The Sedimentology and Paleohydrology of Waldsea Lake, Saskatchewan, an Ectogenic Meromictic Saline Lake

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Master of Science
in
Geology

by

Timothy H. Schweyen

Winnipeg, Manitoba, 1984

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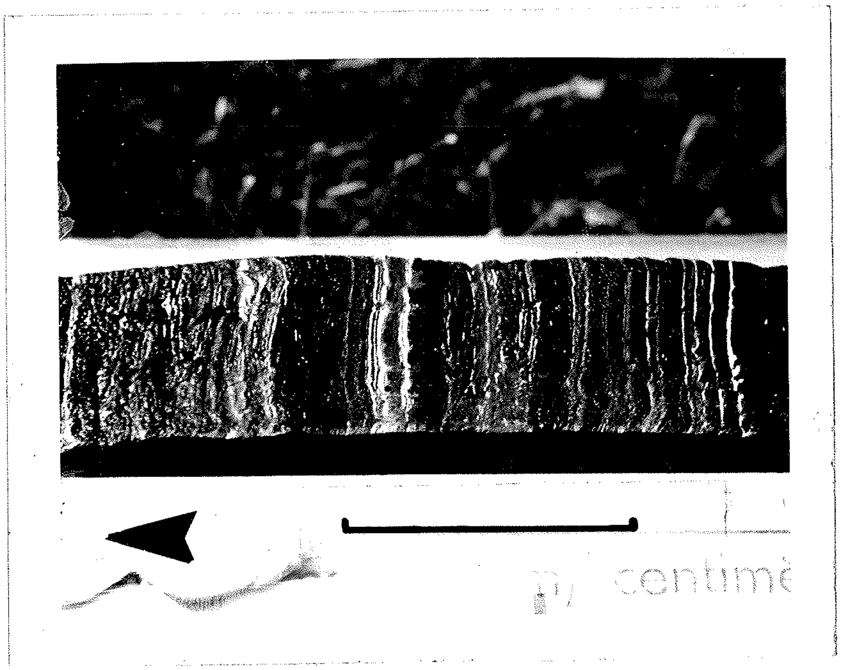
ABSTRACT

Waldsea Lake is a small (5 km^2), shallow (14.5 m maximum depth) saline lake near Humboldt, Saskatchewan. It has been meromictic at least since 1971. Despite its salinity (25 g l^{-1} mixolimnion, 68 g l^{-1} monimolimnion) it is the locus of a regional park. Sediment cores and dredge samples were obtained in order to study its geochemical/sedimentological regime and developmental history.

The post-Hypsithermal basinal sediment record consists of five major stratigraphic units. Each represents major changes in lake level, water chemistry, and trophic state. Unit 1 is a black silty mud with plant fibre mats and crystals of mirabilite. Unit 2 is a grey to green gypsum-rich silt containing calcite-coated twigs and algal fibres. Unit 3 is a black sapropel with abundant aragonite laminae. Overlying this are: Unit 4 (similar to Unit 2) and Unit 5 (similar to Unit 3). Units 3 and 5 represent relatively deep water phases of the lake. In contrast, Units 2 and 4 were deposited during shallow phases. Gypsum and dolomite laminae were likely produced under schizohaline conditions by the periodic influx of relatively dilute Ca-rich waters. Unit 1 represents deposition in a hypersaline lake with very low water levels and saline mudflats.

The meromixis of Waldsea Lake is primarily ectogenic in nature. Drainage diversions and alteration of the peripheral vegetation funnel runoff into the lake. Increased surface runoff and groundwater input has doubled the lake's volume in the last two decades. An initial high salinity and rapid increase in volume with only a small increase in surface area created a relatively stable meromixis. Since 1971 the level of the chemocline has dropped 4 m, suggesting that meromixis is not permanent, and that Waldsea Lake will eventually revert to its previous dimictic state.

> "If we knew all the laws of Nature, we should need only one fact, or the description of one actual phenomenon, to infer all the particular results at that point. Now we know only a few laws, and our result is vitiated, not, of course, by any confusion or irregularity in Nature, but by our ignorance of essential elements in calculation. Our notions of law and harmony are commonly confined to those instances which we detect; but the harmony which results from a far greater number of seemingly conflicting, but really concurring, laws, which we have not detected, is still more wonderful."
>
> Walden
> Henry David Thoreau



Photograph of Waldsea Lake sediment (Unit 1), approximately 30-45 cm from sediment-water interface. Top is to the left. Scale bar is 10 cm.

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NAME	FINANCIAL SUPPORT	ANALYSES	FIELD HELP	DRAFTING AND PHOTOGRAPHY	READING MANUSCRIPT	THOUGHT-PROVOKING DISCUSSIONS
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Chapter I

NATURE AND SCOPE OF STUDY

1.1 INTRODUCTION

In an attempt to understand the physical and chemical conditions prevailing in Waldsea Lake, several important factors must be delineated. These include:

1. basin and landscape genesis and evolution,
2. climate and hydrology of the region, and
3. anthropogenic influence on the physical and chemical regimes of the lake.

The objectives of this thesis are threefold:

1. to describe the aforementioned factors and their interrelationships,
2. to discuss the relationship of the lake's physical and chemical regime to the material which is sedimented or produced by the system, and
3. to delineate a physical and chemical model of the lake over the time interval represented in the sediment sampled.

1.2 PREVIOUS STUDIES OF WALDSEA LAKE

Nearly all of the previous studies of Waldsea Lake and its basin have been strictly biologically oriented. These studies have provided a good chemical and morphological data base which can be used in more detailed sedimentological investigations. An annotated bibliography is presented in Appendix A.

1.3 GENERAL SETTING

Waldsea Lake is one of thousands of small (<10 km^2) lakes on the northern Great Plains. Salinities [1] in these lakes range from fresh (<10 parts per million) to hypersaline (400 parts per thousand, Hammer, 1983). Waldsea Lake is located approximately 110 km east of Saskatoon and 5 km northeast of Humboldt, Saskatchewan (Figure 1).

Precipitation in the region varies greatly both spatially and from year to year, but is reported to average 15 cm per year (Transport Canada, 1963:1983). Evaporation is estimated for the region to be from 2 to 3 times precipitation (CNC/IHD, 1978). With evaporative loss and consequent water deficit, any closed body of water with groundwater input and overland flow increases in salinity with time.

Eugster and Hardie (1978) suggested three conditions which must occur for saline lakes to be formed. These are:

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[1] Salinity is meant to indicate total dissolved solids (tds), rather than its oceanographic definition.

