judging from the broad and diffuse nature of basal reflections the clay minerals have poor crystallinity. Semiquantitative analysis (Weaver, 1958 a), shows there is little variation in the abundance of individual clay mineral species throughout the lake and that the following values are typical : illite $\gg$ chlorite $>$ montmorillonite = mixed-layer illite-montmorillonite.

Selected clay samples were subjected to mild treatment with potassium hydroxide (Weaver, 1958 b) to distinguish montmorillonite derived from non-micaceous minerals such as volcanic material and hornblende and that derived from micas. Weaver showed that when mica-derived montmorillonite is subject to KOH treatment it will collapse to IOÅ, indicating the montmorillonite has inherited much of the high interlayer

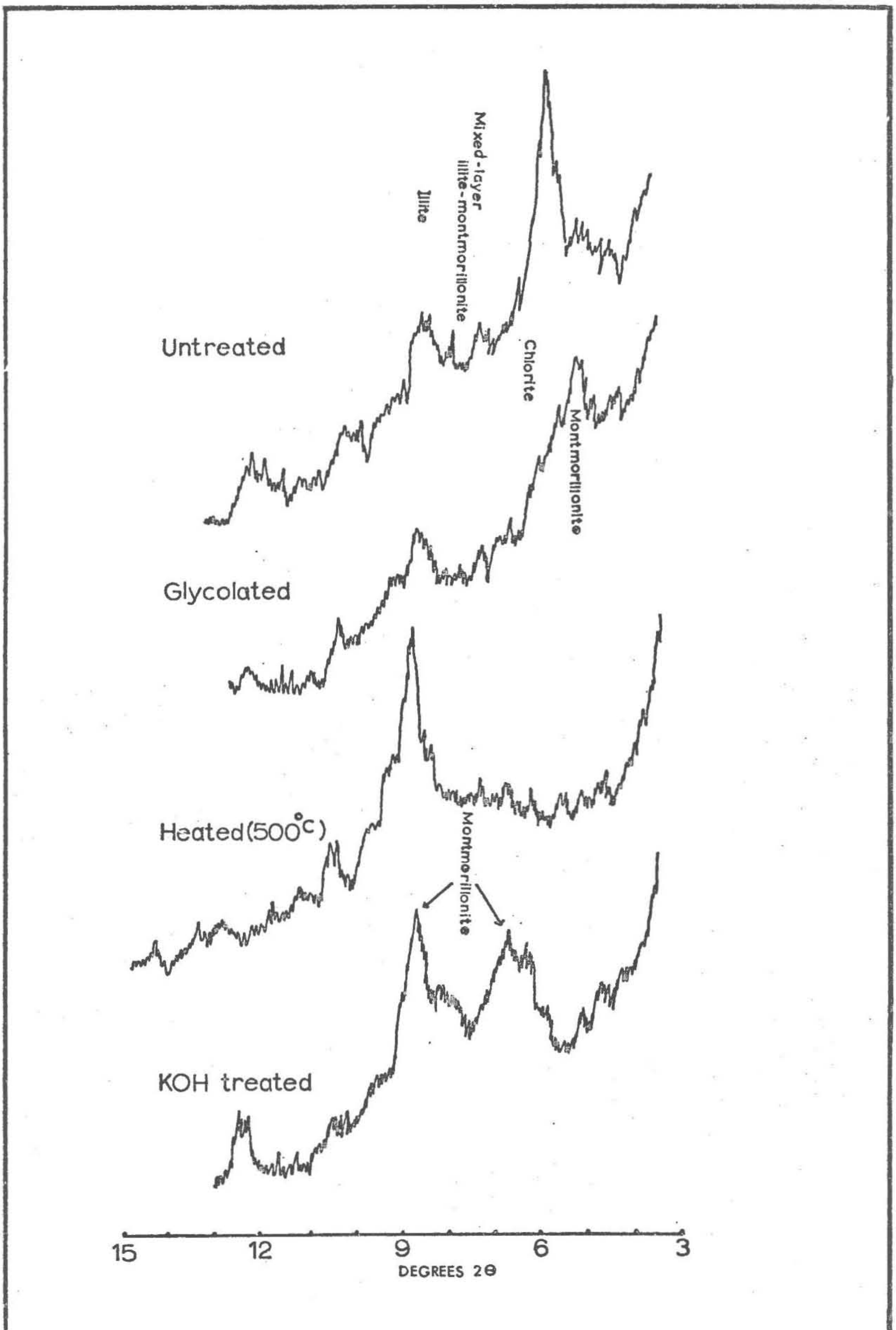


Fig. 3.11 Representative X-ray diffraction patterns of the patterns of the < 2 μ fraction from the site 6 sediments of Lake Vanda.

charge of the mica. If there is no collapse, or only slight collapse to 12 to 13 Å, the montmorillonite is of non-micaceous origin. Fig. 3.11 shows that approximately 50% of the montmorillonite in the lake sediments appears to be of micaceous origin.

It is concluded that the illite, micaceous montmorillonite and mixed-layer clays are derived from the micas present in the granites. The chlorite is also derived from granite.

3.5 CHEMICAL PRECIPITATES.

Table 3.5 and Figures 3.8 and 3.12 show the percent chemical precipitate in the lake sediments. The chemical precipitate content increases with depth, particularly below 64m, where the environment is non-turbulent. The percent inorganic carbon in the sediments (Fig. 3.8 and 3.13) is taken as representing the amount of calcite present.

Prominent white evaporitic beds up to 6cm thick occur in cores 5, 7 and 6 (deep core). Although occasionally massive, the beds typically consist of numerous varve-like alterations of gypsum-calcite and/or terrigenous silt (Fig. 3.14). At least 20 bands of gypsum, calcite and terrigenous silt occur at the 55cm level in core 6 and the 12cm level in core 5. The amount of calcite present in each gypsum-calcite band varies from 7 to 32%. Poorly developed and possibly reworked evaporitic layers occur at the 110cm, 165cm and 195cm levels

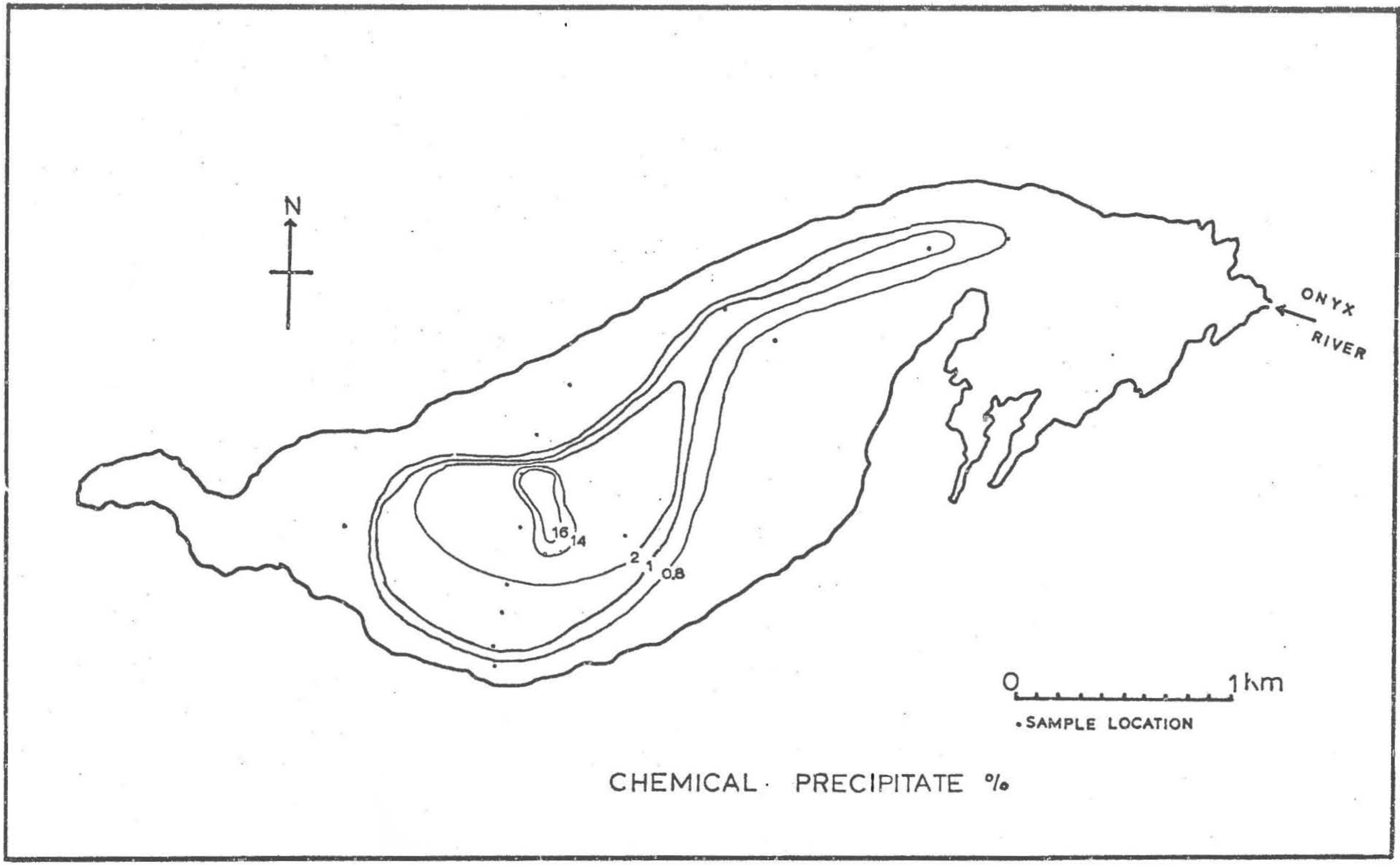


Fig. 3.12 Chemical precipitate content of Lake Vanda bottom sediments.

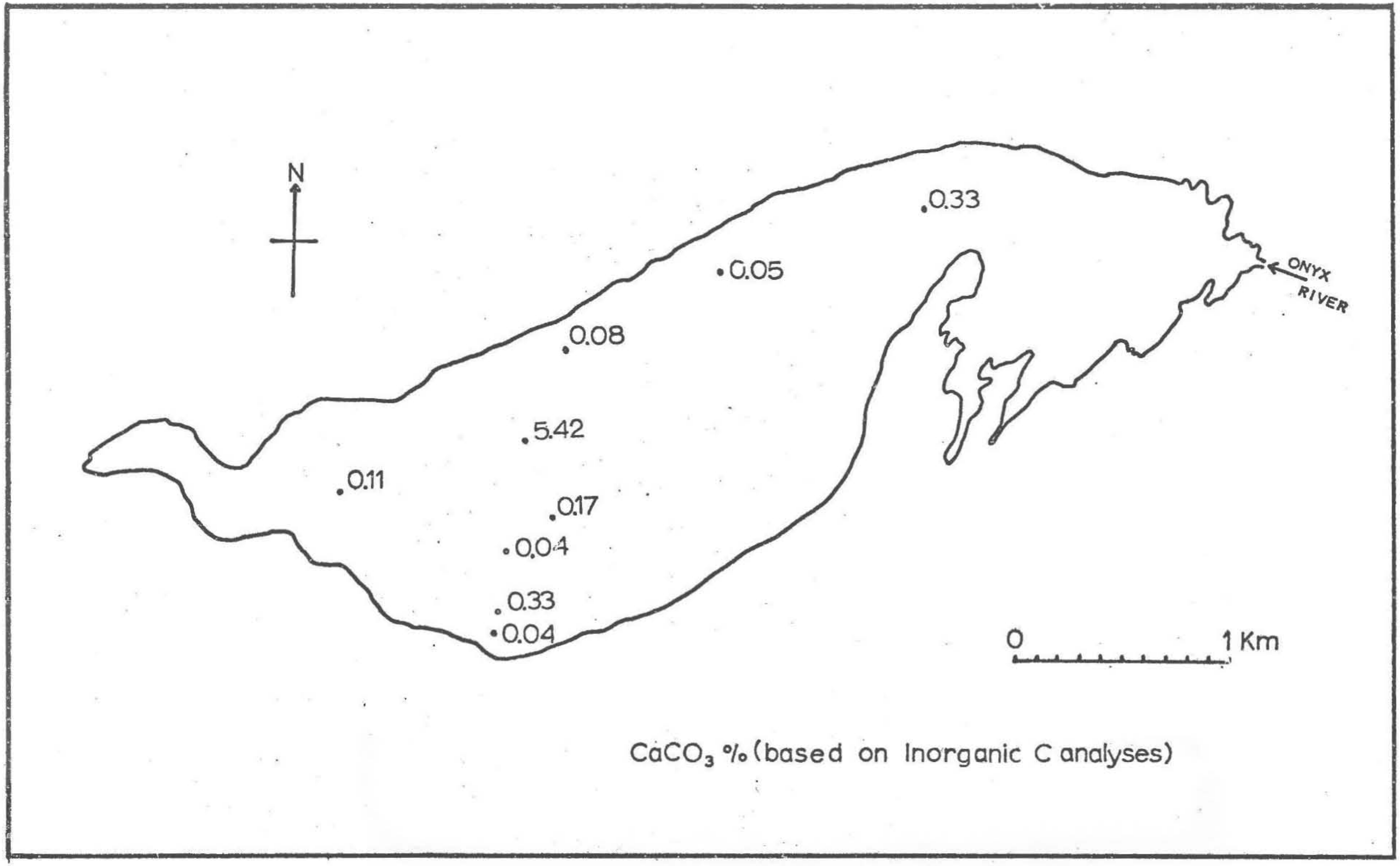


Fig. 3.13 $CaCO_3$ content of the bottom sediments of Lake Vanda.

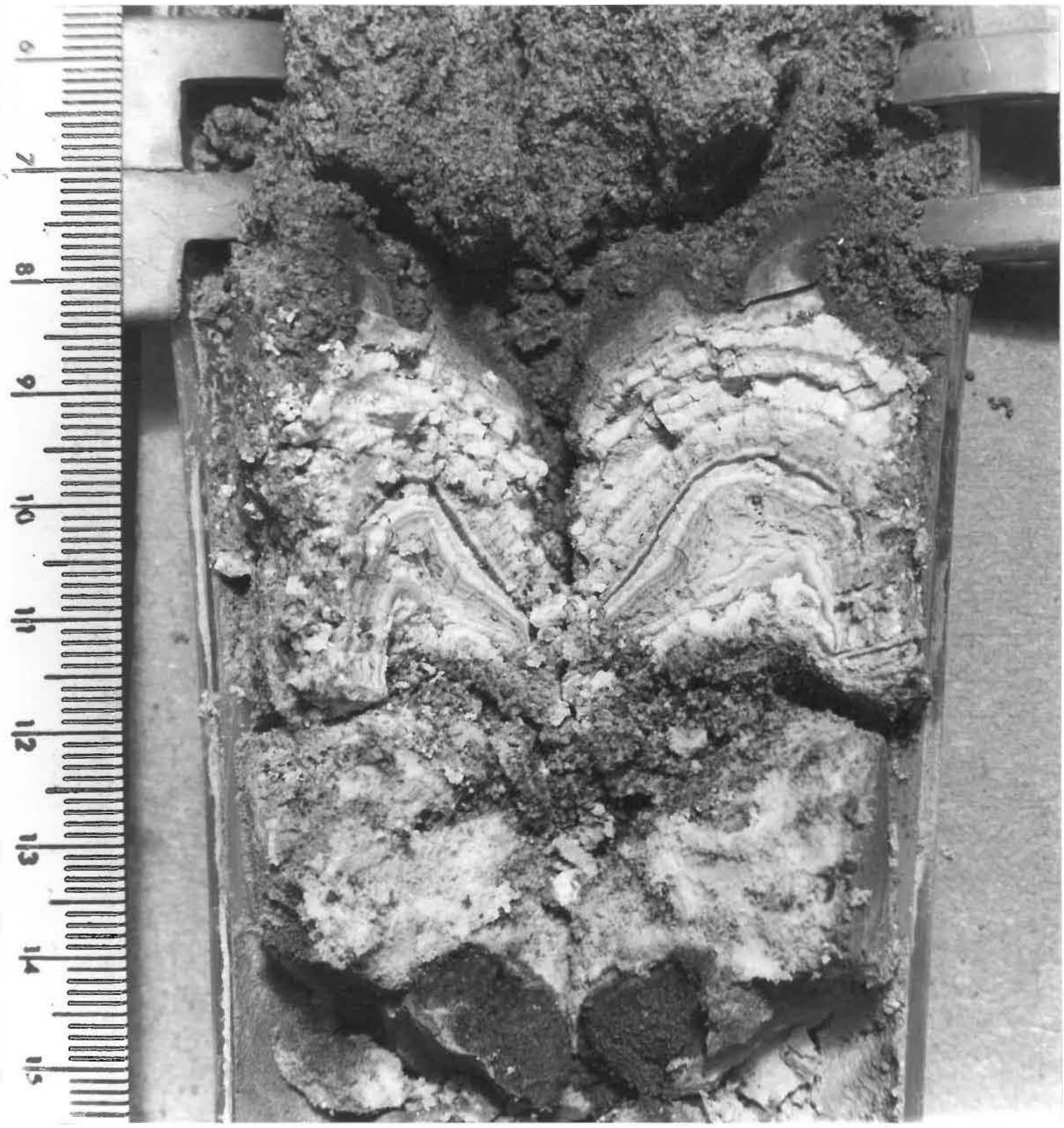


Fig. 3.14 Calcite-gypsum/terrigenous silt bands at the 55- to 60-cm level in the Lake Vanda site 6 core.

Table 3.5 Weight percent chemical precipitates in the bottom sediments of Lake Vanda.

Sample number (depth cm)	% Chemical precipitates
1	0.2
2	0.6
3	1.0
4	1.0
5	2.1
7 (5)	16.1
7 (25)	19.4
7 (38)	1.7
8	0.3
9	0.3
10	1.2
11	0.5
12	1.4

in the site 6 deep core (Fig. 3.8). These reworked beds may be the product of frost riving.

The multibanded evaporitic beds in the sites 5 and 7 cores occur at 10 to 15cm depth. These bands are similar in structure to the 55cm evaporitic band in core 6. The core 6 15cm evaporitic band has a more massive structure. X R F analyses (Table 3.6) for specific elements, also suggests a correlation between the 55cm evaporitic bed in two cores from site 6 with the 10cm bed in core 7. Comparison between the 18cm and 55cm evaporitic beds in core 6 indicates that the upper bed has more P, K, Ca, Mn and Fe than the lower bed. Variation between the evaporitic beds is however

Table 3.6 X-ray fluorescent analyses of the Lake Vanda evaporite bands.

Sample (depth cm)	6 (55, core i)	6 (55, core ii)	6 (18, core i)	7 (10)
Elements		Intensity		
P	0.19	0.20	0.16	0.19
S	0.22	0.48	0.51	0.29
Cl	0.76	0.44	0.39	0.52
K	0.27	0.22	0.15	0.26
Ca	2.35	2.41	1.98	2.35
Mn	0.53	0.38	0.25	0.45
Fe	3.19	1.98	0.81	2.81
Br	0.30	0.30	0.31	0.29
Sr	0.34	0.36	0.38	0.34
Background level	32.56	27.28	27.94	31.38

apparent and the possibility of correlation between the 15cm beds in cores 5, 6 and 7 cannot be discounted.

While the gypsum is interpreted as being evaporitic, the calcite may have originated from (1) the calcite-bearing rocks in the area, (2) authigenic growth or (3) have precipitated under evaporitic conditions. The formation of calcium carbonate by the reduction of carbon dioxide in the presence of algae, bacteria and diatoms in the bottom sediments may also account for some of the calcium carbonate present (Table 3.9). However, the quantity of calcite present suggests an evaporitic origin is the dominant source.

Field (1975) states that groundwater flow is more important than river flow in the transportation of salts into Lake Vanda. The groundwater contains Cl^-, Ca^{2+} and Na^+ in the same order of concentration as in the lake bottom water. From the measurement of ionic ratios Boswell et al. (1967) suggested that Lake Vanda received its saline contents from glacial meltwater and not seawater. The high magnesium content of the lake bottom water (Table 1.2) would have a "salting out" effect (Braitsch, 1971) and contribute to the precipitation of evaporites. Chemical analyses of the lake bottom waters show the salinity at 66m depth is in the appropriate range for calcium carbonate precipitation (Table 1.3).

The evaporitic beds may indicate colder climatic periods in the lake history. In a cold period the supply of lake water from the catchment glaciers decreases and the lake level drops to an extent that, depending on the salinity, calcite or gypsum precipitates. The fine bands in the evaporitic beds are suggestive of short-term fluctuations in temperature and rates of evaporation which control also fluctuations in salinity. The precipitation of the salts is undoubtedly complex.

The precipitation of salts as a result of freezing of brines has commonly been neglected in the literature on evaporite deposition. The cold climate of the Dry Valleys has probably influenced the precipitation of salts, referred to here as evaporitic, to a significant extent. When salts are added to fresh water the temperature of maximum density, as well as the freezing point, is lowered (Thompson and Nelson, 1956). Thompson and Nelson noted that for seawater with a salinity of 24.7‰ (Chlorinity 13.67‰), the freezing point and the temperature of maximum density are identical, namely -1.33°C. The temperature of maximum density of pure water is 3.98°C. For each increase of one part per thousand in salinity, the temperature of maximum density is lowered 0.215°C. With sufficient lowering of the temperature, crystals of ice will form which further increases the density of the saline water, causing it to sink.