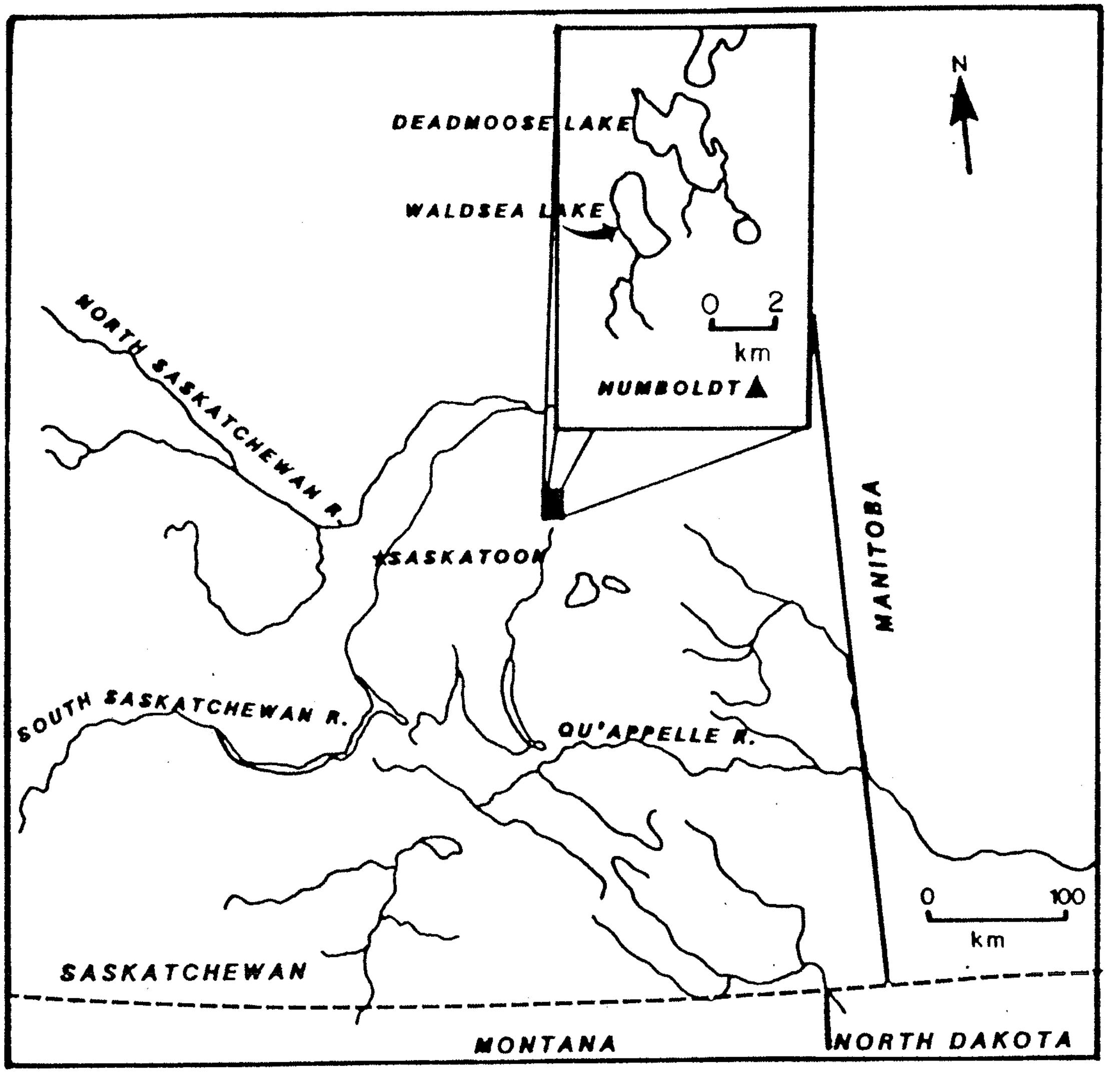

Figure 1: Location Map

- outflow must be restricted,
- evaporation must exceed inflow, and
- inflow must be sufficient to sustain a standing body of water.

The wide variation of salinities in the Saskatchewan lakes can be ascribed primarily to the degree to which each lake is restricted. Lakes which either have an outlet via surface flow or are influent will not be able to build great salinities.

Because Waldsea Lake has no outlets and maintains a permanent body of water, it can be identified as a terminal lake. Waldsea Lake is recharged by three main mechanisms. These are: direct precipitation on the lake's surface, "runoff", and groundwater input by diffuse efflux. Runoff includes both surface runoff and snow blown into the lake or onto its surface during the winter. These three mechanisms maintain Waldsea Lake's water level, and, over the past twenty years, have provided for an increase in lake level of over 4 m (Figure 2). Most of this increase can be attributed to:

- increases in infiltration due to farming practices resulting in an increase in water table elevation,
- clearing of peripheral vegetation (predominantly cottonwood and shrubs), resulting in increased runoff,
- cabin-building and development of picnic areas, resulting in a decrease in trees and evapotranspiration, and

- excavation of drainage ditches to make large ephemeral sloughs (both inside and outside of the natural drainage basin) arable for farming earlier in the spring.

The drainage diversions have resulted in a 40% increase in Waldsea Lake's drainage basin area (Figure 3).

The increase in lake level which has resulted from the combined effects of these disruptions has, in turn, greatly affected the ecosystem within and around the lake (Swanson, 1978). Tones (1976) reported on the effects of the inundation of the trees and shrubs along the shoreline. Salt-water encroachment is evident on the trees within approximately 10 m of the water's edge. Hammer et al. (1978) postulated that the increase in lake level probably was the original cause of the inception of recent meromixis within the lake.