A cold period will result in more water freezing than is added to the lake and eventually only a single residual brine layer will remain. The residual brine's freezing point may be depressed by its salinity to the point where ice can no longer form except during unusually low temperatures in the winter (Jones and Faure, 1969).

Preliminary analyses of the Dry Valley Drilling Project 4 (Lake Vanda) core, by this writer, suggest that at least two additional evaporite-forming cold climatic phases occurred prior to those recorded in the site 6 core. The two additional calcite-gypsum beds occur in the lower half of the 4 metre core that was interpreted by Cartwright et al. (1974) as being lacustrine sediment.

3.6 ORGANIC MATTER.

During the summer months prolific biological growth occurs in the lake environment. Organic carbon analyses of the water column in January 1974, showed a high organic carbon content immediately below the ice-cover (Table 3.7). At deeper levels uniformly low organic carbon values occurred down to 45m where the organic carbon content slightly increased. This stratification, due essentially to algae, appears to be related to the temperature profile for Lake Vanda (Fig. 1.4). Table 3.8 summarises the biological content of the lake sediment (Flint, 1972 pers. comm. to A.T. Wilson).

Table 3.7 Carbon content of the water column near site 6 at Lake Vanda.

Water (depth cm)	Total C (mgm/l)	Inorganic C (mgm/l)	Organic C (mgm/l)
10	22.70	7.70	15.00
15	16.75	8.60	8.15
20	21.25	12.70	8.55
30	15.50	7.00	8.50
35	20.75	12.25	8.55
45	20.00	18.00	2.00

Table 3.8 Biological content of the bottom sediments of Lake Vanda (Flint, pers.comm. to A.T. Wilson).

<u>Site 9:</u>

Numerous diatoms.

- mainly empty frustules
- some living <u>Nitzschia</u> and <u>Hantzschia</u>

Algae

green algae : <u>Chlorella</u>

<u>Bracteacoccus</u>

<u>Troschia</u> - like spores

<u>Site 10:</u>

Living diatoms.

- <u>Navicula</u> and <u>Nitzschia</u>

Microscopic clumps of green algae

- <u>Bracteacoccus</u>

The highest content of organic carbon (Table 3.9 and Fig. 3.15) appears to occur where the lake waters are least turbulent, namely the deep part of the lake (eg. sites 6, 7 and 10) and the gently sloping locations at sites 1 and 12. In the site 6 deep core the highest organic carbon content occurs in the silt bands, and particularly in those associated with the evaporitic beds (eg. 18cm, 88cm and 112cm depth). Many laboratory studies (eg. Loder and Hood, 1972) have shown that large quantities of organic compounds may be absorbed onto clays, especially in brackish waters. Fine silts and clays such as those associated with the evaporitic beds may act as a substrate

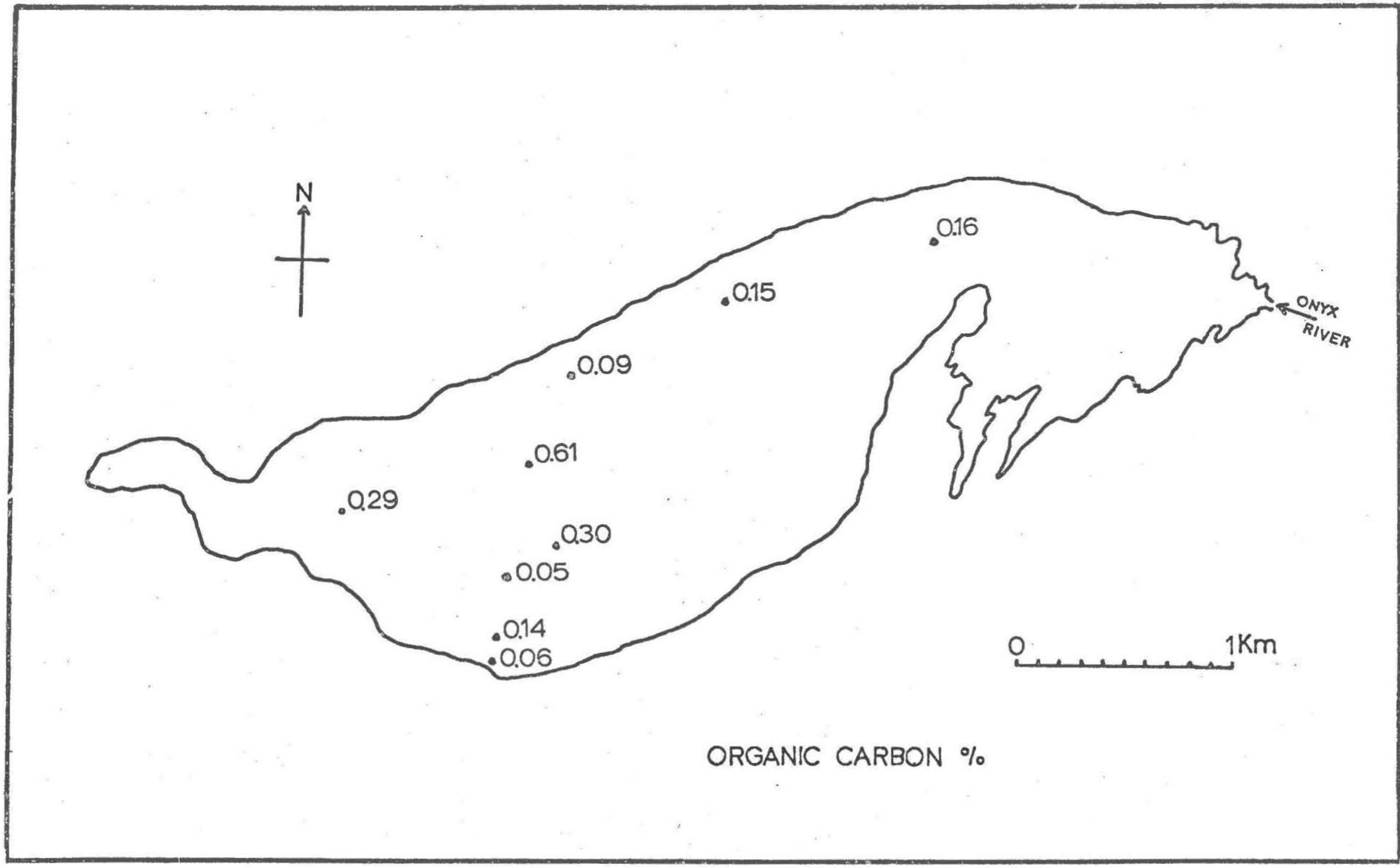


Fig. 3.15 Organic carbon content of the bottom sediments of Lake Vanda.

for the adsorption of macromolecules by microorganism populated natural detritus and thereby account for its comparatively high organic content.

Table 3.9 Carbon content of the bottom sediments of Lake Vanda.

Sample number	% Total C	% Inorganic C ($\%CaCO_3$)		% Organic
1	0.31	0.01	(0.1)	0.29
2	0.06	0.01		0.06
3	0.18	0.04	(0.3)	0.06
5	0.06	0.01		0.05
7	1.26	0.65	(5.4)	0.61
10	0.16	0.07		0.15
12	0.20	0.04	(0.3)	0.16
6 (depth cm)				
8	0.32	0.02	(0.1)	0.30
20	0.89	0.03	(0.2)	0.86
22	0.72	0.01		0.71
80	0.08	0.01		0.07
87	0.13	0.01		0.12
100	0.09	0.05	(0.3)	0.04
113	0.45	0.26	(2.1)	0.19
185	0.08	0.01		0.07

3.7 RATES OF SEDIMENTATION AND URANIUM/THORIUM DATING RESULTS.

On the basis of Pb^{210} levels in a core from site 9, McCabe (1974) calculated that the rate of sedimentation in Lake Vanda is 0.2 $kgm/m^2/yr$ (0.02 cm/yr), assuming a uniform sedimentation rate. On the basis of total suspended sediment deposited in Lake Vanda by the Onyx River during the 1971/72 summer

(Table 1.1) the rate of sedimentation is 5.54×10^{-4} cm/yr.

U/Th dating (C. Hendy, 1974 pers. comm.) indicates no detectable age difference between the 18cm and the 55cm evaporitic beds from the deep core at site 6 (Fig. 3.8); they are, however, post glacial and in the order of 2,000 to 13,000 years old.

On the basis of the above data, and considering the relative unimportance of river-derived compared to directly wind-derived sediment in the lake, a sedimentation rate of about 0.01 cm/yr appears reasonable, suggesting an age of about 2,000 and 5,500 years for the 18cm and 55cm evaporitic beds in core 6, respectively.

Based on C^{14} analyses of algae present in strandlines around the lake, Wilson and Wellman (1962) suggested Lake Vanda reached its highest water level about 3,000 years B.P. Chloride concentration gradients (Wilson, 1967) suggest a low lake level some 1,200 to 2,000 years B.P. at which time the volume of water in the lake may have been similar to the highly saline Don Juan Pond (Fig. 1.1) whose salts presently crystallise-out during the winter.

3.8 SUMMARY AND CONCLUSIONS.

Broadly the Lake Vanda bottom sediments consist of two contrasting facies each sharply separated by the 60m depth contour. Shallower than 60m the environment is aerobic and the sediments are pale fawn, massive medium sands overlain by organic detritus. Below 60m depth the environment is anaerobic and the sediments are grey to grey-green, medium- to fine-grained sand containing finely disseminated organic matter and variable but significant amounts of calcite and gypsum.

Textural analyses of Lake Vanda bottom sediments emphasise the prime importance of wind-derived detrital sediment. Sediment transported by the Onyx River is of comparatively minor importance in the total lake sediment budget. In general the detrital sediment is either blown onto the lake-ice cover where it eventually sinks through to the lake floor, or is blown into the lake's summer moat. Sediment blown into the moat is either deposited at shallow depth or, in the case of the silt fraction, is kept in suspension before settling in the non-turbulent deeper part of the lake. Water turbulence on the steeper slopes of the lake between 25 and 52m depth is suggested by the improved sorting of these sands compared to the bottom sediments in shallower and deeper locations. The stratigraphy of the deep core shows a series of grain-size cycles which suggest that the level of Lake Vanda has varied in the recent past.

The detrital mineralogy indicates the sediments are probably of local origin and wind transported. The detrital sediment is largely derived from the granites and lamprophyre and porphyry dykes of the Granite Harbour Intrusive Complex, and the Ferrar Dolerites.

Chemical precipitates in the lake bottom sediments consist of gypsum and comparatively minor amounts of calcite. The chemical precipitate content increases with depth, the highest values occurring below 64m depth. The origin of the chemical precipitates is undoubtedly complex. From the measurement of ionic ratios Boswell et al. (1967) suggested that Lake Vanda received its saline contents from glacial meltwater. Based on the quantity of chemical precipitates an evaporitic origin is suggested. The formation of evaporites was aided by such factors as a high magnesium content of the lake water and by frigid conditions. Prominent white calcite-gypsum/terrigenous silt bands occur at 18cm and 55cm depths in the site 6 core, with reworked evaporitic phases at the 165 cm and 195cm levels. Two further evaporitic phases are suggested in the lower half of the 4m long D.V.D.P. (Lake Vanda) core. The evaporitic/terrigenous silt bands further suggest fluctuations in the salinity and level of Lake Vanda in its recent history.

Organic matter in the lake consists mainly of algae, bacteria and diatoms. The organic content of the bottom sediments is highest in the deepest part of the lake and in restricted shallower locations where water turbulence is minimal.

Based mainly on various dating techniques, notably U/Th dating methods, a rate of sedimentation for Lake Vanda is calculated to be about 0.01 cm/yr. The presence of evaporitic beds in the sediments has provided a datable record of past climatic changes. It is suggested from the site 6 deep core stratigraphy that cold climatic periods lead to low lake levels which, depending on the salinity of the lake water reached, permit precipitation of evaporitic sediment phases. Based on the occurrence of evaporitic beds, at least two and possibly four cold climatic phases have occurred in about the last 15,000 years, the ages of the two youngest cold periods being about 2,000 and 5,500 years B.P.

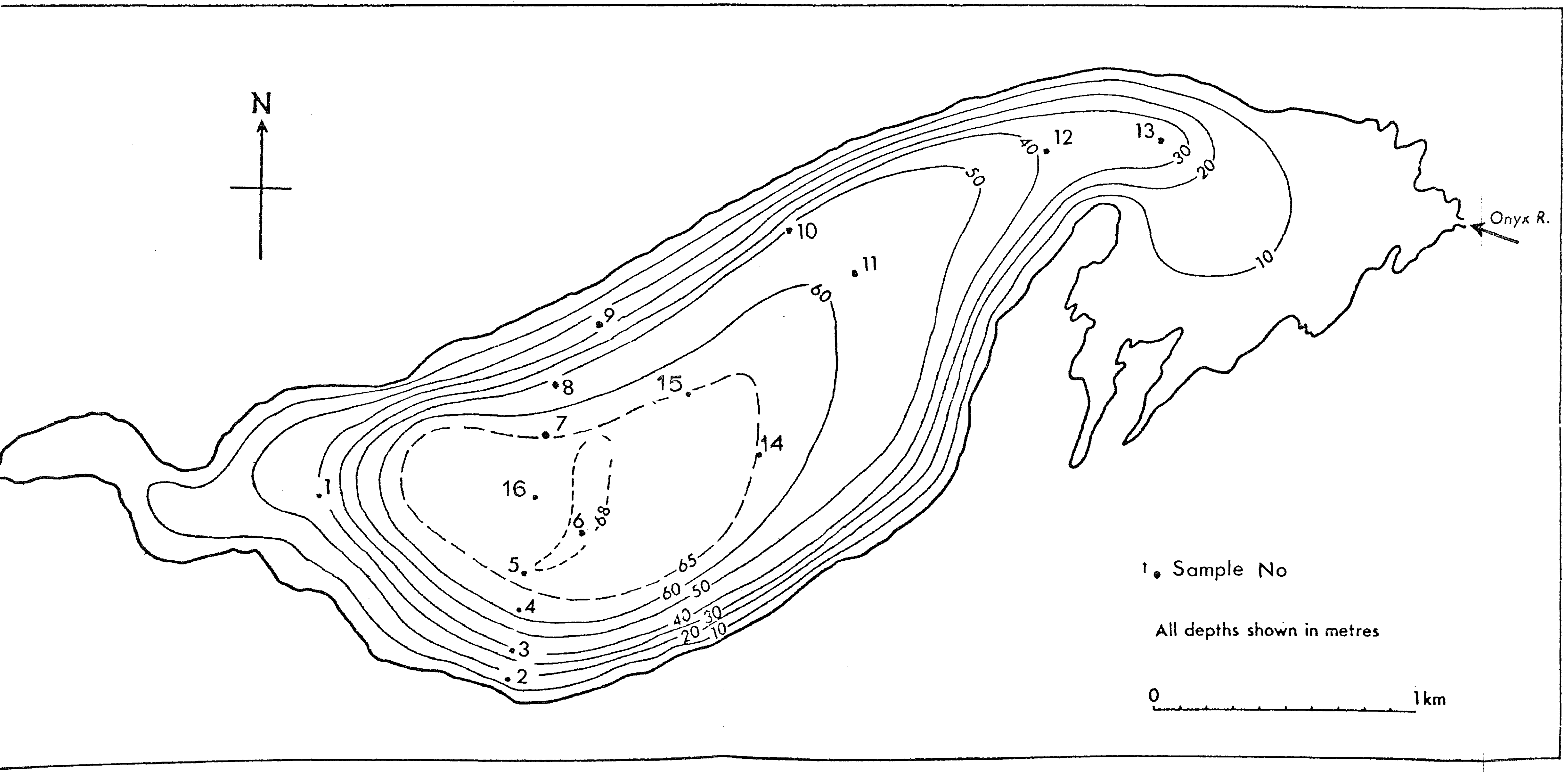


Fig. 3.16 Bathymetry and sample locations for Lake Vanda.

CHAPTER IV

LAKE BONNEY AND TAYLOR GLACIER SEDIMENTS

4.1 INTRODUCTION.

To date the study of Lake Bonney sediments (Fig. 4.23) has been restricted to notes on the halite crystals discovered on the floor of the Lake Bonney east lobe (Goldman *et al.*, 1967; Craig *et al.*, 1974). The present study of the bottom sediments and stratigraphy of the deep cores has elucidated the recent history of Lake Bonney, particularly the different environmental processes operating in the west and east lobes. Analysis of the "debris bands" exposed in the snout of the Taylor Glacier has also been included to determine the origin of these bands and their possible relationship to the history of the Lake Bonney west lobe.

4.2 TAYLOR GLACIER AND ADJACENT OUTWASH SEDIMENT.

Detrital sediment and chemical precipitates were collected from the Taylor Glacier snout "debris bands" and "ablation platform", and the meltwater stream of the Rhone and Taylor Glaciers (Figs. 4.1, 4.2 and 4.3).

The sandy "debris bands" are best exposed on the sides of the Taylor Glacier and range from 0.5 to 20cm thick, averaging about 1 to 2cm. The bands dip 20° to 30° west and, although

Fig. 4.1 The summer moat on the southern shore of Lake Bonney west lobe. The Taylor Glacier is in the background. Note the "debris bands" on the glacier snout. Photo taken in January, 1974 by C.P. Reynolds.

Fig. 4.2 The snout of the Taylor Glacier viewed from the north slope of the Taylor Valley. Note the ice cone on the top of the glacier and the "debris bands", "ablation platform" and "red stain" on the glacier face. Photo - A.B. Field.

Fig. 4.3 "Debris bands" exposed on the Taylor Glacier snout. The writer is standing on the debris -covered "ablation platform". Photo - T.R. Healy.

coalescing of bands is not uncommon, they are often conformable for several metres. The "debris bands" are composed of 60% sediment and 40% ice, whereas the ice between the bands is relatively clean, consisting of less than 5% sediment. The "ablation platform" is composed of glacial ice containing "debris bands", but covered by a veneer of sediment dumped as a result of the ablation of overlying ice. The sediment on the "ablation platform" consists of both sand and gravel.

4.2. 1 SEDIMENT ANALYSES. The glacier sediment and sediment from the adjacent outwash fan consists of medium sand which is very poorly sorted and exhibits near symmetrical skewness (Table 4.1). The river sample is very platykurtic whereas the samples from the glacier are mesokurtic and very leptokurtic.

Table 4.1 Textural parameters of the detrital Taylor Glacier sediments.

Sample number		Mean size (Mz Ø)	Sorting (σ_IØ)	Skewness (Sk_I)	Kurtosis (K_G)
1	river sediment	1.1	3.3	0.0	0.6
2	"debris bands"	1.4	2.6	+0.2	1.9
3	"ablation platform"	1.3	2.7	0.0	1.0

On the basis of textural parameters three broad facies of bottom sediments occur in the Lake Bonney west lobe (Section 4.3. 1). The first facies is derived from the Taylor Glacier and from river-transported sediment and the second facies is derived from mainly wind-transported sediment. The third facies occurs in the deepest part of the west lobe and consists of both

Taylor Glacier and river-transported sediment and wind-transported sediment. The sediments analysed from the "debris bands" and "ablation platform" are texturally similar to the third facies described above.

The "debris bands" and outwash detrital sediments consist mainly of subangular to subrounded feldspar and quartz (Table 4.2) although grains from the river sediment are the more angular. Plagioclase is the dominant feldspar species. The quartz grains in the glacier sediment occasionally exhibit effects of physical weathering such as pitting. The heavy minerals comprise 8 to 12% of the bulk sediment fraction and consist dominantly of brown hornblende, augite, hypersthene and minor amounts of biotite and magnetite, especially in the fine sand grade. Sub-angular to angular slabs of granite, up to 0.6m long, are found on the Taylor Glacier "ablation platform". The clay mineralogy is dominated by illite with minor amounts of chlorite, montmorillonite and mixed-layer illite-chlorite.

Table 4.2 Quartz and feldspar ratios of the Taylor Glacier sediments.

Sample number	Feldspar/Quartz	Plagioclase/ Potash feldspar
1 river sediment	1.1	1.4
2 "debris bands"	1.8	2.0

The detrital mineralogy suggests the sediments are locally derived, probably from the granites of the Granite Harbour Intrusive Complex (Fig. 1.2) which consist of quartz, plagioclase, biotite and minor hornblende. The lamprophyre and porphyry dykes and Ferrar Dolerites found on the valley sides are also contributors to the bulk detrital mineralogy, but to a lesser extent.

The percentage of chemical precipitates in the outwash fan is low with only slightly higher amounts from the glacier sediment (Table 4.3). Gypsum is the principle precipitate in the sediment with minor amounts of calcite (Table 4.4). However, salts of gypsum, calcite, thenardite ($Na_2 SO_4$) and tachyhydrite ($Ca Mg Cl_6 . 12 H_2O$) occur in the glacial ice. X R D analysis of the "red stain" on the snout of the Taylor Glacier (Fig. 4.2) showed the presence of gypsum, although chemical analyses by Keyes (1972) revealed a variety of salt compounds are also present.