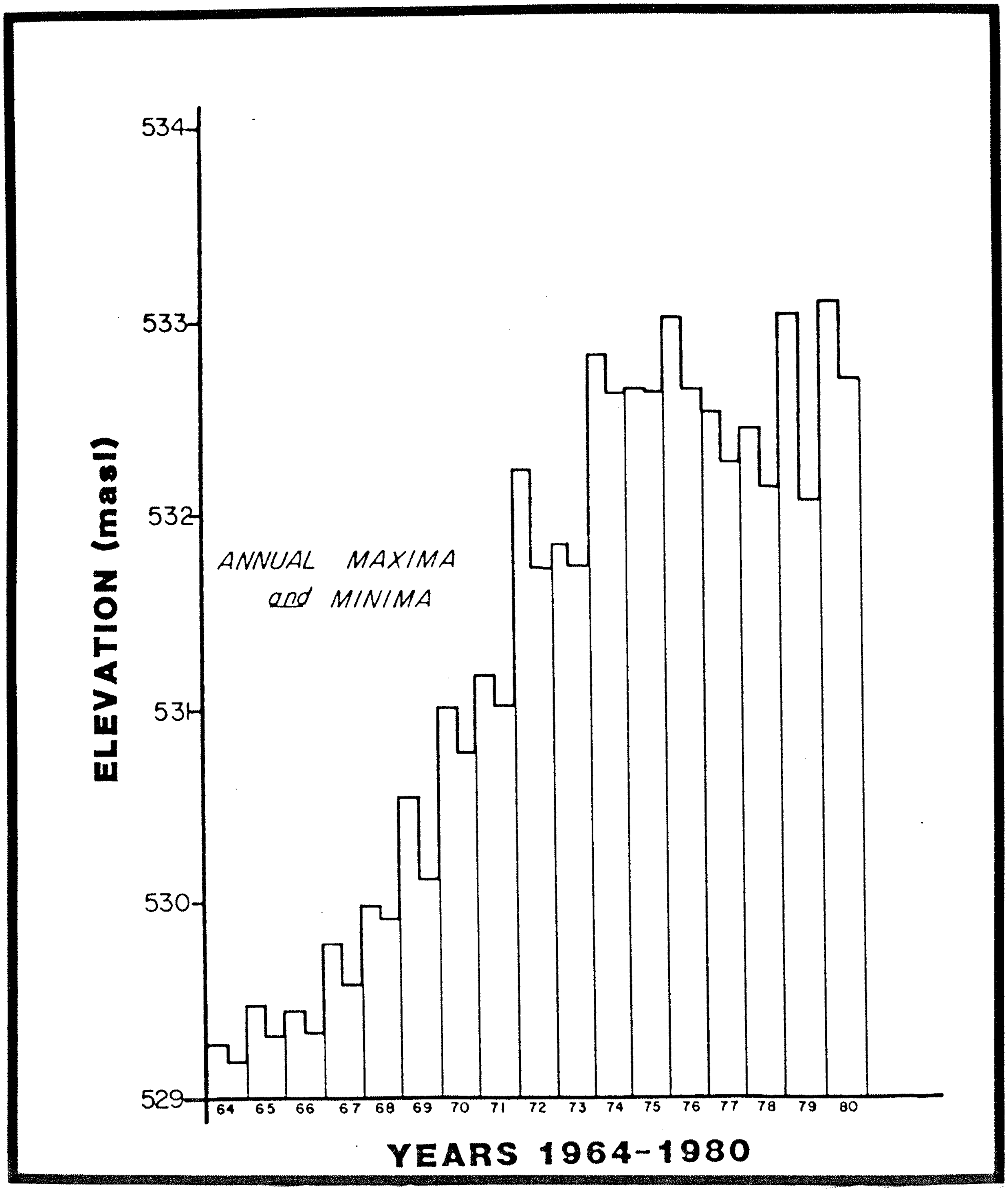

Figure 2: Recent lake level changes

(Data taken from Surface Water Data, 1960-1980)

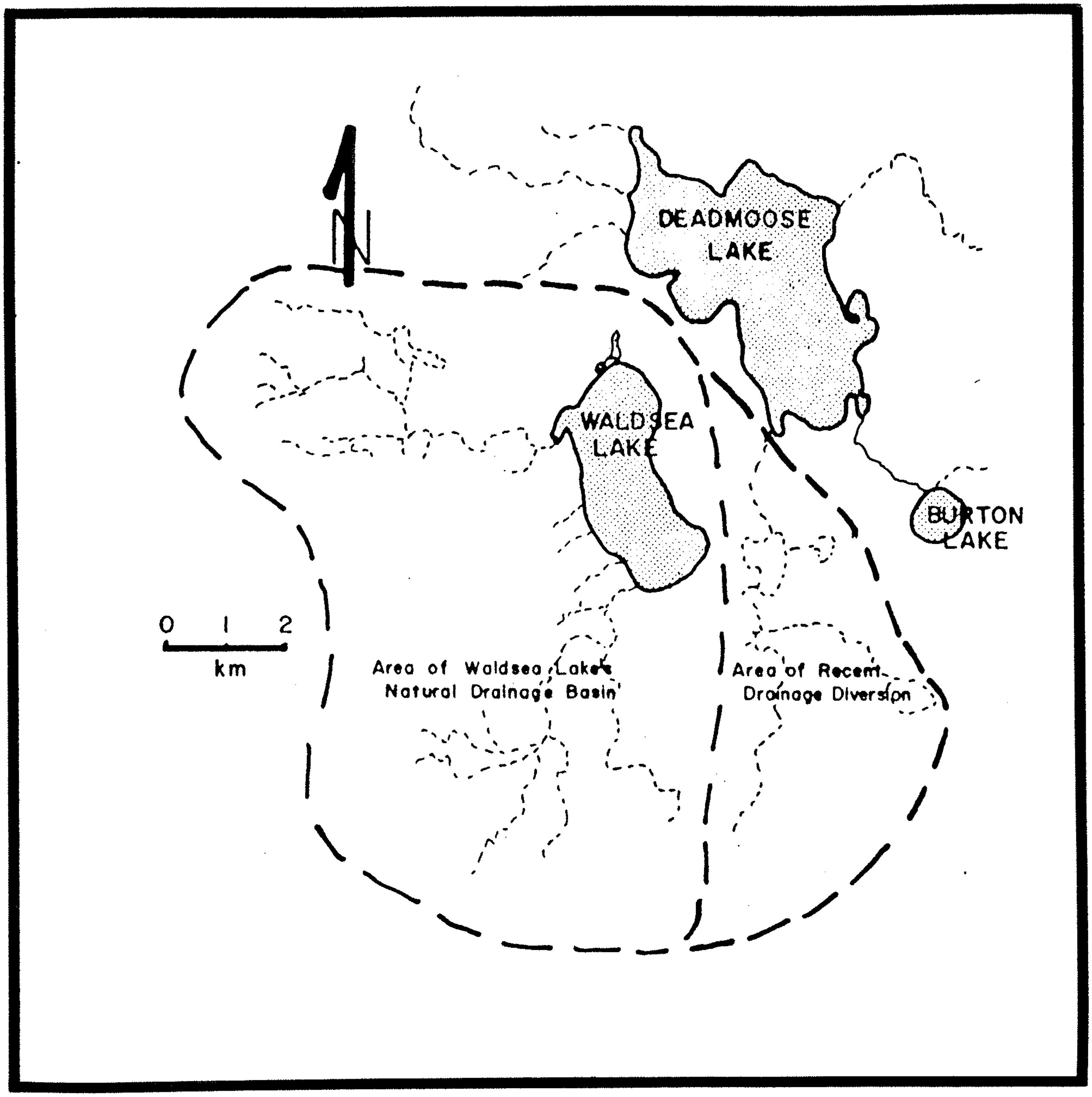

Figure 3: Drainage basin area of Waldsea Lake

Chapter II

METHODOLOGY

2.1 FIELD METHODS

2.1.1 Water Samples

Water samples were obtained using a 1.4-l acrylic modified Kemmerer water sampler and were stored in tightly sealed Nalgene bottles for later analysis of major ions. Major cations were measured by Paul Beaudoin (University of Manitoba) using standard atomic absorption methods. Chloride determinations were done by titration with silver nitrate using potassium chromate as the indicator according to the methods of the American Public Health Association (1971).

2.1.2 Carbonate Saturometry

Samples taken for carbonate saturometry were kept as close to in-situ temperature as possible; saturometry was run within four hours of sample collection. During saturometry, the samples were stirred with a magnetic stirrer and maintained at field temperatures in an ice bath. A Corning Portable pH meter with combination glass pH/reference electrode was used in a configuration similar to Brunskill (1969); the vessel was open to the atmosphere. Reagent grade calcite, natural aragonite (Sinai), and natural stoichiometric dolomite (Bavaria) were used as the solid phases in various trials.

2.1.3 Coring

Cores of the basinal[2] sediment in Waldsea Lake were obtained with a modified Livingstone corer according to the methods described in Last (1980). Summer coring was done from a boat; winter cores were acquired using the ice as a stable platform. Core locations are shown in Figure 4. After extrusion in the field, the cores were briefly described and tightly wrapped in polyethylene and stored in plastic trays made by cutting 4 inch diameter ABS pipe longitudinally and approximately into 1 m sections. Winter cores were allowed to freeze for ease in field storage and manipulation. These cores were described according to Munsell colour, sediment type, texture, identifiable mineralogy, and obvious organic types. Summer cores presented storage problems and consequently were not described in great detail because of changes in colour due to oxidation.

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[2] In the context of this thesis, the term 'basinal' will refer to sediment which occurs within the lake and has not been deposited by normal clastic shorline sedimentary processes.