Table 4.3 Weight percent chemical precipitates in the Taylor Glacier sediments.

Sample number	% Chemical precipitates
1 river sediment	1.0
2 "debris bands"	1.8
3 "abalation platform"	2.0

The organic carbon content of the glacier "ablation platform" sediment and river sediment (Table 4.4) is low compared to the "debris bands" sample which is similar to the organic content of the west lobe sediments that range from 0.13 to 0.26% organic carbon.

Table 4.4 Carbon content of the Taylor Glacier sediments.

Sample number	% Total C	% Inorganic C ($\% CaCO_3$)	% Organic C
1 river sediment	0.01	0.10 (0.8)	0.04
2 "debris bands"	0.30	0.04 (0.3)	0.25
3 "ablation platform"	0.13	0.09 (0.7)	0.04

Dating of gypsum from the glacier snout proved difficult because of the low U content; however, an age of about 28,000 years B.P. has been calculated (Appendix I).

4.2. 2 ORIGIN OF THE TAYLOR GLACIER SEDIMENT. The detrital mineralogy shows the sediment is locally derived from the granite, dolerite and lamprophyre and porphyry dyke rocks exposed on the valley sides. It is suggested that the sand in the Taylor Glacier, was originally windblown, and probably to a minor extent river-transported along with gravel, from the adjacent valley slopes onto a more westward extension of the present Lake Bonney west lobe.

The west lobe is envisaged as having been sufficiently saline to allow the precipitation of salts under probably evaporitic conditions and, with the subsequent advance of the glacier during the Taylor I Glaciation (Denton et al., 1970) this extreme western portion became covered. The chemical precipitates may not be entirely palaeo-lacustrine sediments, for they may have been concentrated through the crystallisation of brines, under frigid conditions, in permeable layers and/or fissures in the glacial ice. The dated sample of 28,000 years B.P. may have precipitated from englacial saline meltwaters.

The debris layers within the glacier have probably formed by a freezing-in process at the glacier bed and by the upwarping of the flow lines at the margins of the glacier. Weertman's theory (1961) adequately explains this type of debris layer in which a grain-size selective process occurs with only sand represented. The process may be the result of the formation of regelation ice during the freezing-in process, which incorporates small particles while blocks and slabs remain on the glacier bed.

The boulders on the "ablation platform" are probably of supraglacial origin. The differential ablation of debris-rich ice and subsequent accumulation of the sediment has produced the hummocky, stagnant-ice platform.

4.3 LAKE BONNEY WEST LOBE SEDIMENTS.

The textural classes of the detrital constituents of the west lobe bottom sediments and the site 11 deep core (Fig. 4.23) range from sand to silt (Fig. 4.4).

4.3. 1 TEXTURE. The mean grain size of the west lobe bottom sediments ranges from medium silt to coarse sand (Table 4.5). Fig. 4.5 shows the source of most of the fine-grained material is in the Taylor Glacier meltwater, with most of the silt component being deposited in the western and in the deep portion of the lobe. The west lobe bottom sediments are poorly to very poorly sorted. The most poorly sorted sediments are found in the area most affected by the deposition of fine-grained sediment introduced into the lake by the Taylor Glacier snout and outwash (eg. samples 4 and 5). The least poorly sorted sediments are at shallow locations on the northern side of the west lobe (eg. sites 7 and 12).

Skewness values (Table 4.5) show near symmetrical values in the sediments of the extreme west and east portions of the west lobe (eg. sites 4, 5 and 21) while in the deep portion of the lobe coarse skewed sediments occur (eg. sites 9, 12 and 16). Skewness values are more complex for the remaining west lobe samples, although fine- to very fine-skewed sediments occur in the eastern portion of the lobe (eg. sites 17, 18, and 20) and strongly coarse-skewed sediments occur in the remaining shallow locations in the western portion of the lobe (eg. 7, 14 and 15). Kurtosis values range from platykurtic to very leptokurtic. Mesokurtic to platykurtic sediments occur in the

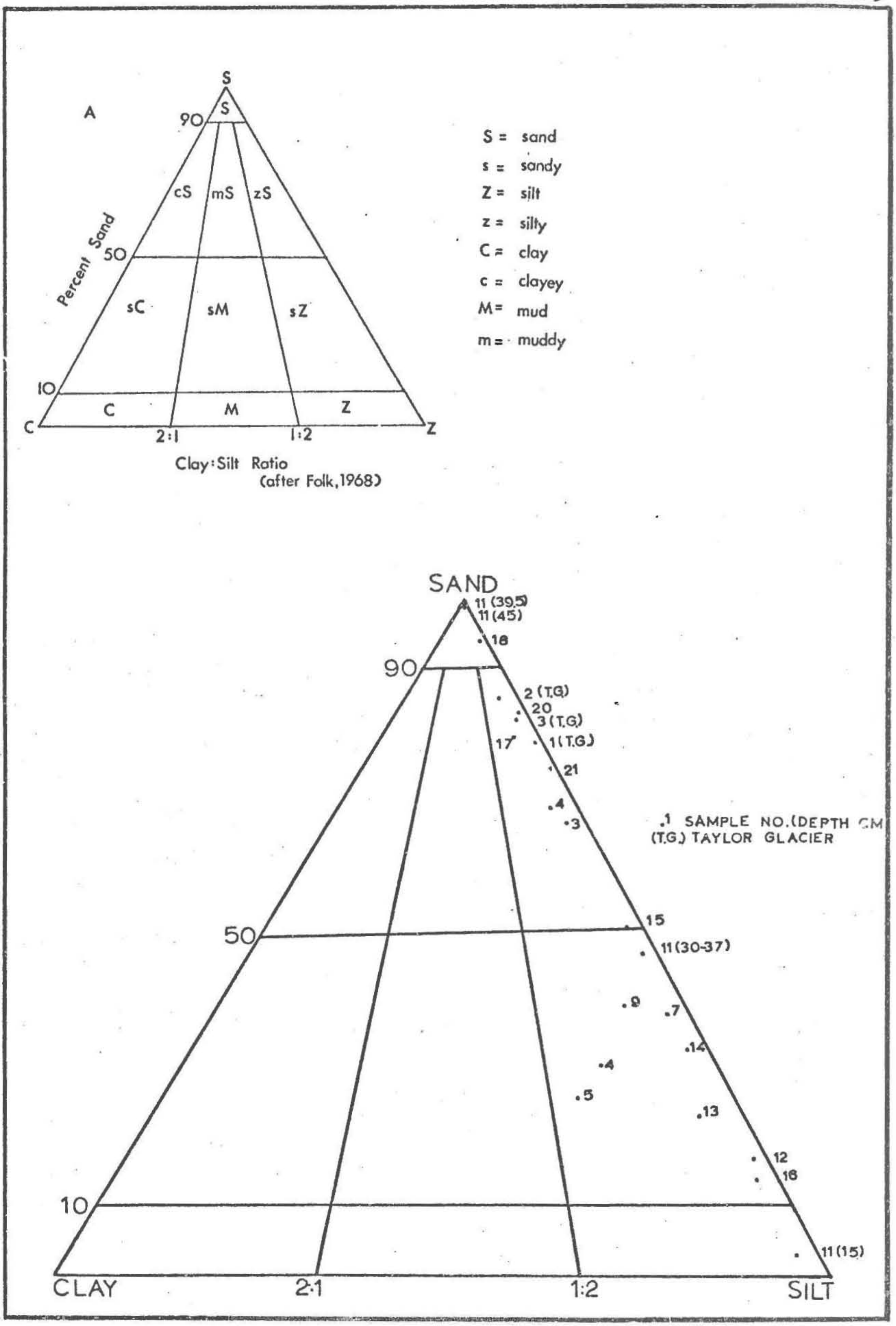


Fig. 4.4 Textural classes of detrital sediments from the Taylor Glacier and Lake Bonney west lobe.

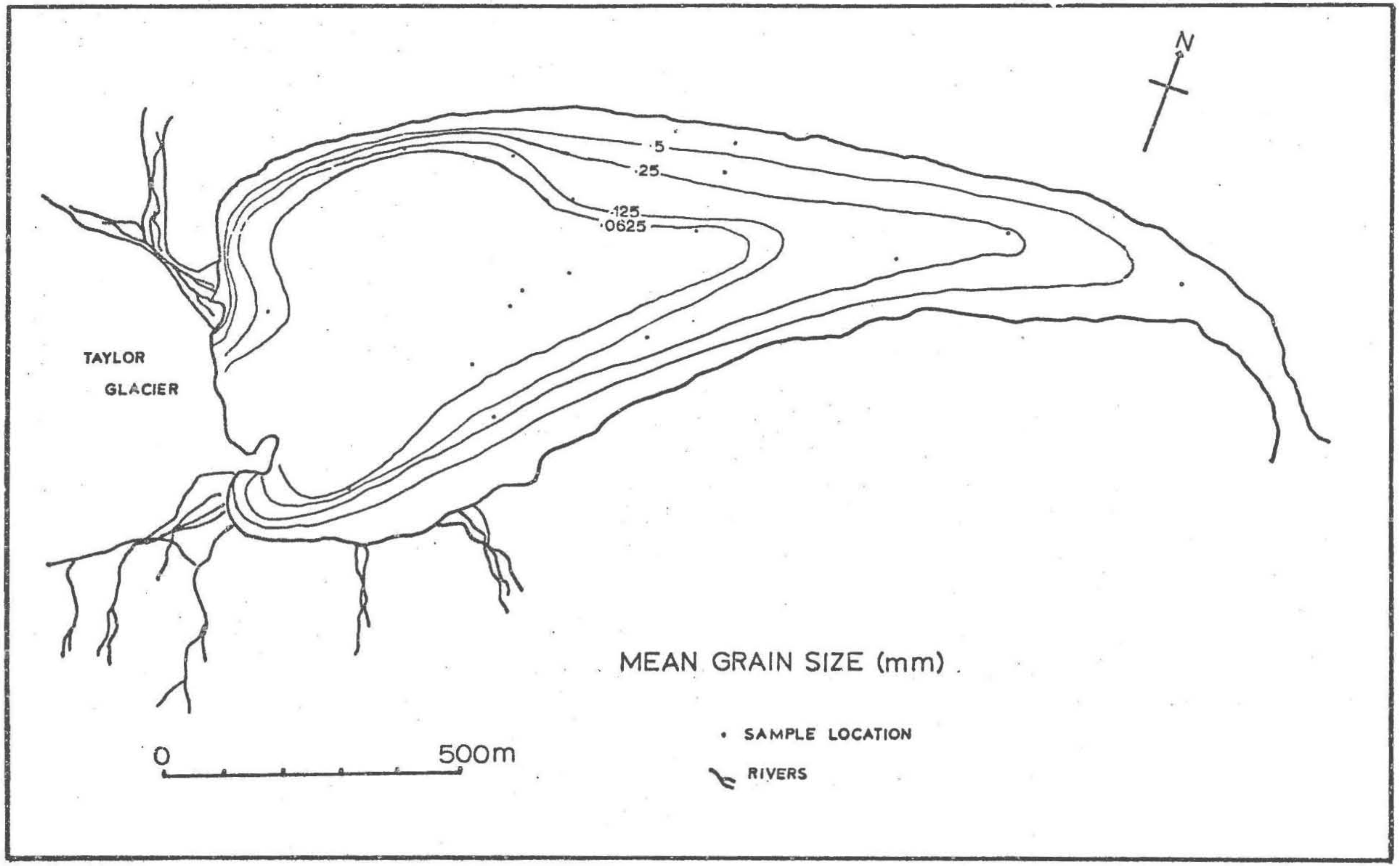


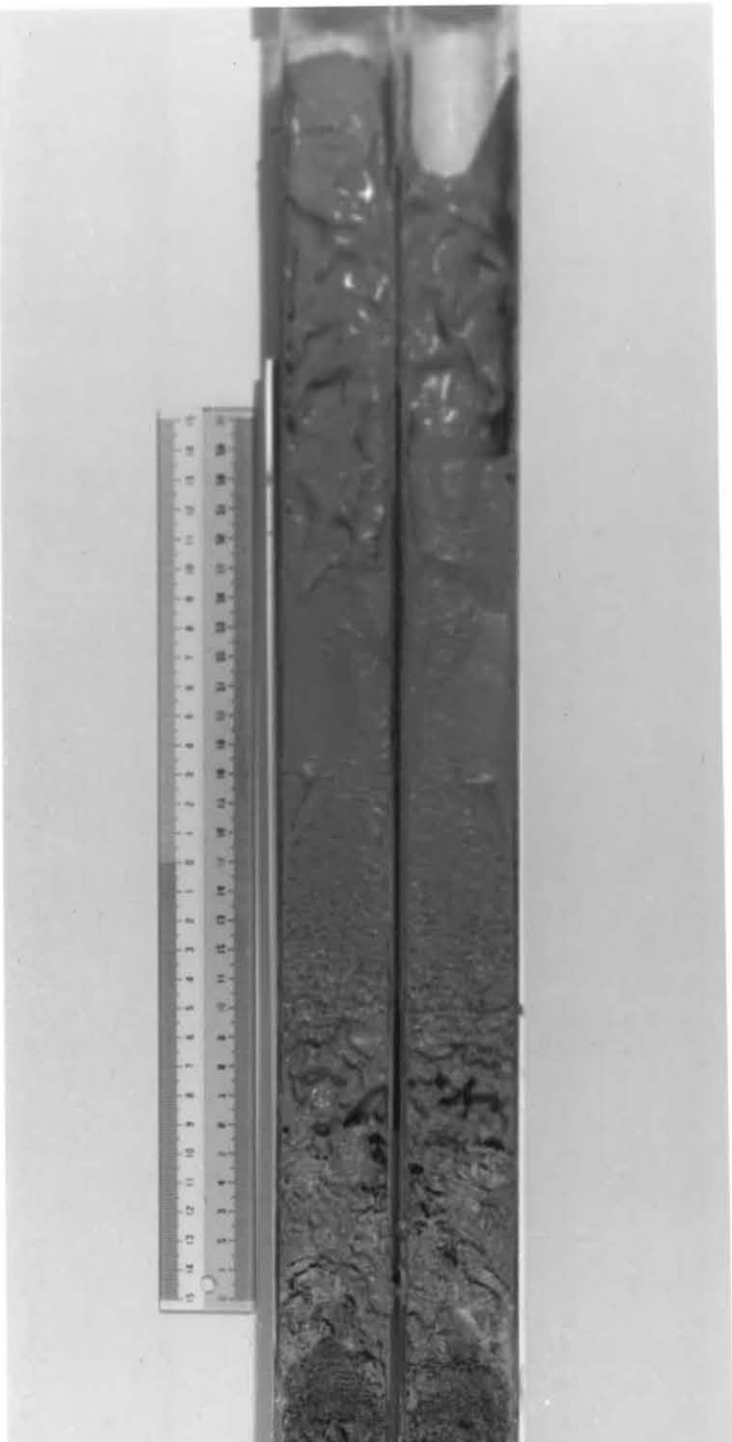
Fig. 4.5 Mean grain size of detrital bottom sediments of the Lake Bonney west lobe.

Table 4.5 Textural parameters of the detrital sediments of Lake Bonney west lobe.

Sample number (depth cm)	Mean size (Mz Ø)	Sorting (σ_IØ)	Skewness (Sk_I)	Kurtosis (Kg)
4	5.2	3.5	0.0	1.0
5	5.3	3.3	0.0	0.8
7	4.0	1.7	-0.3	1.1
8	1.8	2.2	+0.3	1.4
9	4.5	2.5	-0.2	1.4
11 (15)	5.8	1.0	0.0	1.0
11 (30-37)	3.9	1.6	-0.3	1.5
11 (39.5)	1.8	0.9	0.0	1.1
11 (45)	-3.5	2.7	0.0	1.5
12	4.9	1.2	-0.1	1.4
13	4.6	2.0	-0.1	2.1
14	3.9	2.1	-0.5	1.5
15	3.7	2.1	-0.4	1.5
16	5.0	1.3	-0.1	2.3
17	1.7	3.3	+0.6	1.4
18	0.2	1.8	+0.1	1.3
19	2.0	2.8	+0.3	0.9
20	2.4	2.9	+0.2	0.8
21	0.6	2.6	0.0	1.0

extreme east and west portions of the west lobe and in the central deep part of the lobe (eg. 4, 7, 11, 19 and 20).

Fig. 4.6 Sedimentological log of core 11 from the Lake Bonney west lobe. The top 22cm consists of gypsiferous silt with occasional detrital sandy phases. At depths of 20- to 35.5cm silty gypsum occurs. The gypsum is either fine-grained or in the form of banded platey chunks. Underlying the gypsum is a 1cm thick fine sand layer, the base of which is iron-stained. The reddish-brown stain is restricted to the fine-grained gypsum present in the sandy layer. At depths of 36.5- to 39.5- a fine- to medium-sand occurs, however the basal section of the core is a pebbly sand. The total length of core 11 is 47.7cm. Scale in centimetres.



Leptokurtic samples occur in shallow to intermediate depths (7 to 27m depth) in the centre of the lobe (eg. site 16, 18 and 15).

The texture of detrital sediments in the site 11 deep core (Fig. 4.6 and Table 4.5) show the silty top section is moderately to poorly sorted and the sandy bed above the iron-stained level to be moderately sorted. The pebbly sand basal section is very poorly sorted. Skewness shows near-symmetrical values at all depths except at the 30 to 37cm which is coarse skewed. Kurtosis shows mesokurtic values at 15 and 39.5cm depth and leptokurtic values at 30 to 37 and 45cm depth.

Scatter plots (Fig. 4.7) of standard deviation versus mean grain size and skewness versus mean grain size show three broad sediment facies. The first facies consists of sediment derived from the Taylor Glacier and deposited adjacent to the glacier snout (eg. samples 4 and 5). The second facies is generally restricted to the deeper part of the lobe and consists of Taylor Glacier derived sediment and wind transported sediment (eg. samples 14, 16 and 12). The third facies is primarily wind blown sediment (eg. samples 17 and 20). The kurtosis versus skewness scatter plot does not show any clearly defined facies differentiation.

West lobe bottom sediments are either derived from the Taylor Glacier or wind-transported into the lake. Wind-transported

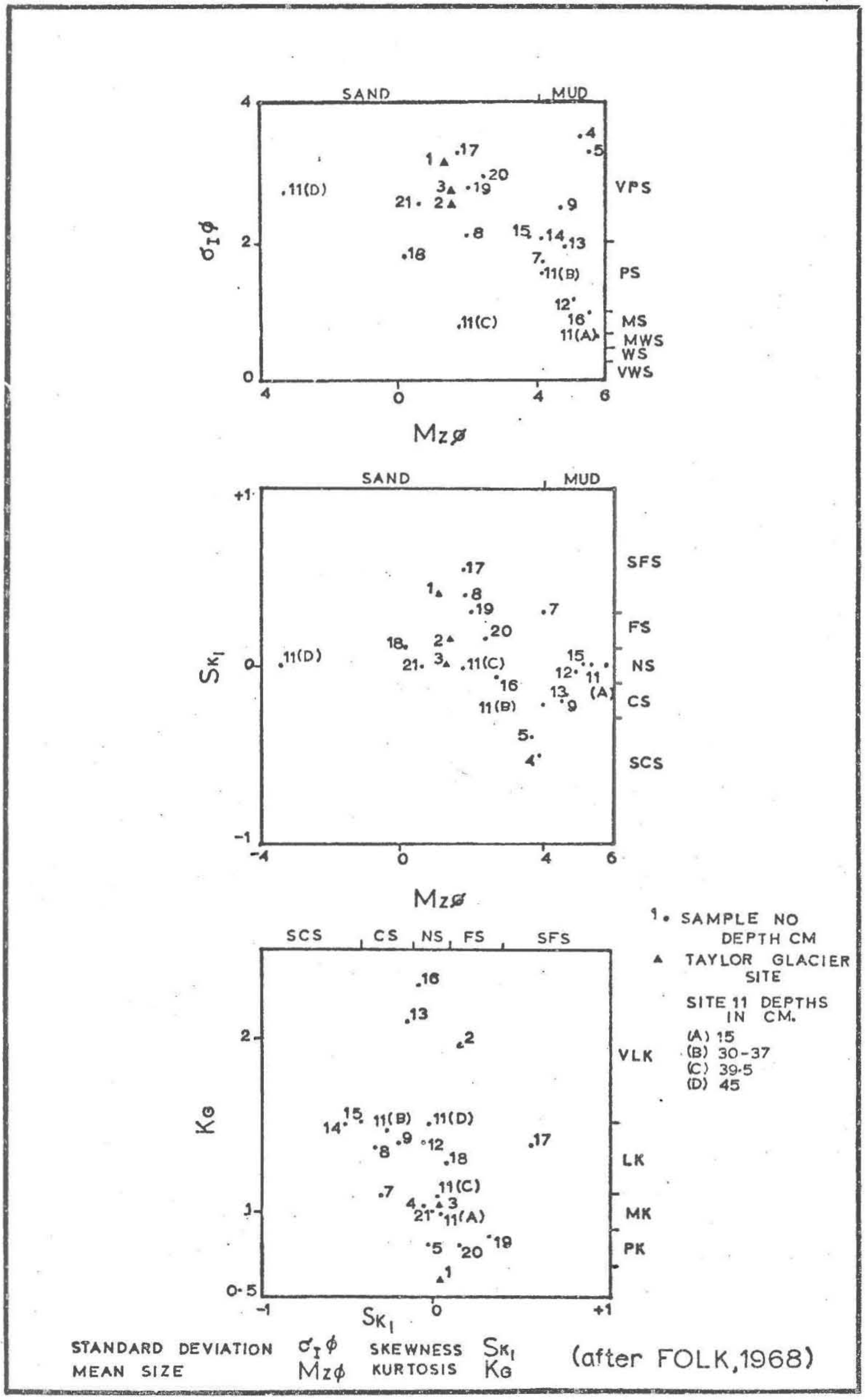


Fig. 4.7 Scatter plots of detrital sediments of the Taylor Glacier and Lake Bonney west lobe.

sediment is either blown onto the lake ice where, eventually, it sinks through to the lake floor, or the sediment, particularly the more silty sands, is blown into the summer moat. Sediment from the Taylor Glacier is either transported by the rivers adjacent to the glacier or is released from the ablating base of the glacier (Fig. 4.8).