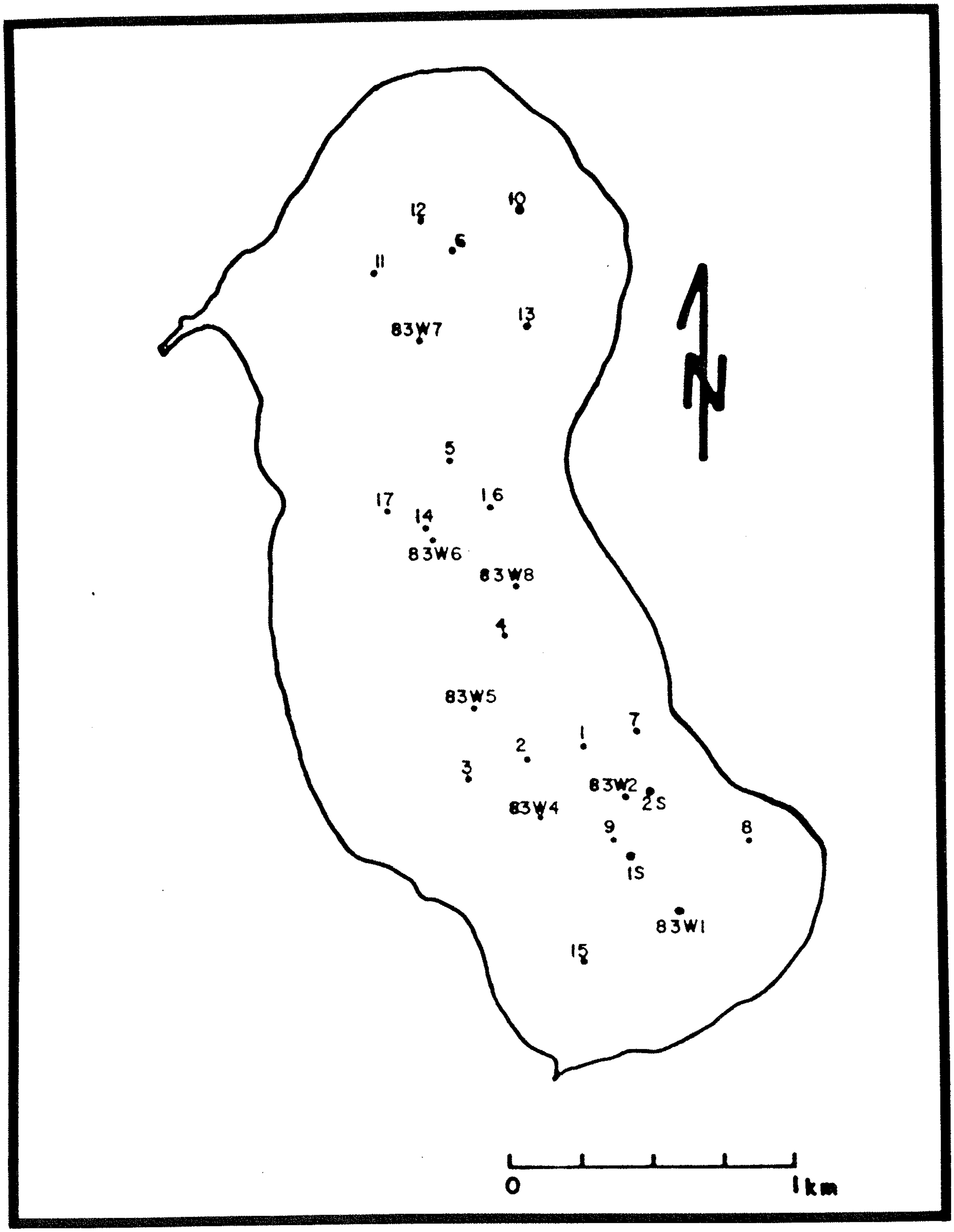


Figure 4: Location map of coring stations

2.1.4 Surface Sediments

Surface sediments were collected using both a 15 cm Petersen dredge and a 22.5 cm Eckman dredge. Eckman dredge samples were frozen in a portable freezer unit for later analyses. For some of these samples, on site subsampling was done, and these subsamples were stored in plastic containers and frozen for later analysis. Petersen dredge samples were described on site and discarded. Shallow nearshore and shoreline sediments were collected and placed in plastic containers for later analysis.

2.2 LABORATORY METHODS

2.2.1 Methods and Handling

Water content was determined on seven fresh cores by weight loss at 100°C. The resulting dried samples were labelled and stored in plastic vials for later analyses. Loss on ignition to 500°C (LOI) and loss on combustion to 1000°C (LOC) were used to evaluate changes in total organic material and total carbonate respectively (Dean, 1974).

2.2.1.1 X-ray Methods

Major mineralogy of one core (13) and part of another (5) was run by X-ray diffraction. The samples were ground to pass a 230 mesh sieve and placed in aluminum sample holders supplied by Philips. A Philips PW1710 series with Cu $k\alpha$ radiation and a graphite crystal monochromator on a computer-controlled goniometer was used. Table 1 gives the machine settings.

Results from the digital output (cps, d, 2Θ) were tabulated, and a series of short WATFIV programs were used to calculate percentage compositions of major mineral phases according to Chung's (1974a,b) adiabatic principle of matrix flushing systems (Appendix B). Quartz was used as the internal standard.

Selected samples showing diversity in the composition and crystallinity of the carbonate phases were rerun at slower speeds. Calculations of rough cell dimensions and magnesium contents were made from the traces according to the methods of Goldsmith and Graf (1958).

2.2.1.2 Radiochronology

Two sets of organic-rich samples were analyzed by Beta Analytical, Inc. (Miami, Florida) for radiocarbon dating. Because of technical difficulties with the first set, the lake sediment was resampled during February 1983.

Procedures used by Beta Labs include acidification for removal of carbonates, rinsing, drying, and combusting the samples. The process is completed by benzene synthesis and liquid scintillation counting. Stable isotope ratios were not calculated. The reference standard was NBS Oxalic Acid Carbon-14 Standard. Ages were calculated using a half-life of 5568 years.

TABLE 1

X-ray Diffractometer settings

Machine--Philips PW1710 series X-ray generator with computer-controlled goniometer

0.1 mm collimation slit

Automatic divergence slit

Radiation--Cu kα

Monochromator--Curved graphite crystal

40 Kv

40 mA

Scan speeds

Fast--0.1° 2θ sec^{-1}

Intermediate--0.01° 2θ sec^{-1}

Slow--0.001° 2θ sec^{-1}

Fast scans were used for rapid identification of materials. Intermediate scans were used for major mineral component analysis. Slow scans were used for detailed carbonate study.

Chapter III

WALDSEA LAKE AND ITS BASIN

3.1 LANDSCAPE AND GROUNDWATER

3.1.1 Bedrock Geology

The uppermost bedrock in the Waldsea Lake area is the Lea Park Formation of the Upper Colorado Group of late Cretaceous age. Christiansen (1967) and Meneley (1964) contend that the preglacial bedrock surface was dissected by numerous channels forming a badlands topography. Though much of the detail of this topography may have been destroyed by glaciation (Meneley, 1964), major trunk valleys and uplands would have remained basically intact. This smoothed though irregular topography would have a profound effect on the flow of ice over the region during glaciation and could have controlled the distribution of the glacially deposited sediment. The sediments from later glacial advances would also be controlled by both the distribution of the bedrock features and also the previous glacial sediments.

The deeper bedrock consists of Paleozoic carbonate-evaporite sequences. This material is completely covered by the Cretaceous and Pleistocene deposits in the Melfort map area (Figure 5).

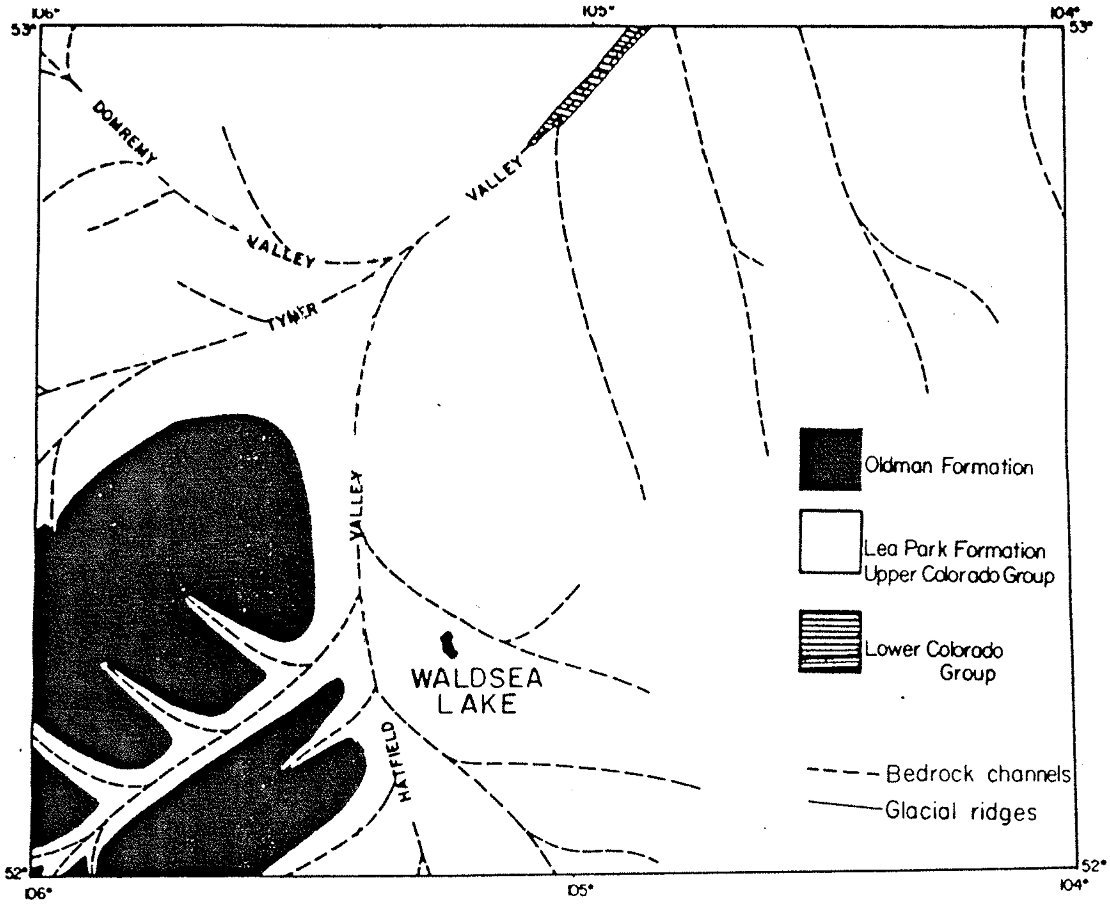


Figure 5: Bedrock geology and buried channel systems (after Meneley, 1967)

3.1.2 Glacial Geology

Meneley (1964) described four major units in the Quaternary deposits of the region. Unit A, the oldest of the units, is composed of stratified drift. It is interpreted as being "deposited at least in part in an ice marginal position" (Meneley, 1964), and ranges from 127 to 278 metres thick in the Hatfield Valley (Figure 5) and from 12 to 52 metres thick in other locations. Its deposition was profoundly controlled by the preglacial topography. The stratified drift of unit A which fills the Hatfield Valley and its tributaries is a major aquifer system, equivalent to the "Empress Group" of Christiansen (1979).

Unit B consists of undifferentiated till and stratified drift and is found throughout the Melfort map area (73A, Figure 5). According to Meneley (1964), it may represent several glacial advances and retreats; the specific till members are not distinguishable on the basis of sediment type, and some may be present in some areas and not in others.

The Naisberry Till is found above unit B. This till unit also contains the Clemens Boulder Pavement Member in the eastern part of the Melfort map area, which can be a major obstacle to groundwater exploration. Several major drumlins and drumlinoid ridges in the western part of the map area are composed of the uppermost till unit, the Reynaud Till. Meneley (1964) reports approximately equal amounts (10% each) of calcite and dolomite in these tills.

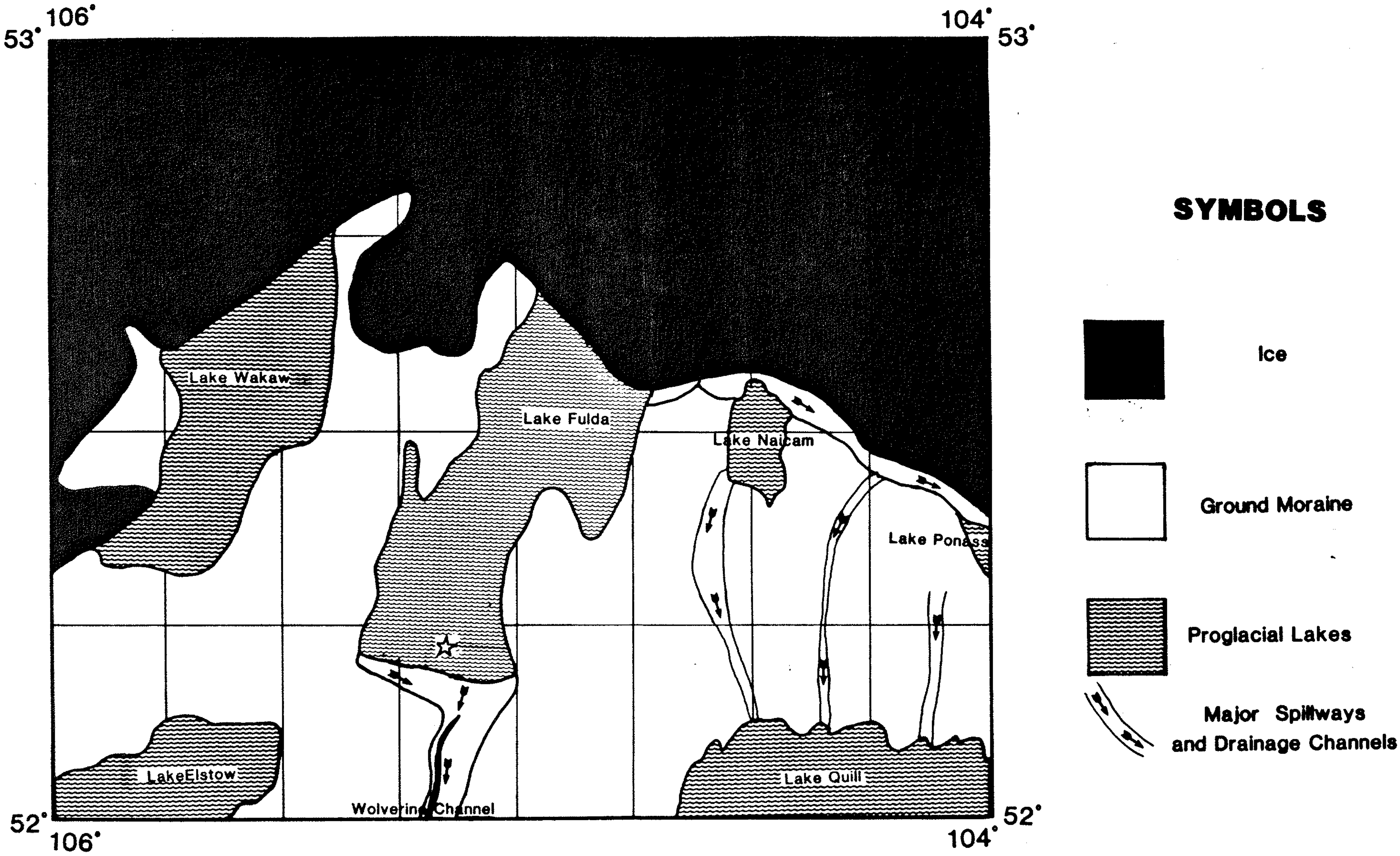
Except for clay minerals, no other mineralogy has been reported on the tills.