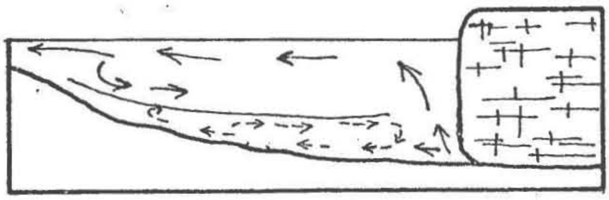


Fig. 4.8 Main circulation in a glacial lake (Duff <u>et. al</u>., 1967). Assumed direction and strength of currents indicated by arrows.

Textural analyses of the west lobe bottom sediment enables three broad sediment facies to be defined. The first facies, located adjacent to the Taylor Glacier, consists of a very poorly sorted, near symmetrically skewed, mesokurtic silt. The sediment is derived from the Taylor Glacier and its associated rivers. The second facies is generally restricted to the deeper parts of the west lobe and consists of both wind-transported and Taylor Glacier sediment. The sediment is very poorly sorted, coarse skewed, mesokurtic to leptokurtic coarse silt. The third facies, located in shallow depths and particularly in the eastern portion of the lobe, is wind-transported sediment that is very poorly sorted, fine skewed medium sand.

Interpretation of the textural data for the site 11 deep core suggest that since the deposition of the silty sediment at 36cm depth, the Taylor Glacier has advanced contributing an increasing amount of sediment to the total west lobe sediment budget. The base of the silty section probably consists mainly of wind-derived sediment. The medium sand at depths of 36.5 to 39.5cm may be either wind-derived sediment or sediment deposited under deltaic conditions. A low lake-level is suggested. The basal pebbly sand section may be outwash or, more likely, Taylor II Glaciation moraine, the extent of which is indicated in Fig. 1.3.

4.3. 2 DETRITAL MINERALOGY. X R D analyses indicate that the detrital sediment consists mainly of quartz and feldspar (Table 4.6). The quartz grains are either frosted and subangular to subrounded or clear and more angular. The feldspars are predominantly plagioclase and are subangular and often contain opaque mineral inclusions. Occasional jagged to rounded mica flakes of biotite, and less commonly muscovite, are present, particularly in the sediments from the deepest part of the lobe.

The heavy mineralogy, which comprises 7 to 16 percent of the total sand fraction, is dominated by hornblende (60 to 80%)

Table 4.6 Quartz and feldspar ratios of the bottom sediments of Lake Bonney west lobe.

Sample number (depth cm)	Quartz/Feldspar	Plagioclase/ Potash feldspar
4	0.8	10.0
7	7.0	4.0
8	1.2	7.0
11 (10)	1.6	5.0
11 (30)	4.2	8.0
11 (30-40)	17.0	N.D.
15	4.0	3.0
16	6.0	2.0
18	0.5	1.4
20	1.0	3.0

N.D. = Not Detectable

with minor amounts of augite and hypersthene, and rare fine-grained opaque minerals, particularly magnetite. The hornblende is generally subangular and mainly of the brown variety, although small amounts of green-brown hornblende occur. Augite is more abundant than hypersthene and both pyroxenes are subangular.

Subangulär, low sphericity, gravel-sized clasts consist mainly of granite with granules of dolerite and lamprophyre dyke rock. The gravel at the base of the site 11 deep core, is of a similar composition and shape although some clasts are iron-stained.

The clay minerals are dominated by crystalline illite with lesser amounts of chlorite, mixed-layer illite-chlorite and montmorillonite. Illite is most abundant in shallower sites.

The quartz, plagioclase, hornblende, mica and magnetite are probably derived mainly from the Larsen Granodiorite, which encloses the lake (Fig. 1.2). The remaining minerals are derived from the Vida granite and, in the case of the pyroxenes, from the lamprophyre dykes and Ferrar Dolerite. Grain shape and surface texture suggest that the sediment is mainly wind-blown and, to a lesser extent, river-transported into the lobe. The detrital sediments are mainly locally derived. Differential settling velocities for clay minerals (Whitehouse et al., 1958) probably account for the larger amounts of illite at shallow depths in the lobe.

4.3.3 CHEMICAL PRECIPITATES. The chemical precipitates in the west lobe bottom sediments are mainly gypsum with a minor amount of calcite (Table 4.8). The percentage of chemical precipitates in the bottom sediments (Table 4.7) ranges from 1.1 to 11.4% with the highest values in the deep central to eastern portion of the lobe. The distribution and concentration of these salts reflect water depth, water movement and sediment influx from the western river sources (Fig. 4.9).

Gypsum occurs as plates or in a fine-grained form. Platey gypsum occurs everywhere at water depths below 18m except near

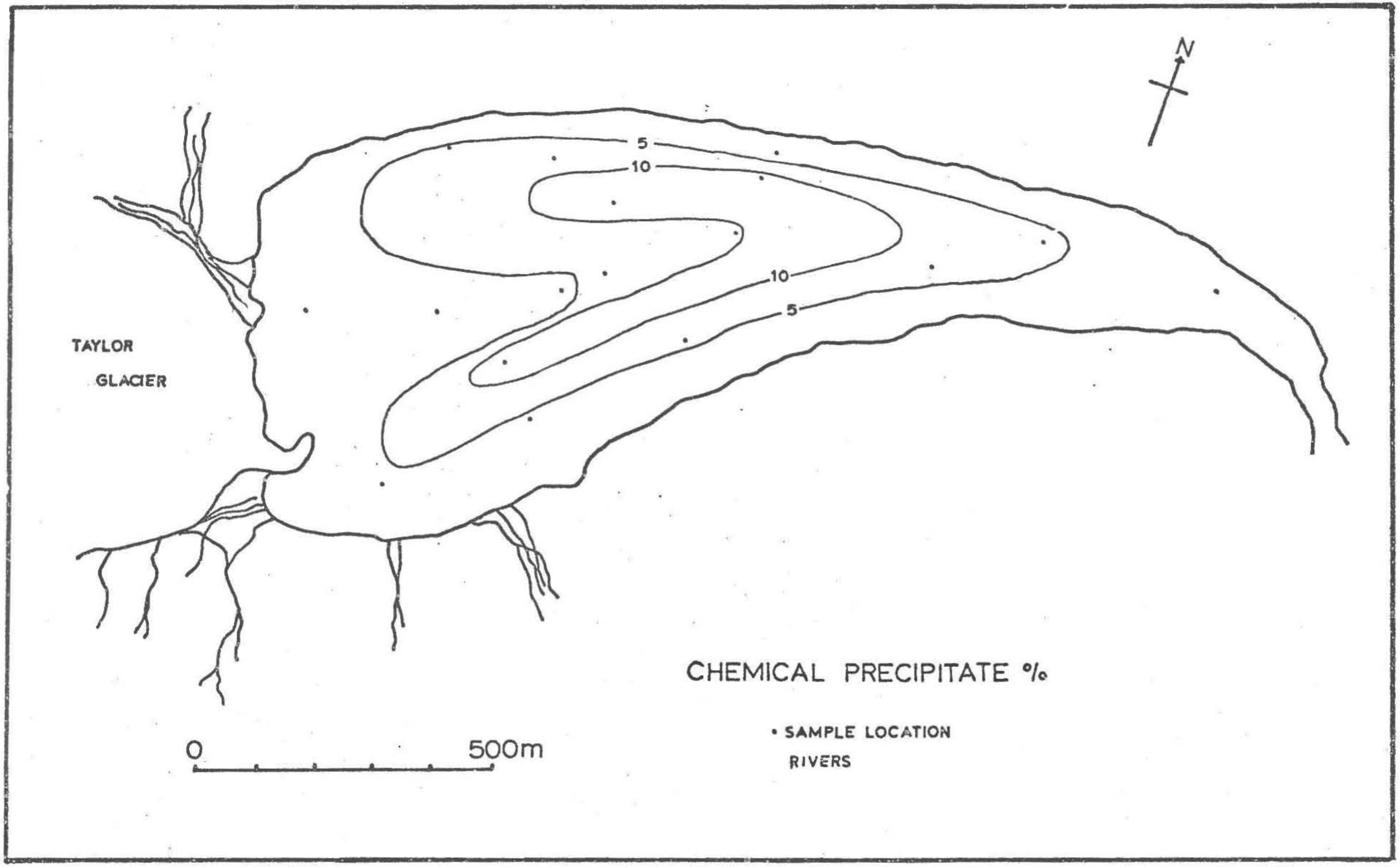


Fig. 4.9 Chemical precipitate content of the bottom sediments of Lake Bonney west lobe.

Table 4.7 Weight percent chemical precipitates in the sediments of the Lake Bonney west lobe.

Sample number (depth cm)	% Chemical precipitates
4	5.8
5	4.9
7	1.4
8	11.4
9	9.8
11 (5)	4.7
11 (30-40)	12.6
11 (45)	0.4
12	8.1
13	8.4
14	11.2
15	5.2
16	5.8
17	11.4
18	1.4
19	8.3
20	6.1
21	1.1

the Taylor Glacier (eg. site 5). The plates are often sharp-edged, less than 1cm across, and contain up to four bands in each plate. The calcite present in all cases is microcrystalline.

The gypsum near the 15cm level in the site 11 deep core (Fig. 4.6) is in the form of strongly curved discs which may be "oolitic" (Fig. 4.10). The "oolites" are 0.3 to 0.8mm in diameter and commonly have a nucleus of calite crystals or a mica flake. The interior of individual "oolites" contains a number of growth rings broken by radial microfractures. The exterior of the "oolites" is generally smooth. The gypsum from 25 to 35cm depth shows occasional swallow-tail twinning (Fig. 4.11).

The chemical precipitates are probably evaporitic, having formed with the aid of a frigid, magnesium-rich lake bottom environment. The gypsum plates have originated by reworking of evaporitic beds (ie. are intraclastic), perhaps as a result of frost riving during a period of lower lake level. The "oolites" attest to at least mild water agitation during their formation, while the twinned gypsum may be diagenetic or have formed by the slow evaporation of gypsum-saturated sodium chloride solutions (Shearman, 1966). The iron-stained gypsum at 36.5cm depth in core 11 (Fig. 4.6) probably formed under anaerobic conditions during the period of associated gypsum formation.

4.3. 4 ORGANIC MATTER. The organic carbon content ranges from 0.13 to 0.26% in the bottom sediments (Table 4.8) and is highest in the finer-grained sediments in the deepest part of the lobe and also in the channel between the two lobes. Prolific algal growth occurs in the channel where the water depth is shallow

Fig. 4.10 Gypsum "oolites" (average diameter 0.7mm) from the 15cm depth in core 11 of the Lake Bonney west lobe. The "oolites", generally found in fragments, consist of a number of growth rings broken by radial fractures. The "oolites" often have a nucleus consisting of a mica flake or calcite crystals.

Fig. 4.11 Swallow-tail twinned gypsum (1.5mm long) present at depths of 25cm to 35cm in core 11 of the Lake Bonney west lobe.

Table 4.8 Carbon content of the sediments of Lake Bonney west lobe.

Sample number (depth cm)	% Total C	% Inorganic C ($\%CaCO_3$)	% Organic C
11 (5)	0.52	0.26 (2.1)	0.26
11 (20)	0.30	0.15 (1.2)	0.15
11 (37)	0.19	0.04 (0.3)	0.15
11 (45)	0.17	0.07 (0.6)	0.10
15	0.25	0.10 (0.8)	0.15
16	0.22	0.05 (0.4)	0.17
18	0.34	0.16 (1.3)	0.18
19	0.16	0.03 (0.2)	0.13
21	0.19	0.02 (0.1)	0.17

and the lake-ice broken thereby providing optimum light conditions for organic growth. The organic carbon content in core 11 appears to be related to sediment size with the lowest values associated with the basal pebbly sands.

4.3. 5 URANIUM/THORIUM DATING. U/Th dating proved difficult because of the low U content (C. Hendy, pers.comm.). The gypsum plates at site 16 give an age of at least 300,000 years (Appendix I). U/Th ages of the gypsum in cores 10 and 11 were not entirely concordant; however, homogeneity in the U_{234}/U_{238} ratio exists indicating a different origin for this uranium compared to that in the gypsum plates at site 16, the latter having a U_{234}/U_{238} ratio of 1.2 which is similar to that in seawater, namely 1.1.

4.3. 6 SUMMARY and CONCLUSIONS. The west lobe detrital bottom sediments are either derived from the Taylor Glacier or wind-transported into the lake. The detrital sediments range from silt to sand and, on the basis of texture, three broad sediment facies are distinguished. The first facies, located adjacent to the Taylor Glacier, consists of poorly sorted, near symmetrically skewed, mesokurtic silt. The sediment is derived from the Taylor Glacier and its associated rivers. The second facies is generally restricted to the deeper parts of the lobe and consists of both wind-transported and Taylor Glacier sediment. The sediment is very poorly sorted, coarse skewed, mesokurtic to leptokurtic coarse silt. The third facies, located in shallower depths and particularly in the eastern portion of the lobe, is wind-transported sediment that is very poorly sorted, fine skewed medium sand.

The detrital sediment is mainly derived from the Larsen Granodiorite which encloses the lake, with minor contributions from the Vida Granite, lamprophyre dykes and Ferrar Dolerite exposed on the valley sides. Sediment surface textures and form show evidence of both wind- and river-transporting processes.

The chemical precipitate content of the bottom sediments increases with depth although this relationship is also affected by water movement and sediment influx from the Taylor Glacier. The chemical precipitates consist of gypsum and calcite and were probably formed under frigid evaporitic conditions. Platey gypsum found in the deeper part of the lobe has probably been derived by reworking of frost riven gypsum layers during a period of lower lake level. U/Th dating gives an age of 300,000 years for the platey gypsum and the U_{234}/U_{238} ratio of this gypsum suggests a marine origin.

The organic carbon content is highest in the deep part of the lobe and in shallow locations where optimum light conditions exist. The relationship between organic growth and the chemical and physical lake sub-environments is undoubtedly complex.

The basal pebbly sands in the west lobe deep cores are at least 300,000 years old and probably represent Taylor II Glaciation moraine. A moderately sorted medium sand, possibly deposited under deltaic conditions, overlies the above-mentioned moraine deposit. A low lake level is envisaged at that time with anaerobic conditions existing. A marine incursion of the Taylor Valley subsequently occurred and under frigid evaporitic conditions salts were precipitated from the seawater about 300,000 years B.P. Seawater is envisaged as at least draining into the Bonney Basin. The gypsum was precipitated in a variably saline environment and, upon induration, was probably broken-up by frost riving during a period when the lake level was perhaps only 18m deep. The very saline conditions existing at that time are indicated by the swallow-tail twinned gypsum, while the gypsum "oolites" indicate at least mild water agitation and very low terrigenous influx.

Since the precipitation of gypsum the rate of sedimentation has been about 3.6×10^{-4}cm / year. The rate of sedimentation has not been uniform as sandy phases are present and there is an overall increase in the silt content towards the top of the core. The fine-grained sediment found in the upper sections of the deep core shows that meltwater from the Taylor Glacier has been an increasingly important source of sediment in the west lobe, probably for at least 10,000 years. The entry of the Taylor Glacier into the Bonney Basin is probably evidence of the Taylor I Glaciation advance.

Denton et al. (1970) report the presence of Ross Sea I and II Glaciation strandlines in the Taylor Valley at 310 and 400m altitude, respectively. Wilson et al. (1974) found 6,000 year old strandlines about 210m above Lake Bonney which may represent the Ross Sea I Glaciation. It is postulated by the above-mentioned authors that during the Ross Sea I and II Glaciations ice tongues from the Ross Sea ice dammed large lakes in the Taylor Valley. A rapid drop in the high lake level was considered likely as a result of the melting of the ice tongues of the Ross Sea Glaciations. The occurrence of these two very high lake levels is not noticeably apparent in the stratigraphy of the Lake Bonney west lobe sediments.

4.4 LAKE BONNEY EAST LOBE SEDIMENTS.

The extent of the 1973/74 summer thaw on the Lake Bonney east lobe was indicated by: (a) the degree of ablation of the lake-ice which annually ablates about 41cm of ice (Fig. 4.13);

(b) the rapid development of melt-water streams and overland flow (Fig. 4.14);

(c) the steadily rising lake level.

Contrary to earlier reports (eg. Taylor, 1922), this running water was clearly an important source of sediment for the east lobe during the 1973/74 field season. Lake Bonney appears to have been increasing in size since the turn of this century. In February 1911, the width of the channel connecting the two lobes was 30.2m (Taylor, 1922), while in January 1974, it was 41m wide and 9m deep. This represents a depth increase of 2.4m. The lake level increased 1.15m during the 1973/74 summer melt.

The east lobe bottom sediments can be grouped into three broad facies, the lithologies of which are largely related to water depth. At depths below 30m the sediment is composed of halite crystals covered by a veneer of organic detritus and silt; the second facies, between 18 and 30m depth, consists of gypsum, aragonite, halite, calcite and detrital sand and silt; the third facies, at depths generally shallower than 18m, is gravel, sand and silt. Proximity to the major meltwater stream outlets largely determines the extent of facies 3. The sediments at the shallowest depths are similar to the lake-shore sediments.

Sand from the eastern slope of the Bonney Reigel (Fig. 4.15) was analysed since the Reigel acts as a trap for wind-blown sand. In addition wind-blown sediment was collected from the ablating

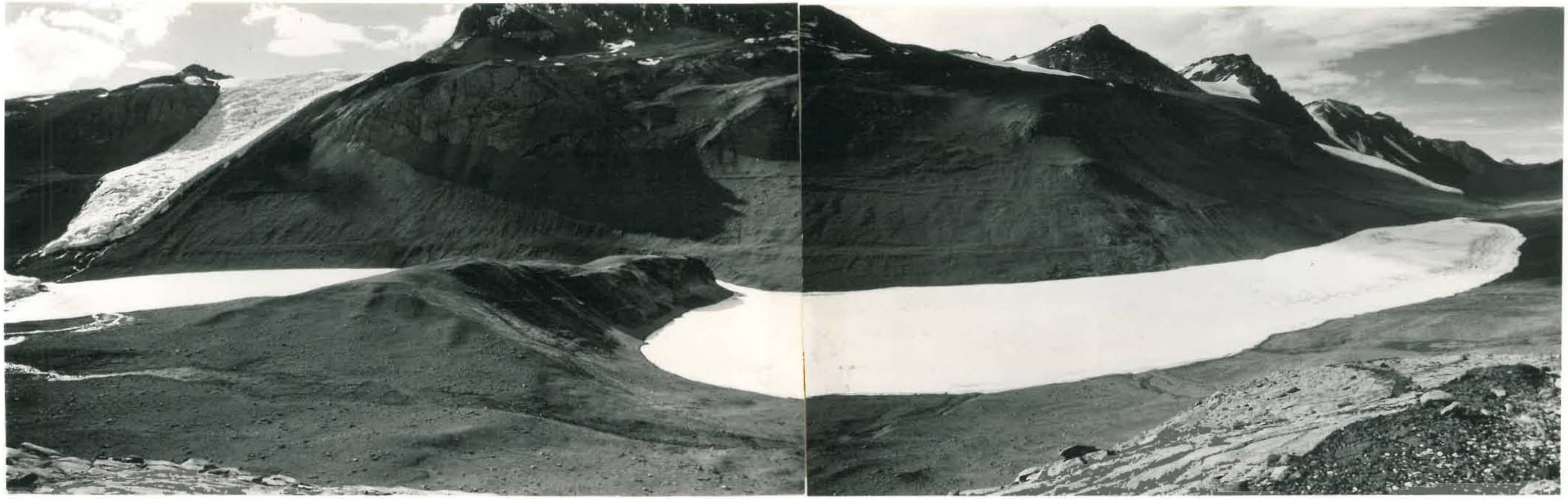


Fig. 4.12 Lake Bonney east lobe with the Bonney Reigel and west lobe on the left side of photo. The Asgard Range in the background forms the north side of the Taylor Valley. Photo - T.R. Healy.