There are many oxidized zones within the tills of Unit B and the Naisberry and Reynaud Tills, but because of the complexity of the glacial stratigraphy, the specific advances have not been delineated. Meneley (1964) assumes that the oxidized zones represent subaerial weathering. Five glacial advances have been postulated by Meneley (1964) on the basis of tills and structures found within the Melfort area.

Christiansen's (1979) glacial stratigraphy of the Saskatoon area is quite similar, although no specific correlation of the Sutherland and Saskatoon Group tills to those found in the Melfort area has been made.

3.1.3 Surficial Geology

The surficial deposits in the region are composed of tills, stratified drift, and glacio-lacustrine materials. Meneley (1964) described the final deglaciation of the area; five major lakes were formed. These are Lakes Naicam, Quill, Elstow, Wakaw, and Fulda (Figure 6). The surficial material of the Waldsea Lake drainage basin can be attributed to sediments deposited in the short-lived ice-marginal Lake Fulda. This lake drained south through Wolverine Channel until retreat of the ice afforded a lower, more easterly path through the Wakaw Channel along the ice front to the north. Waldsea Lake's drainage basin soil is quite stony, possibly indicating that some of Lake Fulda's sediment has been eroded or that only a thin blanket of lacustrine material was deposited. In either case, agronomic practices have made surficial identification of this deposit difficult.



(after Meneley, 1964)

Figure 6: Glacial Lakes of the Melfort Region

3.1.4 Soil

The predominant soil type in the region is black chernozemic (Clayton et al., 1977). It is dominantly well drained. The soils may supply dissolved carbonates and salts which are transported into the lake. Minor associations of grey luvisolic (grey wooded) soil also occur within the region.

Because no mineralogical analyses of soils from the region have been reported, and the soils were not sampled for this study, it is assumed that the soils have approximately the same carbonate content as their parent material, the underlying till (10% calcite, 10% dolomite).

3.1.5 Groundwater Systems

Though little is actually known about the groundwater systems within the Waldsea Lake basin and their interplay with the surface waters, some relationships can be deduced. Possible groundwater sources to Waldsea Lake include:

1. Bedrock sources such as:
    a) Paleozoic carbonate-evaporite sequences. These waters are generally considered to be connate, and highly saline with a dominance of NaCl (Meneley, 1967).
    b) Cretaceous fine-grained clastic sequence (Christiansen et al., 1971). This material is predominantly "marine" shales and silts, and contains sa-

line groundwater; the upper surface is considered to be the base of groundwater exploration in the region (Meneley, 1967).

2. Shallow sources, such as: Pleistocene deposits, which are the most probable sources of groundwater inflow to Waldsea Lake. These deposits can be divided into:
   a) The Empress Group, "dirty" sands (Christiansen et al., 1971). These deposits may be either preglacial or proglacial, and possibly represent filling of preglacial drainage systems with meltwater-borne sediment. Of these major aquifer systems, three, namely, the Hatfield Valley, Tyner Valley, and Domremy Valley aquifers, are present in the Melfort Area (Figure 5), and are capable of producing 3.785×10^4 m^3 per day by pumping. Though there is no direct evidence that this groundwater influences the surface waters, artesian flow from wells drilled into these aquifers indicates that its water is under pressure.
   b) The glacial tills. These units are thought to be relatively impermeable.
   c) Surficial and intertill outwash units. These units are permeable silts, sands, and gravels.

Though both the bedrock and the glacial sediments could contribute groundwater to the lake systems in the region, most of this component will be derived from the glacial material. In either case, groundwater survey results from the region (Meneley, 1967) conclude that the shallow groundwater is generally of low salinity (less than 3 parts per thousand) and of Na-SO_4 dominance.

3.1.6 Lake Level and Isostatic Rebound

Waldsea Lake has had a long history of lake level changes. During the draining of glacial Lake Fulda, at least one stable level was established long enough to form "beach ridges", or cut a notch approximately 8 to 9 m above the present-day lake level. A similar ridge occurs near Deadmoose Lake, above the elevation of the barrier between the two lakes. Though these two ridges are not connected and do not presently occur at the same elevation, they probably were formed contemporaneously and reoriented by isostatic rebound. Meneley (1964) presented an isobase map for the Melfort area showing differential isostatic rebound based on relative changes in elevation of beach ridges from some of the large glacial lakes in the region (Figure 7). Because of Waldsea's orientation with respect to the isobases, a differential uplift of approximately 1.5 m has been experienced between the north and the south ends in the last 12,000 years (0.4 m over the last 4000 years). This means that 4000 years ago, the north end of the lake was 0.4 m lower relative to the south end than it is today.