Fig. 4.13 Ablation of the lake-ice surface, Lake Bonney east lobe. The flat ice platform (a) in the extreme foreground was formed in 1973; the ice-axe is on the partially ablated ice platform (b) formed in 1972. An annual ablation rate of about 41cm can be deduced. Photo taken in January 1974.

Fig. 4.14 Meltwater streams from the Hughes Glacier, Taylor Valley. Photo taken from the Lake Bonney east lobe in January, 1974.

b b a a

Fig. 4.15 The sandy eastern slope of the Bonney Reigel viewed from the south on the Lake Bonney east lobe ice-cover.

lake ice-cover at site 26. Although the sediment on the lake-ice is almost entirely of sand grade, two near-spherical granite boulders, 1.2 and 2m across, were found on the lake ice about 100m from the north shore (Fig. 4.23). The boulders probably rolled down the adjacent hillslope onto the lake-ice prior to the formation of a summer moat. The insulating properties of the rocks were sufficient to prevent ablation of the underlying ice and the boulders have subsequently been rafted towards the centre of the lake in a manner similar to the Lake Vanda "dirtlines" (Section 3.1).

4.4. 1 TEXTURE. The detrital sediments range from sand to muddy sand to silt (Fig. 4.16). The mean grain size of the bottom sediments ranges from a medium silt to very coarse sand and sorting ranges from moderately to very poorly sorted (Table 4.9). Fig. 4.17 shows the relationship of mean grain size and sorting to the location of meltwater streams and to water depth. Skewness values for the bottom sediments range from strongly fine skewed to strongly coarse skewed with most samples being fine skewed. Kurtosis values range from very platykurtic to very leptokurtic. The wind-blown sediments are moderately well sorted, near symmetrically skewed, mesokurtic medium sands.

The stratigraphy of core 6 (Fig. 4.22) shows a silty upper 3cm underlain by a variety of chemical precipitates intermixed with detrital silt and sand. The silt probably represents sediment washed from shallower depths by the east lobe water circulation. The bathymetry of the site 6 area (Fig. 4.23) suggests that the basal pebbly sand is outwash material that was deposited as a terrace.

Two modes of sediment transport operate in the east lobe, namely the wind and meltwater streams. The scatter plots

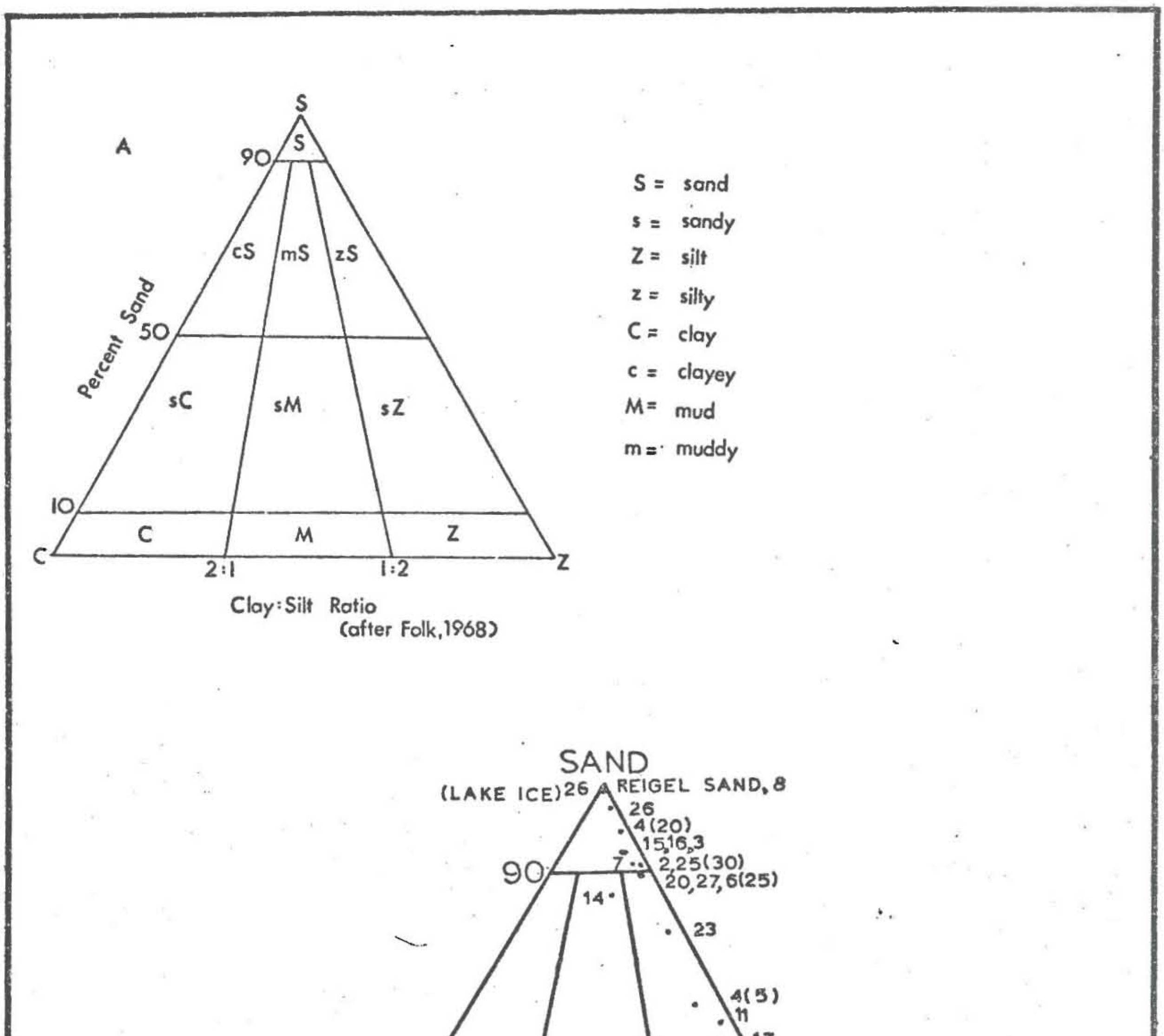


Fig. 4.16 Textural classes of detrital sediments of Lake Bonney east lobe.

Table 4.9 Textural parameters of the detrital sediments of Lake Bonney east lobe.

Sample number (depth cm)	Mean size ($Mz\ \phi$)	Sorting ($\sigma_I \phi$)	Skewness (Sk_I)	Kurtosis (Kg)
1	4.0	2.0	-0.3	0.7
2	2.0	0.9	+0.3	2.0
3	0.4	1.8	+0.2	1.5
4 (5)	3.3	2.4	+0.6	1.2
4 (20)	0.6	1.6	+0.5	1.2
5 (5)	3.8	2.9	-0.2	1.2
5 (20)	2.3	2.8	+0.3	0.8
6 (5)	6.0	1.7	-0.6	1.4
6 (25)	-0.3	3.5	-0.4	0.8
7	0.7	1.9	+0.2	1.6
8	0.9	1.2	-0.2	0.9
11	2.7	1.7	+0.4	0.9
13	6.0	2.1	-0.4	0.8
14	1.5	1.8	+0.3	2.3
15	1.1	1.4	+0.1	1.5
16	1.8	0.8	+0.2	1.4
17	2.5	2.7	+0.2	0.9
20	1.9	1.2	+0.3	1.7
22	0.5	3.0	+0.6	0.7
23	2.5	1.6	+0.1	1.0
25 (5)	2.4	2.4	+0.5	0.6
25 (30)	0.7	1.9	+0.2	0.9
26	-0.8	1.6	+0.1	1.2
27	0.9	2.5	-0.2	1.2
26(from lake ice)	1.0	1.1	-0.1	1.0
Reigel sand	1.4	0.4	+0.1	1.1

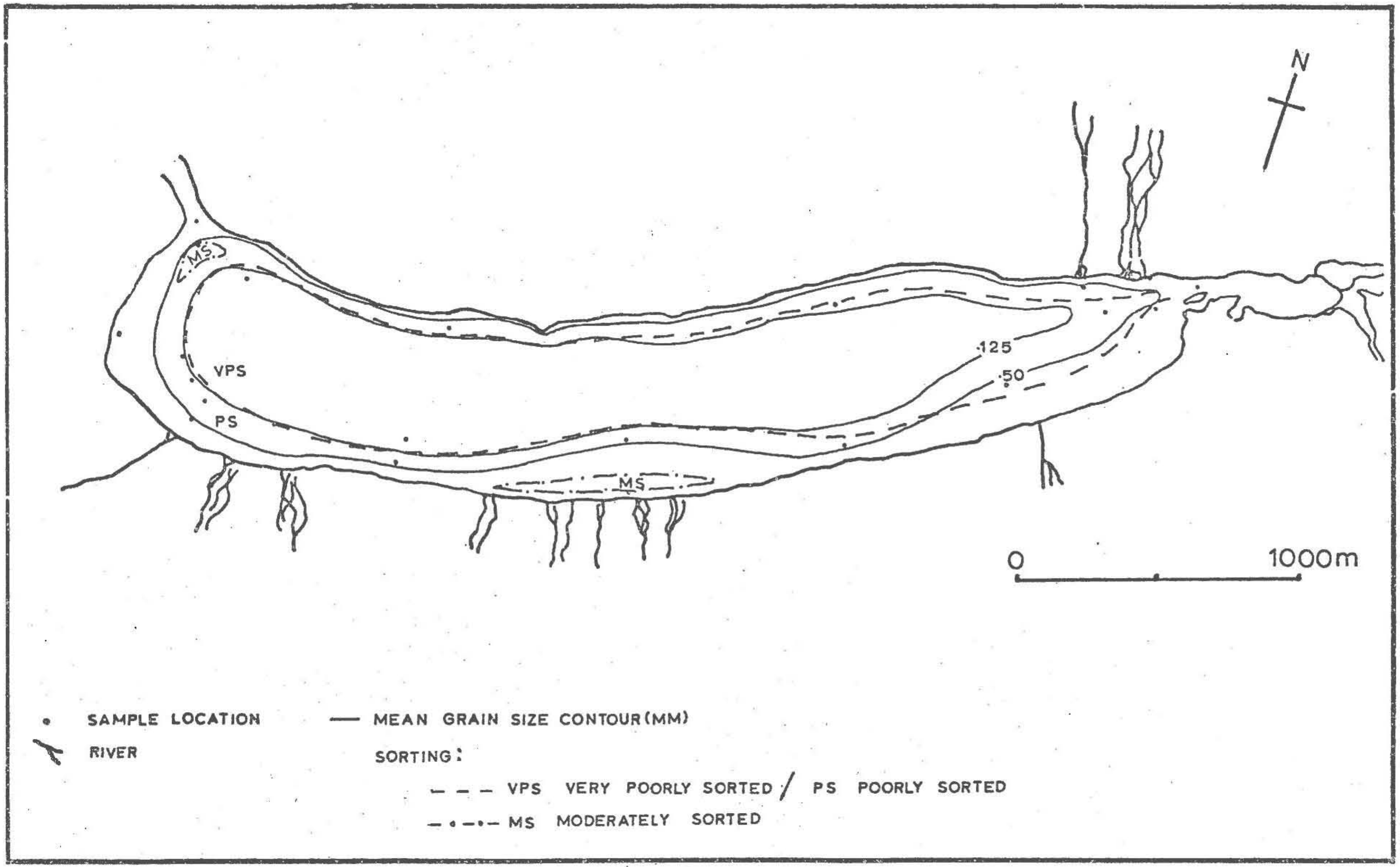


Fig. 4.17 Mean grain size and sorting of the detrital bottom sediments of Lake Bonney east lobe.

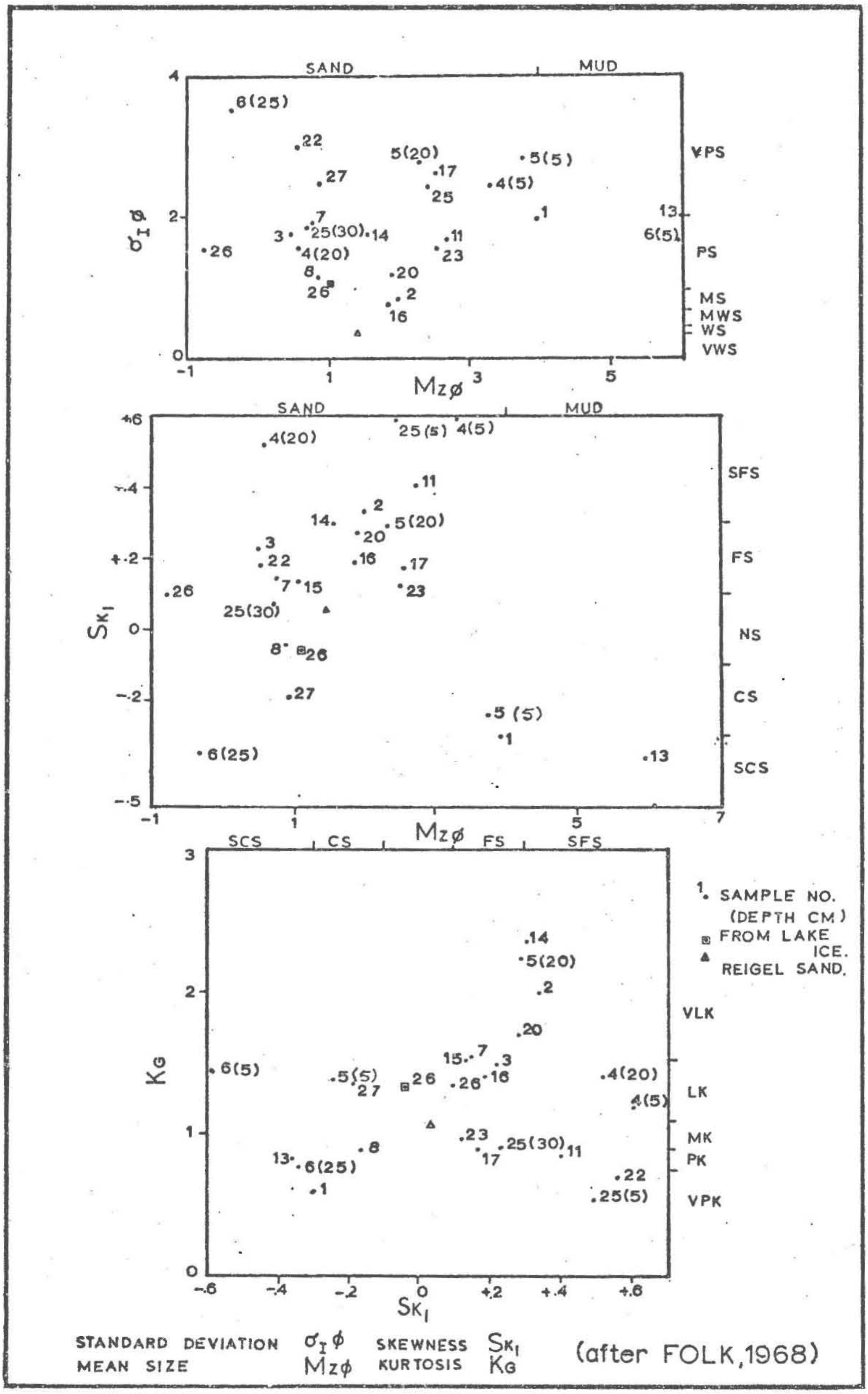


Fig. 4.18 Scatter plots of the detrital sediments of Lake Bonney east lobe.

(Fig. 4.18) separate the silts from the deepest part of the lake (eg. sample 15) and the remaining samples; however, no clear differentiation of sediments according to mode of transport is apparent. Sorting of terrigenous sediment decreases with depth although the content of detrital sediment is minimal on the flat lake-floor where chemical precipitates are dominant. The bulk of the sediment is probably wind-blown onto the lake-ice or, more importanly, into the moat developed about the lake in summer. However inflow of sediment from meltwater streams is important locally. The silt transported into the lobe at shallow depths remains largely in suspension and is ultimately deposited in the non-turbulent environment in the deepest part of the lobe.

4.4. 2 DETRITAL MINERALOGY. The detrital components of the sediments are dominated by quartz and feldspar. Sand grains are generally subrounded to subangular, the latter being particularly evident in sites close to the major meltwater streams on the southern shore (eg. sample 16). The light and heavy mineralogy of the east lobe sediments exhibit the same general characteristics as the west lobe mineralogy although relative abundances differ within the light minerals. Plagioclase is the dominant mineral species (Table 4.10). Together with quartz and potash feldspar, the light minerals also include relatively large sub-rounded flakes of biotite and lesser amounts of muscovite, particularly in the deeper sites. The heavy minerals comprise less than 22% of the total sand fraction and consist of hornblende, augite, hypersthene and opaque minerals (mainly magnetite).

Terrigenous subangular pebbles in the analysed sediments consist mainly of granite with occasional granules of Ferrar Dolerite.

Table 4.10 Quartz and feldspar ratios of the bottom sediments of Lake Bonney east lobe.

Sample number (depth cm)	Feldspar/Quartz	Plagioclase/ Potash feldspar
2	0.7	11.0
3	1.1	18.0
5	2.3	4.3
6 (25)	2.6	2.8
11	2.7	4.4
14	2.1	4.7
23	2.3	2.5
25	2.6	3.3
27	1.4	2.9

Clay mineral content does not appear to vary with depth and is dominated by relatively crystalline illite with minor amounts of chlorite and montmorillonite.

The source of the detrital minerals, as was the case for the west lobe detrital sediments, is mainly the granites of the Granite Harbour Intrusive Complex, the Ferrar Dolerites and the lamprophyre dykes found on the adjacent valley slopes.

4.4. 3 CHEMICAL PRECIPITATES. Two of the three general sediment facies mentioned in the introduction to this section contain significant amounts of chemical precipitates. The distribution and amount of chemical precipitate is indicated in Figure 4.19 and Tables 4.11 and 4.13.

The first facies, found at depths below 30m, is exemplified by cores 9 and 10 (Figs. 4.20 and 4.21) and consists of halite crystals whose sizes range up to at least the internal diameter of the core liner, namely 3.4 cm. The translucent halite crystals often have well-developed cubic faces, exhibit hopper growth and

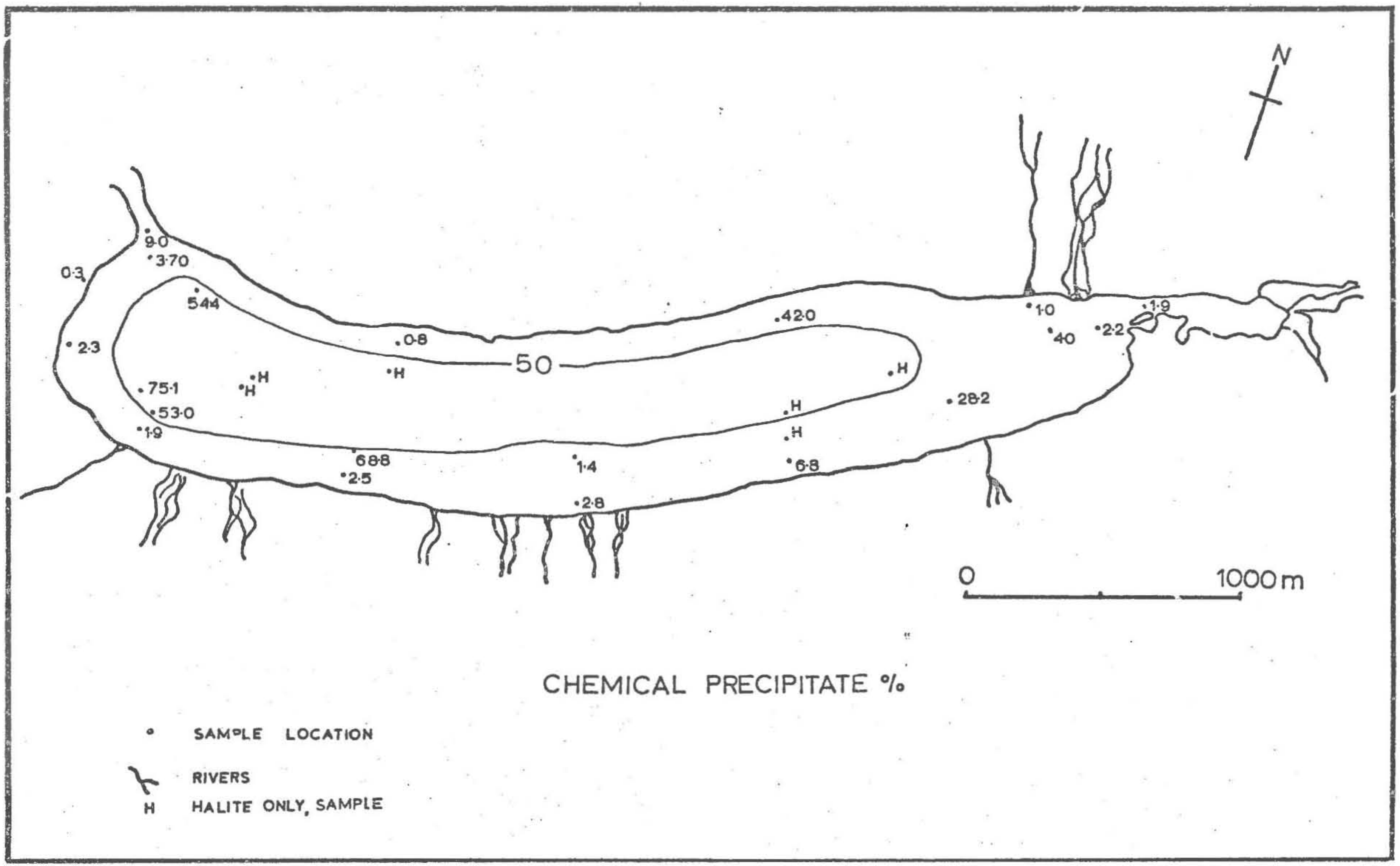


Fig. 4.19 Chemical precipitate content of the bottom sediments of Lake Bonney east lobe.

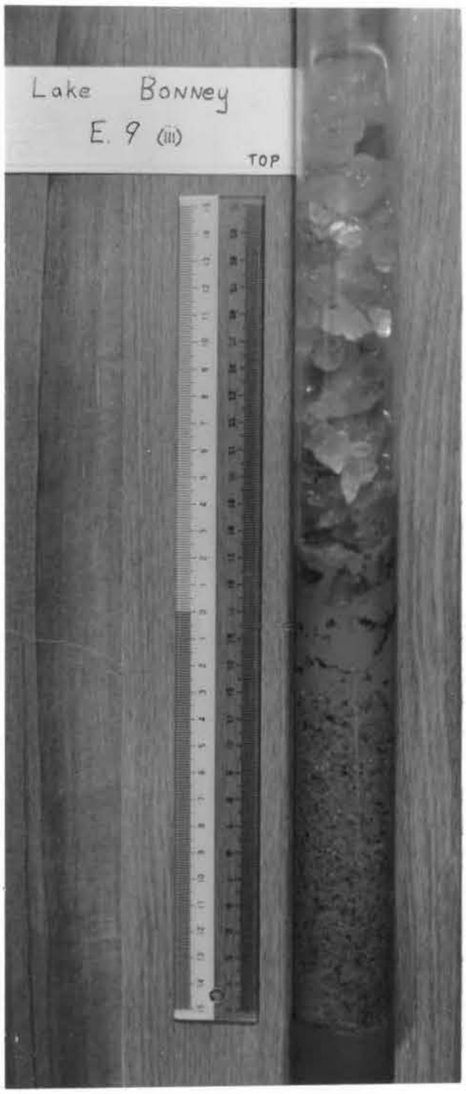
Table 4.11 Weight percent chemical precipitates in the sediments of Lake Bonney east lobe.

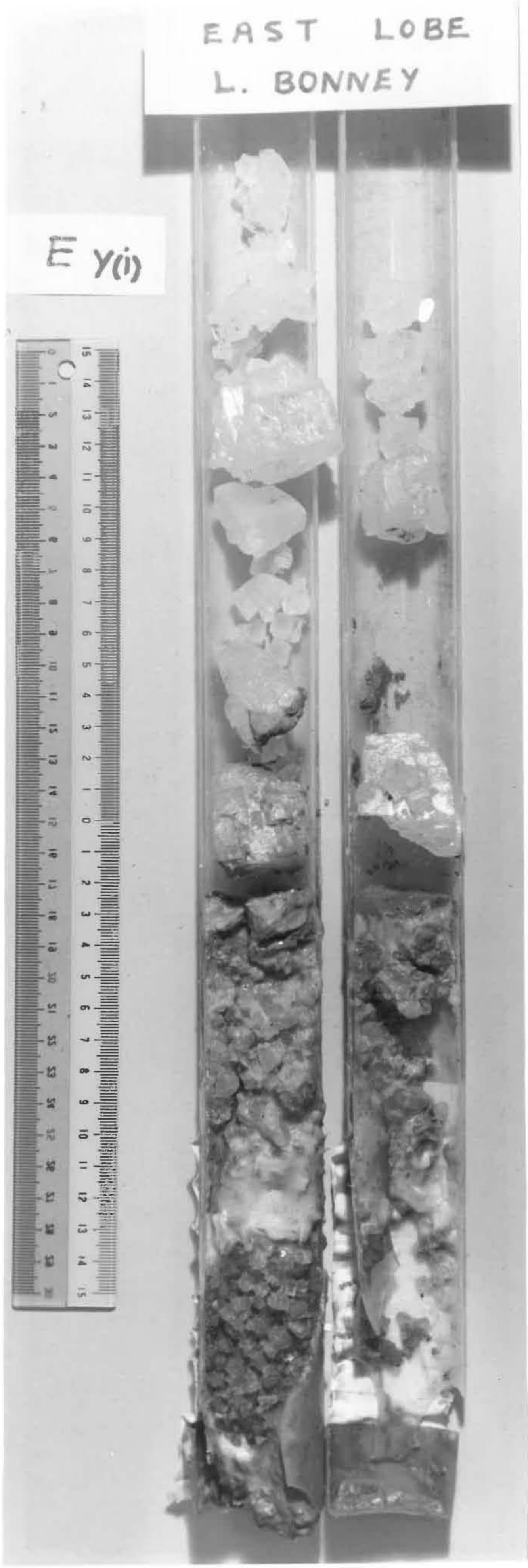
Sample number (depth cm)	% Chemical precipitates
1	9.1
2	3.7
3	2.3
4 (5)	54.0
4 (20)	10.0
6 (5)	75.1
6 (25)	2.0
7	17.4
8	1.9
11	0.8
13	68.8
14	2.5
15	1.4
16	2.8
17	42.0
20	6.8
22	28.2
23	1.0
25 (5)	4.0
25 (30)	2.3
26	2.2
27	1.9
Reigel sand	0.3

appear to be in equilibrium with the lake waters, as the thin algal mat overlying some of the samples is neither continuous nor impermeable.

Fig. 4.20 Core 10 (field notation E 9), unsplit, from 33m depth in the Lake Bonney east lobe. The core consists of halite crystals intermixed with organic floc and terrigenous silt with a gypsiferous band at 20cm depth. Scale in centimetres.

Fig. 4.21 Core 9 (field notation Ey) from the Lake Bonney east lobe. The sediments consist almost entirely of halite with minor amounts of terrigenous silt occurring in phases throughout the core length. Although not as distinct in core 9 as in the adjacent core 10, a gypsiferous band occurs 20cm below the large, loose, hopper halite crystals on the sediment surface. Scale in centimetres.


Lake Bonney
E. 9 (iii)
TOP


EAST LOBE
L. BONNEY
E Y(i)

Cores indicate that almost pure halite persists in depth with but minor amounts of terrigenous silt. In core 10, however, a silty gypsum band containing some calcite and aragonite is found from 19.5 to 21cm depth and yields a U/Th age of about 100 years B.P. (Appendix I). X R F analyses (Table 4.12) shows there is significant differences in the halite stratigraphy of core 10 with more Ca and S, and less Fe and Cl occurring towards the bottom of the core. The 1974/75 University of Waikato expedition obtained a 1.6m long halite core from the Lake Bonney east lobe, the bottom two-thirds of which consists mainly of dihydrohalite (A.T. Wilson, pers. comm.). Calculations indicate that at least 3 million tonnes of salt occur on the bottom of the Lake Bonney east lobe.

Table 4.12 X-ray fluorescent analyses of the Lake Bonney east lobe evaporites.

Sample number (depth cm)	10 (5) halite	10(20) gypsum	10(28) halite	13 gypsum
Elements		Intensity		
P	0.02	0.08	0.03	0.14
S	0.13	0.24	0.19	0.14
Cl	6.68	0.82	5.69	1.37
K	0.04	0.33	0.04	0.29
Ca	0.09	0.93	0.19	1.82
Mn	0.16	0.41	0.16	0.30
Fe	0.57	7.12	0.27	3.22
Br	0.32	0.89	0.37	0.69
Sr	0.33	0.50	0.32	1.04
Background level	23.59	29.30	22.71	27.06

Craig et al. (1974) suggested that hydrohalite ($NaCl \cdot 2H_2O$) may be the primary precipitate in the Lake Bonney east lobe. The total dissolved chloride in the lake waters (Table 1.2) suggests that salinity conditions close to the halite saturation curve may exist during the Antarctic winter (Table 1.3).

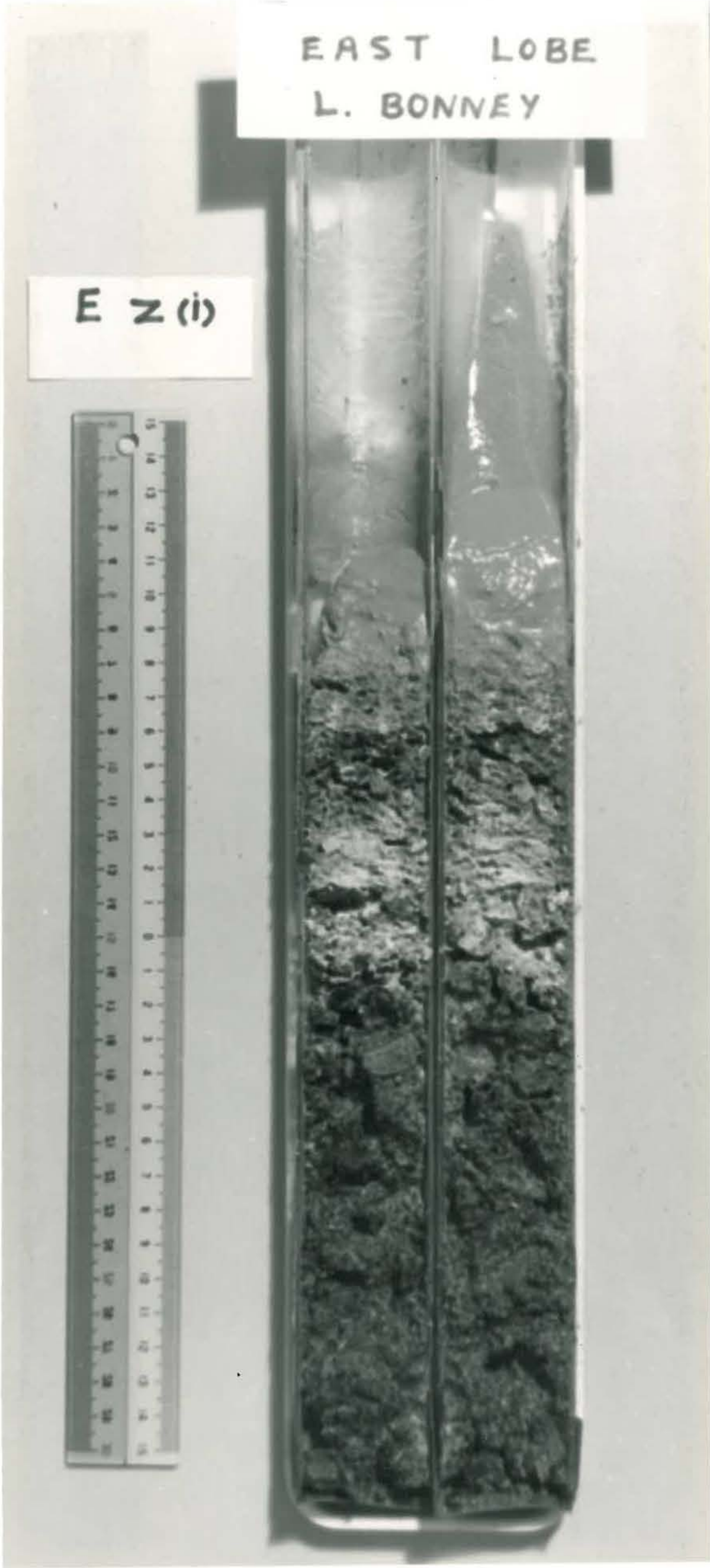
The second facies, found from 18 to 30m depth, consists of halite, gypsum, aragonite, calcite and possibly mirabilite. Halite is found as crystals less than 1cm in diameter while gypsum, aragonite and calcite occur either in a microcrystalline form or as multibanded plates. The plates, which are composed of up to four bands, are generally less than 1sq. cm in area and 2cm thick. They are creamy white, relatively indurated, and composed mainly of microcrystalline gypsum. The plates are either intermixed with terrigenous sand, particularly in shallow sites and in wind exposed locations (eg. site 22), or are overlain by terrigenous silt and fine-grained chemical precipitates in areas of low sediment input (eg. site 6 - Fig. 4.22). The calcium carbonate content in the east lobe chemical precipitates is generally low however percentages for the bottom sediments range from 0.5 to 18.9% (Table 4.13); the highest values occur in the facies 2 sediments (eg. site 6).

U/Th dates of the chemical precipitates in facies 2 are summarised as follows:

Site number (depth)		Years B.P.	
6	(5 to 7 cm)	240	(± 240)
	(11 to 12 cm)	1200	(± 150)
7	aragonite	900	
	gypsum	1050	

Chemical precipitates in the facies 1 sediments are mainly calcite although the total precipitate content is generally less than 2%.

Fig. 4.22 Core 6 from the Lake Bonney east lobe. The stratigraphy consists of a silty top 3cm underlain by gypsum, aragonite, halite, calcite, and terrigenous silt and sand to a depth of 11cm. The chemical precipitates are either fine-grained or multibanded plates. The basal 15cm section is pebbly sand. Scale in centimetres.


EAST LOBE
L. BONNEY
E Z (i)

The origin of the Lake Bonney east lobe salts is complex. Jones and Faure (1968) speculated that the salts were the product of chemical weathering of bedrock. An important contribution of salts comes from dissolved salts entering the lake via meltwater streams and groundwater flow. Chemical analyses of these waters, originally derived largely from atmospheric precipitation, indicate the presence of Cl^-, Na^+, Mg^{++} and Ca^{++} ions in decreasing order of abundance (Field, 1975). On the basis of ionic ratios (Angino et al., 1964; Boswell et al., 1967) and the recent age and extent of the salt deposits, it is also likely that seawater has contaminated the lake water. The Lake Bonney east lobe water is probably a combination of seawater and water derived from the catchment glaciers which has been concentrated to an extent that salts have precipitated under frigid evaporitic conditions. The high concentration of Mg^{++} in the lake water would also have aided the precipitation of halite since it markedly decreases the salt's solubility (Braitsch, 1971).

The cemented halite crystals in cores from the deepest part of the lobe attain a maximum size of generally less than 1cm, presumably because of variations in salinity and possibly increased water turbulence and sedimentation at the time of their formation. The large, loose, hopper halite crystals on the bottom surface indicate relatively constant salinity, mild water agitation and low sediment input. Underlying the halite one might expect gypsum and, at the base, calcite-aragonite to have precipitated under the evaporitic conditions.

The precipitation of the banded gypsum and subsequent induration and break-up into plates may be indicative of periods of salinity variation associated with lake-level changes, similar to the situation envisaged for the west lobe. A lower lake level might have allowed the gypsum to indurate with the subsequent break-up into plates being caused by frost-riving. The largely gypsiferous nature of the plates may be explained by the non-precipitation of calcite in the presence of aragonite once the calcite saturation point has been exceeded (Reeves, 1968).

4.4. 4 ORGANIC MATTER. The unique biological character of Lake Bonney is at present the subject of study by members of the Virginia Polytechnical Institute of the U.S.A. Evidence of high biological productivity in the lake is seen in the summer months with occasionally algae visible beneath the lake-ice, especially at shallow water-depths. Algal growths are particularly noticeable in the shallow gap between the two lobes.

The organic carbon content of the bottom sediments ranges from 0.08 to 1.31% (Table 4.13) with highest values found in fine-grained sediment particularly where the lake-ice has broken or melted (eg. site 1).

Table 4.13 Carbon content of the bottom sediments of Lake Bonney east lobe.

Sample number (depth cm)	% Total C	% Inorganic C ($\%CaCO_3$)	% Organic C
1	1.41	0.10 (0.8)	1.31
2	0.20	0.12 (0.9)	0.08
6 (5)	3.13	2.27 (18.9)	0.86
6 (20)	0.18	0.10 (0.8)	0.08
17	1.58	0.79 (6.5)	0.79
19	0.89	0.54 (4.5)	0.35
22	0.30	0.14 (1.1)	0.15
25	0.21	0.08 (0.6)	0.13
27	0.18	0.07 (0.5)	0.11

Part of the evidence for a marine origin of the lake is described by Angino et al. (1964) with their discovery of several complete specimens of Globigerina sp. Sediment analyses by this writer, however, have not revealed calcareous fossils in Lake Bonney.

4.4. 5 SUMMARY AND CONCLUSIONS. The extent of the summer thaw was more evident in the 1973/74 field season than that indicated in previous reports. The field season saw rapid development of meltwater streams and overland flow. Lake Bonney appears, however, to have been increasing in size since the turn of this century.

The east lobe sediments can be grouped into three broad facies, the lithologies of which are largely related to water depth. At depths below 30m the sediment is composed of halite crystals covered by a veneer of organic detritus and terrigenous silt; the second facies, between 18 and 30m depth, consists of gypsum, aragonite, halite, calcite and detrital sand and silt; the third facies, at depths generally shallower than 18m, is gravel, sand and silt. Proximity to the major meltwater stream outlets largely determines the extent of facies 3.

The detrital sediments range from sand to muddy sand to silt. Two modes of sediment transport operate in the east lobe, namely the wind and meltwater streams. However, no clear differentiation of bottom sediments according to mode of transport is apparent. Sorting of terrigenous sediment decreases with depth although the content of detrital sediment is minimal on the flat lake-floor where chemical precipitates are dominant. The sediments below about 30m depth are generally very poorly sorted very fine sands ($<$0.125mm). At depths shallower than 30m the sediments are poorly to moderately sorted and range up to coarse sand size. The bulk of the detrital sediment is probably wind-blown, with sediment derived from meltwater streams being important locally. Silt that is transported into the lake appears to remain largely in suspension until eventually being deposited in the non-turbulent lake bottom.

The detrital sediments consist mainly of quartz and feldspar. The source of the detrital minerals is mainly the granites of the Granite Harbour Intrusive Complex, the Ferrar Dolerites and the lamprophyre dykes found on the adjacent valley slopes. Detrital mineral form and surface texture show that wind- and river-transporting processes operate in the east lobe.

The facies 1 "halite" cores contain only minor amounts of terrigenous silt and sand, and a single band of gypsum, aragonite and calcite at 20cm depth. The halite crystals on the lake-floor exhibit hopper growth and reflect the relatively constant salinity and low sediment input at that depth. The flat-bottom lake topography suggests the halite is in equilibrium with the lake bottom water with possibly hydrohalite forming in the colder winter months. Dating of the "gypsum" band yields a U/Th age of about 100 years.

The facies 2 chemical precipitates occur either in a microcrystalline form or as multibanded plates. The plates consist mainly of gypsum and give a U/Th age of 240 to 1200 years B.P.

The Lake Bonney east lobe salt deposits are probably the product of the precipitation of salts from both seawater and water derived from the catchment glaciers. The saline brines were concentrated, and the salts precipitated, under frigid evaporitic conditions.

The organic content is highest in fine-grained sediment particularly where the lake-ice has melted or broken-up.

The sequence of events recorded in the Lake Bonney east lobe bottom sediments suggest: 1. that at least 2,000 years B.P., outwash terraces were being deposited in the east lobe during a period of lower lake-level;

2. that prior to 1,200 years B.P. a marine incursion of the Taylor Valley occurred resulting in at least contamination of the east lobe with seawater;

3. that since 1,200 years B.P. evaporitic conditions have concentrated the saline lake water and precipitated various salts;

4. that 900 to 1,200 years B.P. the salts precipitated on the 18m depth outwash terrace were broken-up, possibly by frost-riving, during a period of lower lake level than at the present time;

5. that dispite an increasing lake level, a highly saline lake bottom environment has been maintained to the present, resulting in the precipitation of halite;

6. that since the precipitation of salts 1,200 years B.P., the rate of sedimentation of detrital sediments appears to be increasing;

7. that since at least 450 years B.P. water from the west lobe has been contributing to the east lobe water budget.

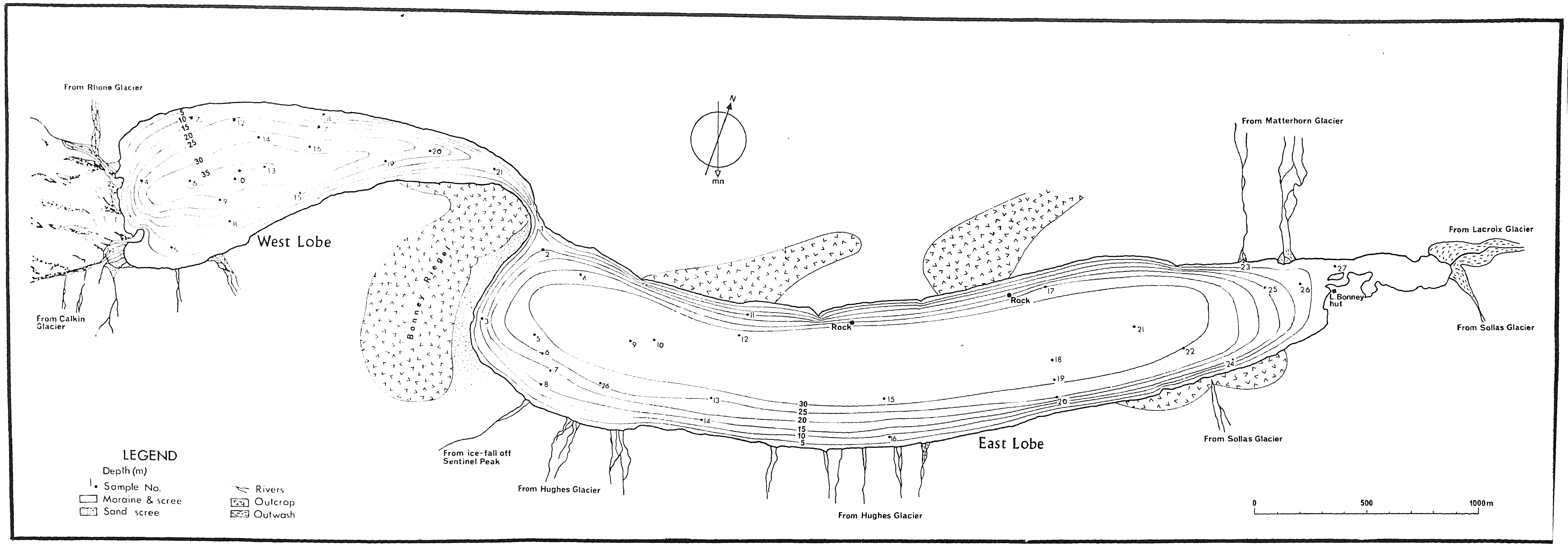
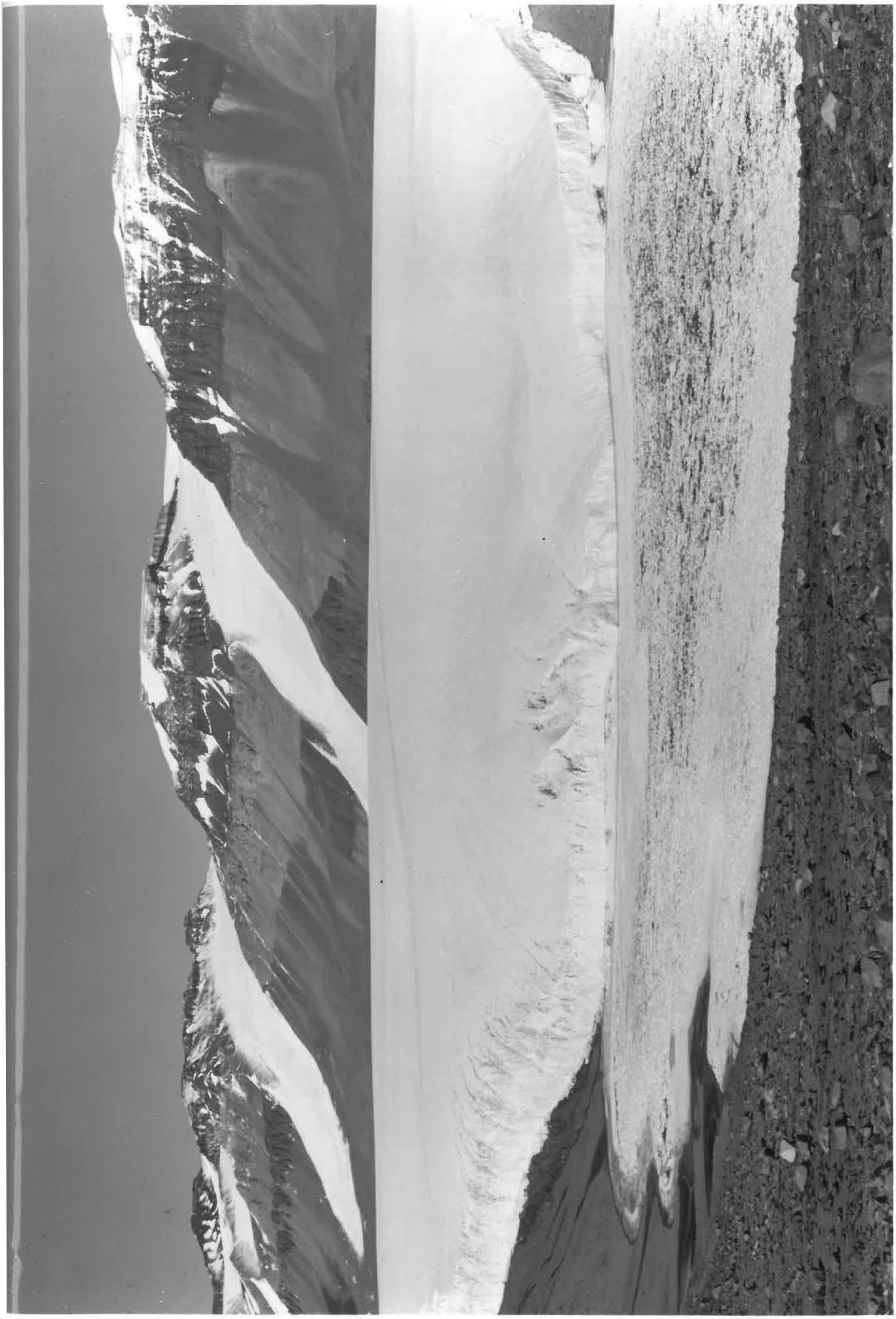


Fig. 4.23 Bathymetry and sample locations for Lake Bonney.

Fig. 5.1 Lake Joyce viewed from the north with the Taylor Glacier forming the south-east boundary of the lake. The Kukri Hills are in the far background.



CHAPTER V

LAKE JOYCE SEDIMENTS

Cores from the bottom of Lake Joyce indicate the sediments are sands and silts, with an aerobic/anaerobic boundary at approximately the 29m water depth (Fig. 5.5). The olive coloured aerobic sediments (Fig. 5.2) are composed of sand and occasionally contain organic floc. The black to greyish-black anaerobic sediments (Fig. 5.2) also consist of sand; however, they smell strongly of hydrogen sulphide and have varve-like sand-silt bands. There are as many as twelve sand-silt bands, each about 1 to 2mm thick, with up to 10 laminae within a single silt band.

5.1 TEXTURE.

The sediments are mainly silty sands (Fig. 5.3). The mean grain size ranges from coarse silt to medium sand (Table 5.1). Differentiation of aerobic and anaerobic facies on the basis of sediment texture is difficult. The main textural distinction between the two sediment facies is that aerobic sediments generally consist of fine sands that are poorer sorted than the medium sands characteristic of the anaerobic facies.

Two modes of sediment transport operate, namely, the wind and meltwater streams. It is suggested that the generally better sorted and coarser grained sediments in the deepest part of the lake are primarily wind-blown onto the lake-ice where they eventually sink through to the lake-floor (eg. sample 5). Sample 4, is probably sediment transported into the lake from the northern outwash fans (Fig. 5.5). Sites at similar depths

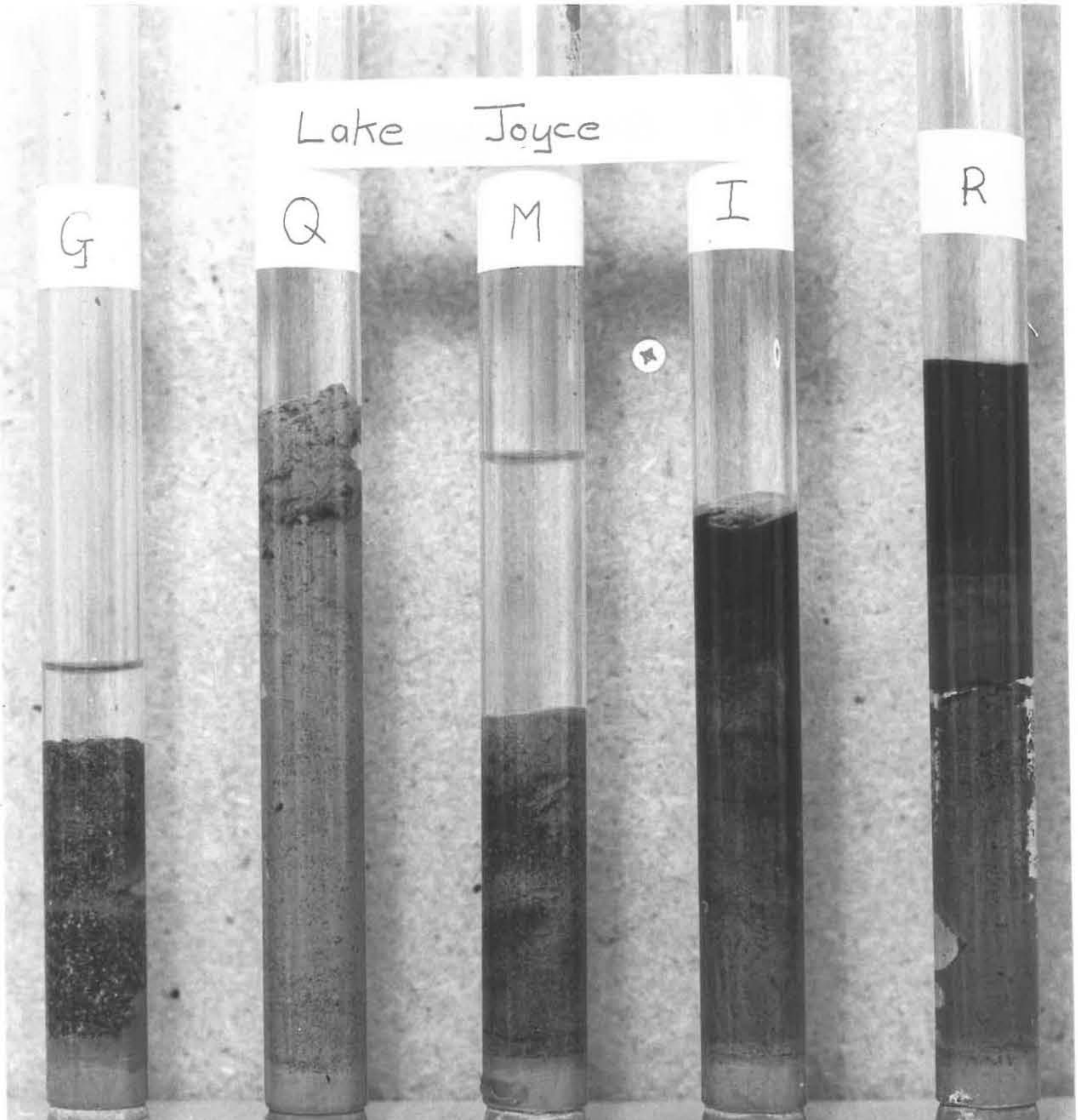


Fig. 5.2 Lake Joyce bottom sediment cores. Cores 1 (field notation G), 2(Q) and 6(M) are anaerobic sediments composed of sand and occasionally organic floc. Cores 5(R) and 7(I) are grey-black anaerobic sediments also composed of sand; however, they smell strongly of hydrogen sulphide and have varve-like sand-silt bands.

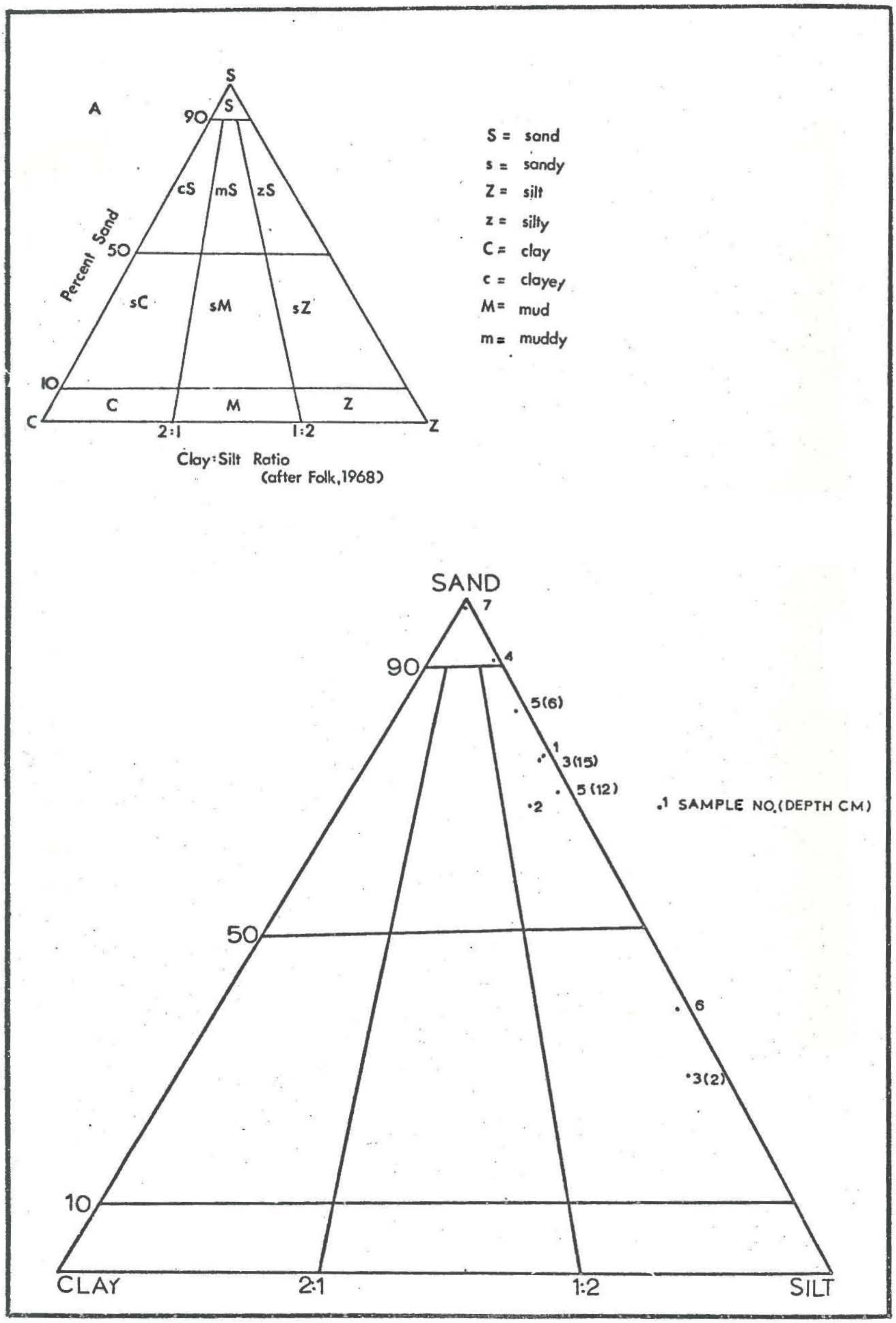


Fig. 5.3 Textural classes of the detrital sediments of Lake Joyce.

Table 5.1 Textural parameters of the detrital bottom sediments of Lake Joyce.

Sample number (depth cm)	Mean size (Mz Ø)	Sorting (σ_IØ)	Skewness (Sk_I)	Kurtosis (Kg)
1	2.3	2.1	+0.4	1.2
2	3.1	2.4	+0.5	1.0
3 (2)	4.2	1.9	-0.8	0.6
3 (15)	2.7	2.1	+0.3	1.4
4	2.3	1.1	+0.1	1.4
5 (6)	1.8	1.7	+0.4	1.4
5 (12)	2.7	2.3	+0.4	0.7
6	3.6	2.3	-0.7	0.6
7	1.1	0.9	-0.3	1.5

(eg. sample 1) are more poorly sorted and positively skewed and are likely to be wind-blown, either onto the lake ice where the sediment eventually sinks through to the lake-floor, or into the summer moat.

The sediments are generally strongly fine skewed, with the exception of the two southern-most sites (samples 6 and 7). Skewness values therefore probably indicate that wind-blown sediment is transported from northerly directions across the lake.

Sediment variation within individual cores suggests changes in lake-level and sediment supply have occurred in the lake's recent history. Textural analyses of the basal sediments of core 3 and 5 suggest possibly a lower lake-level at the time of their deposition. During this period, the basal silty sands may have been wind-blown similar to the situation found at site 1. The varve-like sand-silt bands found in the anaerobic cores at 4 to 5cm depth suggest periods of variable but low sediment input, at least below the present 29m water depth, at the time of deposition.

Comparison of textural parameters (Fig. 5.4) confirms the association of sediment texture to the modes of sediment transport described above (eg. the similarity of samples 3 (15cm) and 5 (12cm) to sample 1).

5.2 DETRITAL MINERALOGY.

In general at least 85% of the detrital minerals of Lake Joyce consist of feldspar and quartz (Table 5.2). Plagioclase is the dominant feldspar species. In decreasing amounts, the heavy minerals consist of brown hornblende, augite and hypersthene. Minor amounts of fine grained biotite, muscovite and magnetite and other opaque minerals are present, particularly in the silty sediments. The clay fraction is composed mainly of illite with minor amounts of montmorillonite and chlorite. There is little variation in the abundance of clay mineral species between samples.

Table 5.2 Quartz and feldspar ratios of the bottom sediments of Lake Joyce.

Sample number (depth cm)	Feldspar/Quartz	Plagioclase/ Potash feldspar
1	1.1	2.5
2	0.6	8.0
5 (6)	1.5	1.4
5 (12)	0.8	12.0

Sand-size grains are most commonly subangular suggesting local derivation from the weathering of the Irizar Granite,

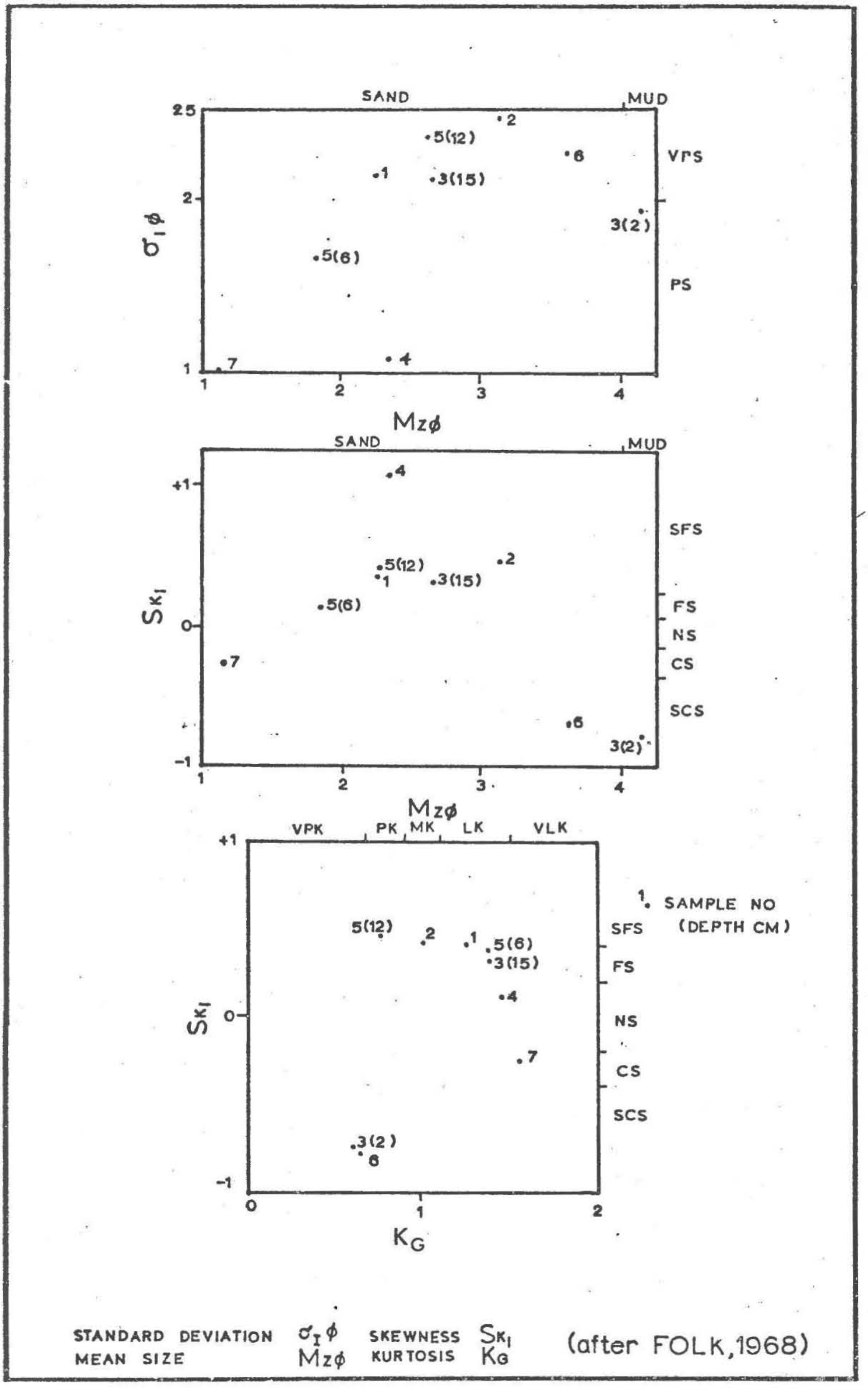


Fig. 5.4 Scatter plots of the detrital sediments from Lake Joyce.

Larsen Granodiorite and Ferrar Dolerite sills that form the adjacent valley slopes (Fig. 1.2).

5.3 CHEMICAL PRECIPITATES AND ORGANIC MATTER.

X R D analyses indicate that calcite is the only chemical precipitate in the Lake Joyce bottom sediments. Although present in amounts of generally less than 2%, highest calcite values are recorded in the anaerobic cores, particularly in the sand-silt "varves". Inorganic carbon analyses (Table 5.3) show the percentage of calcite ranges from 0.1 to 1.9%. The low calcite value for sample 5 (12) suggests the environment of deposition, indicated by textural analyses, was one of shallow water.

Table 5.3 Carbon content of the bottom sediments of Lake Joyce.

Sample number (depth cm)	% Total C	% Inorganic C ($\%$ $CaCO_3$)	% Organic C
1	0.17	0.06 (0.5)	0.11
2	0.80	0.23 (1.9)	0.56
5 (3)	0.54	0.15 (1.2)	0.39
5 (12)	0.33	0.02 (0.1)	0.31
6	0.22	0.06 (0.5)	0.16
7	0.46	0.10 (0.8)	0.36

The organic carbon content (Table 5.3) ranges from 0.11 to 0.56% with the highest values occurring generally in the deepest part of the lake. The comparatively high organic content of site 2 may reflect the non-turbulent bottom water at that location. The organic matter is probably similar in nature to that in the lakes described previously, consisting mainly of algae, diatoms and bacteria.

The calcium carbonate in the sand-silt "varves" may be the product of the concentration of brines and the precipitation of salts under frigid evaporitic conditions, possibly during a period of low lake level. However the presence of calcite in the surficial sediments may be the product of carbonate precipitation following the formation of carbon dioxide by the bacterial oxidation of organic matter, since the present salinity of the lake water (Fig. 1.4) is too low to account for carbonate formation.

5.4 SUMMARY AND CONCLUSIONS.

The bathymetric map of Lake Joyce (Fig. 5.5) does not suggest moraine walls exist within the lake and therefore the Taylor Glacier has probably not advanced beyond its present position since the basin was formed. There has, however, been a considerable influx of deltaic sediments from the north wall of the Taylor Valley, derived from the Catspaw and an adjacent unnamed glacier, and as overflow from Lake Hause, filling about half the original basin. This has caused the original round and flat-bottomed depression to become an elongated trough.

Cores from the bottom of Lake Joyce indicate the sediments are sands and silts, with an aerobic/anaerobic boundary at approximately the 29m water depth. The aerobic sediments are generally fine sands that are more poorly sorted than the fine to medium sands in the anaerobic zone. The anaerobic sediments also contain varve-like sand-silt bands and smell strongly of hydrogen sulphide.

Two modes of sediment transport operate, namely, the wind and meltwater streams. Sediments transported by meltwater streams occur in the northern part of the lake. The remaining sediments are mainly wind blown, with more silty sands being deposited in shallow depths presumably because the silt component, unlike the sand, is not wind-saltated across the lake-ice. The silt is deposited at shallow depths in an apparently non-turbulent lake environment created possibly by the thickness of the lake-ice and narrow summer moat. The wind transports sediment from the north Taylor Valley side and deposits it either into the summer moat or, more commonly, onto the lake-ice where it eventually sinks to the lake floor.

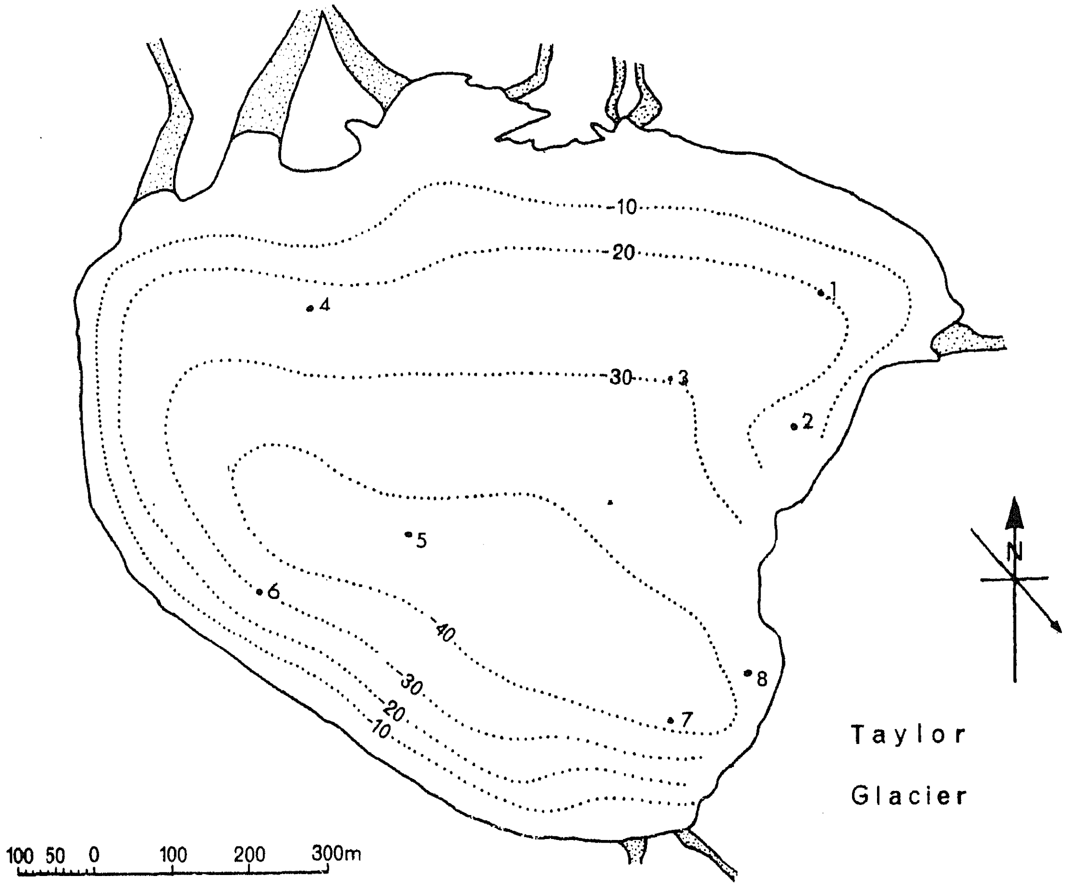
The detrital sediments are locally derived from the weathering of the Irizar Granite, Larsen Granodiorite and Ferrar Dolerite sills that form the adjacent valley slopes.

Calcite is the only chemical precipitate in the bottom sediments and occurs mainly in the anaerobic sediments, particularly in the sand-silt varves. Its presence in the surficial sediments may be the product of carbonate formation following the formation of carbon dioxide by the bacterial oxidation of organic matter. The organic content is highest in the anaerobic sediments and probably consists mainly of algae, bacteria and diatoms.

The existence of an aerobic/anaerobic boundary is probably related to a chloride diffusion cell, the bottom of which is close to the 29m water depth (Fig. 1.4). The diffusion cell represents a zone in the lake in which oxygen can only be supplied by diffusion whereas organic matter is being supplied by the rain of algal debris from above (Hendy et al., 1973). The chloride concentration gradients measured in 1963 by A.T. Wilson (pers. comm.) are believed to have been operating for 2,000 to 3,000 years.

It is suggested that the 2,000 to 3,000 year old "residual brine" comprising the Lake Joyce bottom water was formed at the same time as the calcareous sand-silt "varves" were deposited, that is, during a period of low lake level. The calcite in the "varves" is probably evaporitic in origin. Textural analyses of sediments below the "varves" suggest a water depth intermediate between the present lake-level and the low lake-level envisaged during "varve" deposition. The possibility cannot be discounted that evaporitic phases occur in the sediment at greater depths.

Fig. 5.5 Bathymetry and sample locations for Lake Joyce.



All contours (approximate only) shown in metres

Sample No •1

CHAPTER VI

6.1 EVAPORITIC PHASES AND CLIMATIC REGIMEN.

The basic assumption in this study is that periods of extreme aridity in the Dry Valleys have occurred during the Holocene, and that such periods are considered indicative of colder climatic phases. The cold dry phases are believed to be associated with periods of lower lake levels which permitted the concentration of brines and formation of chemical precipitates under frigid evaporitic conditions. The sediment contribution from meltwater streams would, under a cold climatic phase, be low because of the locking-up of the water supply to meltwater streams by valley glaciers. The main source of detrital sediment during such a phase would probably be wind-derived material.

The incursion of seawater further contributes to the salinity of some of the lakes. However, lake level and salinity appear dependent on the balance of discharge of meltwater and the rate of sublimation of ice. The dense brines on the bottom of the lakes, and particularly the evaporitic bands in the lake sediments, could represent residual liquids from earlier periods when loss of water may have exceeded discharge of meltwater.

6.2 THE NATURE OF THE DRY VALLEYS AND DRY VALLEY LAKES.

The Dry Valleys consititute the largest ice-free area in Antarctica. To account for this Wilson (1967) explains that it is necessary to consider the precipitation/evaporation balance in the region. In the Dry Valleys the nett precipitation is negative (ie. sublimation exceeds precipitation) while above the snowline it is positive. For a given region the nett precipitation increases as altitude increases. Thus the dry areas are those areas which lie below the snowline and into which ice from above the snowline cannot flow. However the nett excess precipitation in a snowfield will flow below the snowline as a glacier (Wilson, 1967). Usually the glacier pushes sufficiently far below the snowline for some summer melting to take place. In such cases, for a few weeks of the year during the hottest part of the summer, a stream flows away from the glacier snout and feeds a lake which occupies the lowest point of that particular drainage basin.

The size of the lake is determined by that area needed to balance the evaporation/precipitation equation for that particular area. If there is a nett precipitation increase to the area the lake level will rise and if there is a decrease in precipitation the lake level will fall. Thus the Dry Valley lakes are very sensitive indicators of changes in nett precipitation and hence of glacial advances and retreats.

The above treatment was considered by Wilson (1967) as an oversimplification of the situation because it deals with climatic change only in terms of nett precipitation. However Wilson (1967) considered the effect of temperature to be limited. A further effect is that the retreating glacier is replaced by a stream which can contribute almost as much evaporation as the glacier it replaces. For example, the 29km length of the Onyx River provides as much evaporation as the whole surface of Lake Vanda (Wilson, 1967).

Calkin and Bull (1974) noted that the history revealed in the Dry Valleys gives no assurance that changes in the past climate are applicable to other parts of the continent and, around most of the ice sheet, the local picture cannot be determined from studies on land because the ice extends to the continental edge. The Dry Valley climatic regimen may be related, therefore, to the position of the Ross Ice Shelf.

Wilson (1967) suggested the hypothesis that during periods of high lake level the Ross Ice Shelf was much further south than its present position. This would mean that there would have been more open sea closer to the snowfields supplying the Dry Valley lakes. The local alpine glaciers, as distinct from those fed from the Polar Plateau, are fed by local snowfall and are therefore controlled by mean distance from the sea (ie. the position of the Ross Ice Shelf).

However, the sequence of climatic events revealed in the bottom sediments of the lakes studied probably reflect the nonsynchronous nature of past fluctuations in the three major glacier systems.

6.3 THE SEQUENCE OF CLIMATIC EVENTS REVEALED IN THE LAKE BOTTOM SEDIMENTS.

The sequence of events in the Taylor and Wright Valleys as revealed by analyses of the bottom sediments of Lake's Vanda, Bonney and Joyce in the present study are as follows:

(1) that the Taylor II Glaciation occurred at least 300,000 years B.P.;

(2) that flooding of the Taylor Valley with seawater occurred about 300,000 years B.P. to an extent that the then shallow Lake Bonney west lobe was at least contaminated by marine water which became sufficiently saline to precipitate salts;

(3) that the Taylor Glacier entered the Bonney basin at least 10,000 years B.P., its advance coinciding with the Taylor I Glaciation;

(4) that Lake Vanda experienced at least four periods of low lake level prior to the 5,500 year B.P. drop in lake level;

(5) that the Lake Joyce water level was lower about 3,000 years B.P.;

(6) that Lake Vanda was only a few metres deep about 2,000 years B.P.;

(7) that prior to 1,200 years B.P. a marine incursion occurred in the Taylor Valley with contamination of the Bonney Basin by seawater;

(8) that at least 900 to 1,200 years B.P. the precipitation of essentially marine salts was initiated in the then shallow Lake Bonney east lobe and has continued to the present, with halite crystals forming on the lake floor;

(9) that since at least 450 years B.P. water from the Lake Bonney west lobe has been contributing to the east lobe water budget;

(10) that the Lake Bonney water level has been steadily rising since the turn of this century.

6.4 SUMMARY OF THE LAKES VANDA, BONNEY AND JOYCE BOTTOM SEDIMENTS.

The sediments of Lake Vanda and Lake Joyce may be broadly categorised into two sediment facies, namely aerobic and anaerobic. In Lake Vanda the boundary of the two facies occurs at the 60m water depth while in Lake Joyce the boundary is at 29m depth. Sediments in the aerobic zone typically consist of light-coloured massive sands that occasionally contain organic floc. The anaerobic sediments are generally blackish sands that smell of hydrogen sulphide, and contain 2 to 3cm thick varve-like calcareous sand-silt bands or, in the case of Lake Vanda, chemical precipitate - terrigenous silt bands. The varve-like bands can often be further subdivided into a number of fine laminae. Deep cores obtained from Lake Vanda show a series of grain size cycles in which medium to fine sands alternate with chemical precipitate - silt bands.

The Lake Bonney west lobe bottom detrital sediments are categorised according to sediment source. The sediment is either derived from the Taylor Glacier or wind-transported into the lake. On the basis of texture three broad sediment facies are distinguished. The first facies, located adjacent to the Taylor Glacier, consists of sediment derived from the glacier and its associated meltwater streams; the second facies, located generally at shallow depth, is mainly wind-derived sediment; the third facies is located mainly in the deep part of the lobe and consists of both Taylor Glacier and wind-transported sediment.

The Lake Bonney east lobe sediments are grouped into three facies, the lithologies of which are mainly related to water depth. At depths below 30m the sediments is composed of halite cystals covered by a veneer of organic detritus and terrigenous silt; the second facies, between 18 and 30m depth consist of gypsum, aragonite, halite, calcite and detrital sand and silt; the third facies, at depths generally shallower than 18m, is gravel, sand and silt.

The detrital mineralogy of the lake bottom sediments is compatible with generally local derivation. Grains are commonly subangular to subrounded and the pitted and frosted surfaces, particularly of quartz grains, is indicative of wind transport. The sediments are composed mainly of quartz and feldspar.

Feldspars consist mainly of plagioclase with lesser amounts of potash feldspar. The remaining light minerals (S.G. < 2.7) consist of biotite and muscovite, and rare volcanic glass occurs in the Lake Vanda deep core. Heavy minerals (S.G. > 2.7) consist mainly of hornblende and lesser amounts of augite, hypersthene and opaque minerals (mainly magnetite). Clay minerals consist mainly of illite with minor amounts of mixed-layer illite-chlorite, chlorite and montmorillonite.

The detrital mineralogy is derived mainly from the granites of the Granite Harbour Intrusive Complex, namely the Irizar Granite (Vida Granite), Larsen Granodiorite and the Olympus Granite Gneiss. However contributions, particularly of heavy minerals, come from the Ferrar Dolerites and lamprophyre and porphyry dykes. Some of the rounded quartz grains may be derived from the sandstones of the Beacon Supergroup.

Textural analyses of the lake bottom sediments have enabled sediments to be differentiated partly according to mode of transport. Sediments are generally wind transported onto the lake-ice, where they eventually sink to the lake-floor, or are blown into the lake's summer moat. In the three lakes studied river-transported sediment is generally of local importance only. However the Lake Bonney west lobe receives much of its sediment from the Taylor Glacier either via the associated meltwater streams or from the release of sediment following basal sublimation of the glacier. The lake bottom sediments are generally poorly sorted sands and silty sands with sediments becoming finer-grained and more poorly sorted with increasing depth. The silty component in the sediments is commonly kept in suspension until deposition occurs in the less-turbulent waters on the lake-floor. Lake Joyce sediments, however, show an improvement in sorting and an increase in grain-size with depth. The silt component of the sediments appears to be deposited at shallow depths because of the seemingly non-turbulent character of the lake water there.

The chemical precipitates present in the lakes vary considerably in origin, mineralogy and abundance. In Lake Vanda chemical precipitates occur mainly in bands that were probably formed under evaporitic conditions. Gypsum is the main chemical precipitate with minor amounts of calcite. In Lake Joyce calcite occurs mainly in the calcareous sand-silt bands which are also considered evaporitic. The calcite present in the surficial anaerobic sediments may, however, be the product of the precipitation of carbonates following the formation of carbon dioxide by the bacterial oxidation of organic matter. Most of the salts in the above-mentioned lakes appear to have been transported in solution by meltwater streams draining the local glaciers.

The Lake Bonney sediments contain chemical precipitates of both marine and meltwater origin. In the west lobe the chemical precipitates are mainly gypsum with minor amounts of calcite. The gypsum chips present in the bottom sediments are probably derived from seawater, being precipited under frigid evaporitic conditions. The east lobe chemical precipitates are probably mainly of seawater origin and consist almost exclusively of halite covering the extensive flat-bottomed east lobe floor. The bottom surface hopper halite crystals appear to be in equilibrium with bottom waters. At shallower depths chemical precipitates occur in either a micro-crystalline form or as multibanded plates. Gypsum is the main precipitate with lesser amounts of aragonite, halite and calcite. The platey chemical precipitates found in Lake Vanda and in Lake Bonney's east and west lobe are thought to be the product of reworking of frost-riven salts.

The organic matter in the sediments consists mainly of algae, bacteria and diatoms. In general the organic content increases with water depth and is most often associated with fine-grained sediment.

Sample number (depth cm)	U ppm	U^{234} / U^{238} (deviation)	Th^{232} / U^{234}	Th^{230} / U^{234} maximum (deviation)	Age Years	Th^{230} / U^{234} (deviation)	Age Years
Taylor Glacier gypsum	0.130	2.6 (0.40)	0.35	0.60 (0.10)	85,000	0.22	28,000
west lobe							
16	1.900	1.2	0.15	0.97 (0.07)	300,000		
10 (30-40)	0.097	2.2 (0.30)	1.30	1.60 (0.20)	infinite	0.37 (0.3)	
11 (30-40)	0.350	2.0 (0.16)	0.72	1.20 (0.11)	infinite	0.17	20,000
east lobe							
6 (5-7)	17.0	3.61	0.015	0.017	1,900	0.002	240 (± 240)
6 (11-12)	28.0	3.29	0.006	0.016	1,800	0.010	1,200 (± 150)
7 aragonite	28.0	3.29	0.011	0.018	2,100	0.0073	900
gypsum	2.3	3.30	0.029	0.037	4,500	0.0083	1,050
10 (20)	3.1	3.82	0.08	0.083	10,000	0.001	≈ 100

Appendix I Uranium / Thorium Dating Data from the Taylor Glacier and Lake Bonney (after C.H. Hendy, pers.comm.).

APPENDIX II

RELATIONSHIP OF THESIS SAMPLE NUMBERS TO UNIVERSITY OF WAIKATO CATOLOGUE NUMBERS

Thesis No.	U. of W. No.	Thesis No.	U. of W. No.	Thesis No.	U. of W. No.
Lake Vanda (depth)		Lake Bonney east lobe		Taylor Glacier (T.G.)	
5	T10025	1	T10052	T.G. 1	T10082
10	T10026	2	T10053	T.G. 2	T10083
7	T10027	3	T10054	T.G. 3	T10084
7	T10028	4	T10055	T.G. Salts	
1	T10029	5	T10056	West lobe	T10085
2	T10030	6	T10057	4	T10086
4	T10031	7	T10058	5	T10087
12	T10032	8	T10059	6	T10088
13	T10033	9	T10060	7	T10089
9	T10034	10	T10061	8	T10090
3	T10035	11	T10062	9	T10091
11	T10036	12	T10063	10	T10092
8	T10037	13	T10064	11	T10093
6(0to75cm)	T10038	14	T10065	12	T10094
6(0to92cm)	T10039	15	T10066	13	T10095
6(93to200cm)	T10040	16	T10067	14	T10096
14	T10041	17	T10068	15	T10097
15	T10042	18	T10069	16	T10098
16	T10043	19	T10070	17	T10099
Wind-blown sand at site 6.	T10081	20	T10071	18	T10100
		21	T10072	19	T10101
Water column samples.	T10104	22	T10073	20	T10102
		23	T10074	21	T10103
Lake Joyce		24	T10075		
1	T10044	25	T10076		
2	T10045	26	T10077		
3	T10046	27	T10078		
4	T10047	Reigel sand.	T10079		
5	T10048				
6	T10049	Wind blown sand at site 26.	T10080		
7	T10050				
8	T10051				

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