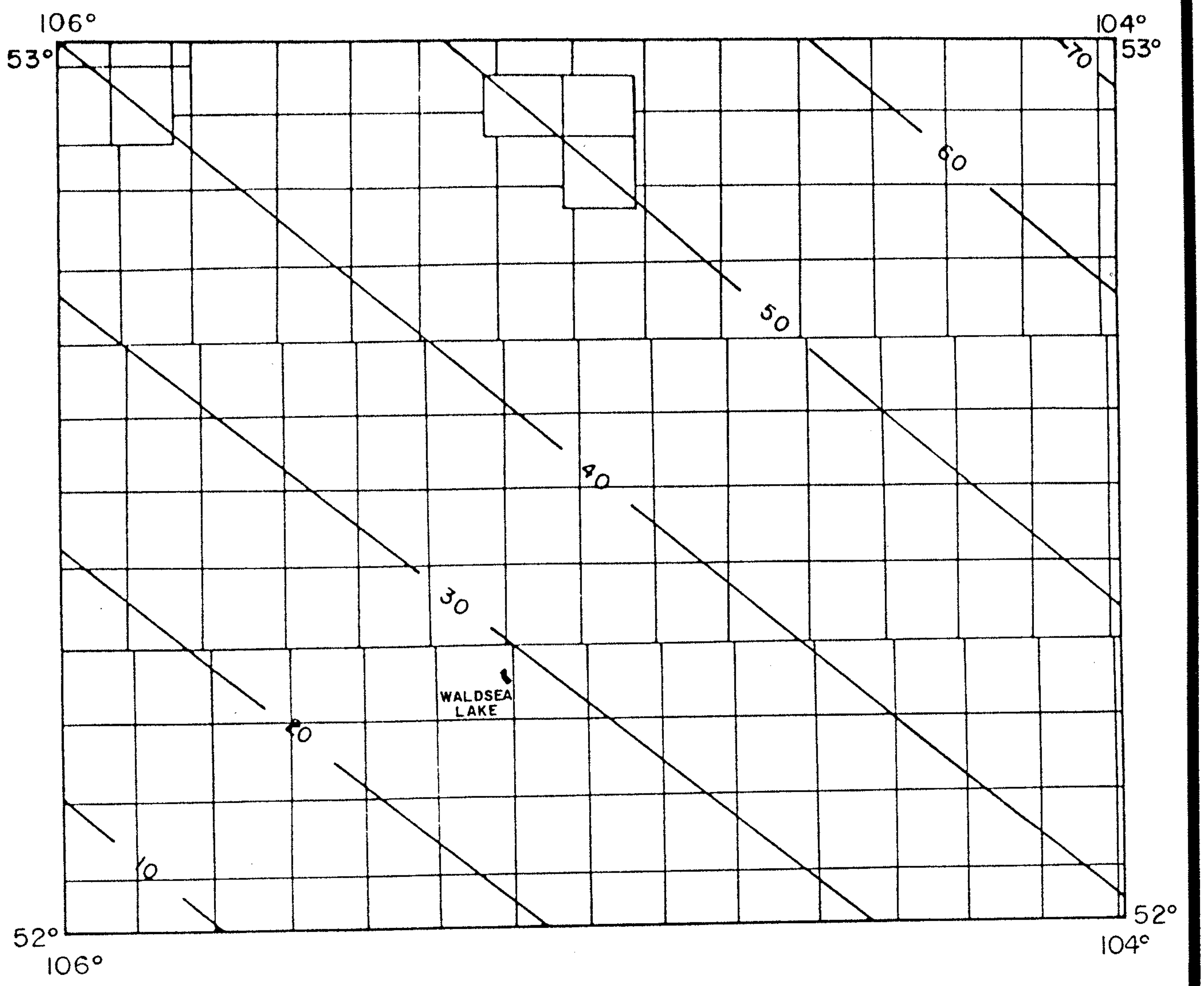


Figure 7: Rebound isobase map of the Melfort Region (after Meneley, 1964)

This map shows the calculated absolute elevation differences of the Melfort area in relationship to its elevations at the end of deglaciation (approximately 12,000 years B. P.). Calculation of relative elevation differences in Waldsea Lake over the last 4000 years is based upon a linear rate of uplift.

3.2 LACUSTRINE STRATIFICATION SYSTEMS

3.2.1 Introduction

Most north temperate lakes exhibit some form of thermal and/or chemical stratification during the course of a normal year. Hutchinson and Löffler (1956), Wetzel (1975), and Cole (1979) review the various types of stratification.

Thermal stratification is much more common than is chemical stratification. Typically three zones can be differentiated in a thermally stratified lake on the basis of density. These are the epilimnion, thermocline (or thermolimnion), and the hypolimnion (Figure 8).

Chemically stratified lakes also exhibit three zones: the mixolimnion, chemocline (or chemolimnion), and monimolimnion (Figure 8). The various types of chemical stratification are discussed in a later section. Under special conditions, thermal stratification or even secondary chemical stratification can also develop within the mixolimnion. Thermal stratification of Waldsea Lake's mixolimnion occurs annually, and development of a secondary chemocline has been documented by Hammer (1978b).

Chemical stratification does not always occur due to salinity. Accumulation of Fe^{2+}, H_2S, or $CO_3{}^{2-}$ by biogenic sedimentation can cause stratification (Dickman, 1974) or increase stability of a pre-existing stratification (as in Längsee, Frey, 1955).

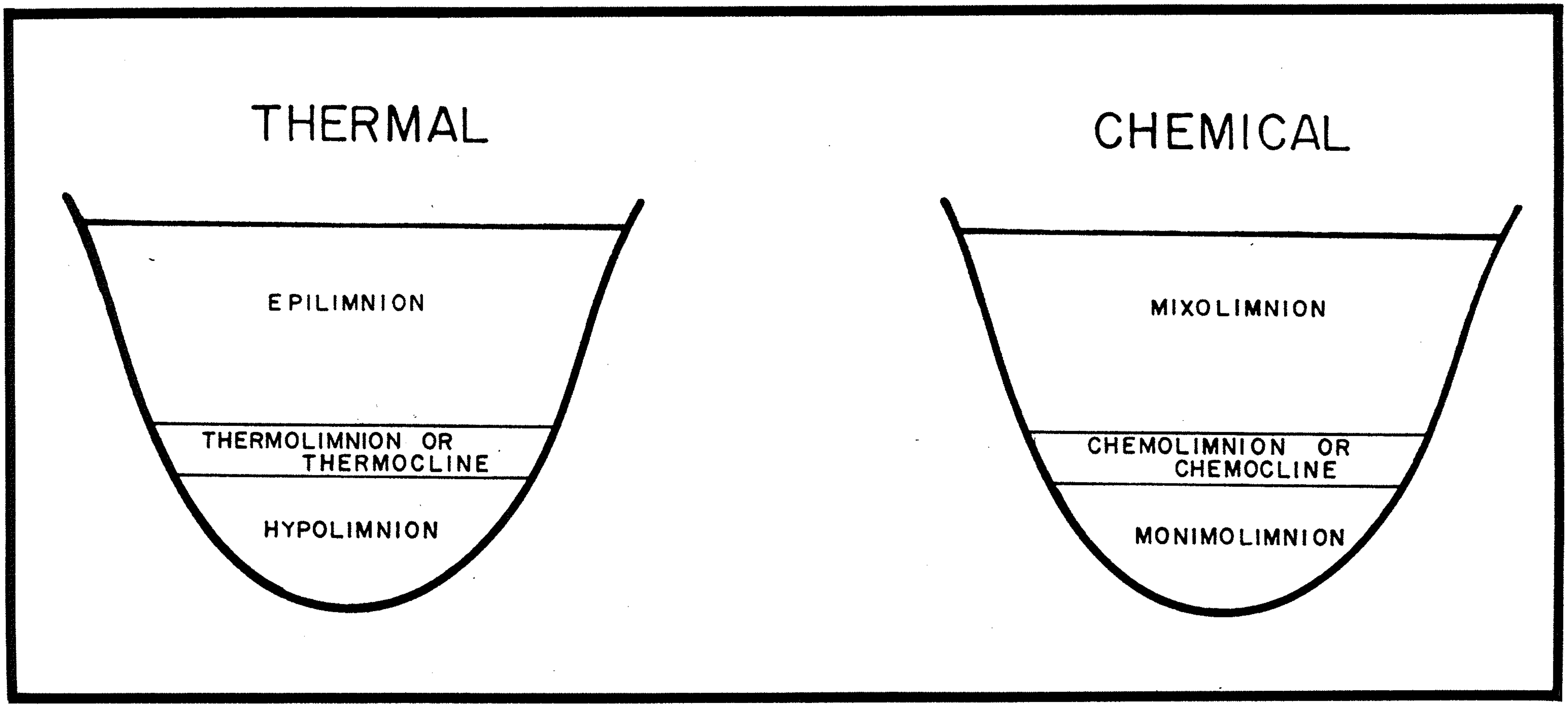


Figure 8: Differences in terminology in stratified lakes

3.2.2 Meromixis

Meromixis was first described by Findenegg (1935). Meromictic lakes can be classified on the basis of the processes by which they were formed. These types of meromixis include:

1. Ectogenic meromixis-- this is a meromixis which is formed when enough freshwater is introduced into a saline lake (or salt water into a freshwater lake) by overland flow such that stratification is maintained despite wind mixing over several years.
2. Biogenic meromixis-- this type occurs when salts or other chemical compounds accumulate in the lower portions of a lake due to biological activity.
3. Crenogenic meromixis occurs when saline-water springs beneath a freshwater lake (or freshwater springs beneath a saline lake) discharge sufficient quantities of water to sustain stratification.
4. Cryogenic meromixis is caused by the elimination of salts from the surface volume of a lake as it freezes. Because the ice crystal structure cannot accommodate foreign ions during crystallization (Spyker, 1981, 1982a,b; Canfield et al., 1983) some of the brine may form fluid inclusions in the ice. The lake water freezes from the surface down, and the thickening of the ice will selectively remove nearly pure water from the solution, leaving a more saline

solution beneath it, which, if supersaturated by cooling, will precipitate salts (as described in nearby Little Manitou Lake, Hammer, 1978b). Grossman (1968) suggested this mechanism of salt precipitation for the buildup of mirabilite (hydrous sodium sulfate) in meromictic lakes to form thick sequences of salts in the Great Plains. Cryogenesis is an important annual event. This process can induce a secondary chemocline during melting (Hammer, 1978b), which probably increases the stability of stratification.

5. Morphometric meromixis was suggested by Northcote and Halsey (1969) and supposedly is based solely on the peculiar nature of the morphometry of the lake.

Waldsea Lake was first identified as being meromictic in 1971 (Hammer et al., 1975; Heseltine, 1976; Tones, 1976; Lawrence, 1978; Hammer et al., 1978). Lawrence (1978) described the contribution of the Chlorobacteriacea of the bacterial plate to the primary production of the lake. These green sulfur bacteria are responsible for much of the organic sediment delivered to the bottom.

Waldsea's meromixis is most probably ectogenic in nature, but may have been dependent in part on a process similar to crenogenesis for its initiation. Though crenogenesis implies saline springs or seeps beneath the lake, it is more probable that dissolution of intrasedimentary salts (mirabilite) by groundwater and addition of brine to the lake through diffuse groundwater efflux increases the stability of stratification and maintains meromixis.

3.2.3 Stability of Stratification

Idso (1973) proposed a method to calculate stability of stratification (an estimate of the amount of work needed to mix the lake to uniform density). The stability was calculated for Waldsea Lake using published information as well as observations made during the present study (Table 2). Results are reported in g cm/cm^2 in the convention of Idso (1973). A graphical method (Cole, 1979) was used to verify the calculations for 1971 (Figure 9). A WATFIV program to run the calculations is found in Appendix C. No pattern is evident in the changes in the stability.

Figure 10 shows the changes in volume of the mixolimnion and monimolimnion over the period of meromictic record (1971-1983).

TABLE 2

Stability of stratification for years with data

YEAR	DEPTH	DEPTH CHEMOCLINE	TOTAL VOLUME	MIX VOLUME	MON VOLUME	MEAN DENSITY	Zrho, cm	S g cm/cm^2
1971	12.2	4.0	17.5	1.5	6.5	1.132	996	2766
1974	13.8	5.0	24.2	20.0	4.2	1.037	758	2371
1975	13.6	6.0	24.9	20.8	4.1	1.046	664	4601
1976	14.0	7.0	24.8	20.7	4.1	1.027	852	923
1980	13.8	7.5	25.5	21.6	3.9	1.045	664	4374
1981	13.9	8.5	25.8	22.0	3.9	1.027	852	902
1982	14.3	8.7	25.8	22.0	3.8	1.027	852	848

MIX	Mixolimnion
MON	Monimolimnion

Mean density is measured in g cm^{-3}.

Zrho is the depth of the lake's center of gravity.

S is the stability of stratification.

All volumes are 10^6 m^3.

Data is taken from Lawrence (1978), Heseltine (1976), Tones (1976), and Hammer et al. (1978), as well as field observations.

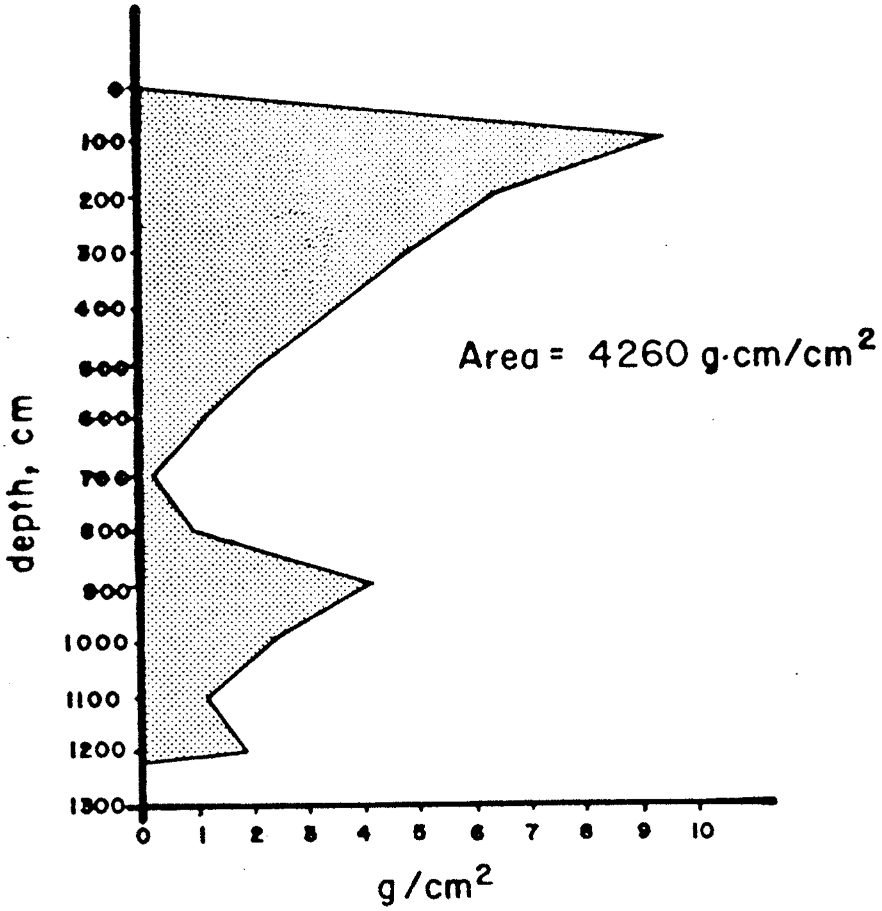


Figure 9: Graphical stability calculation for Waldsea Lake for 1971

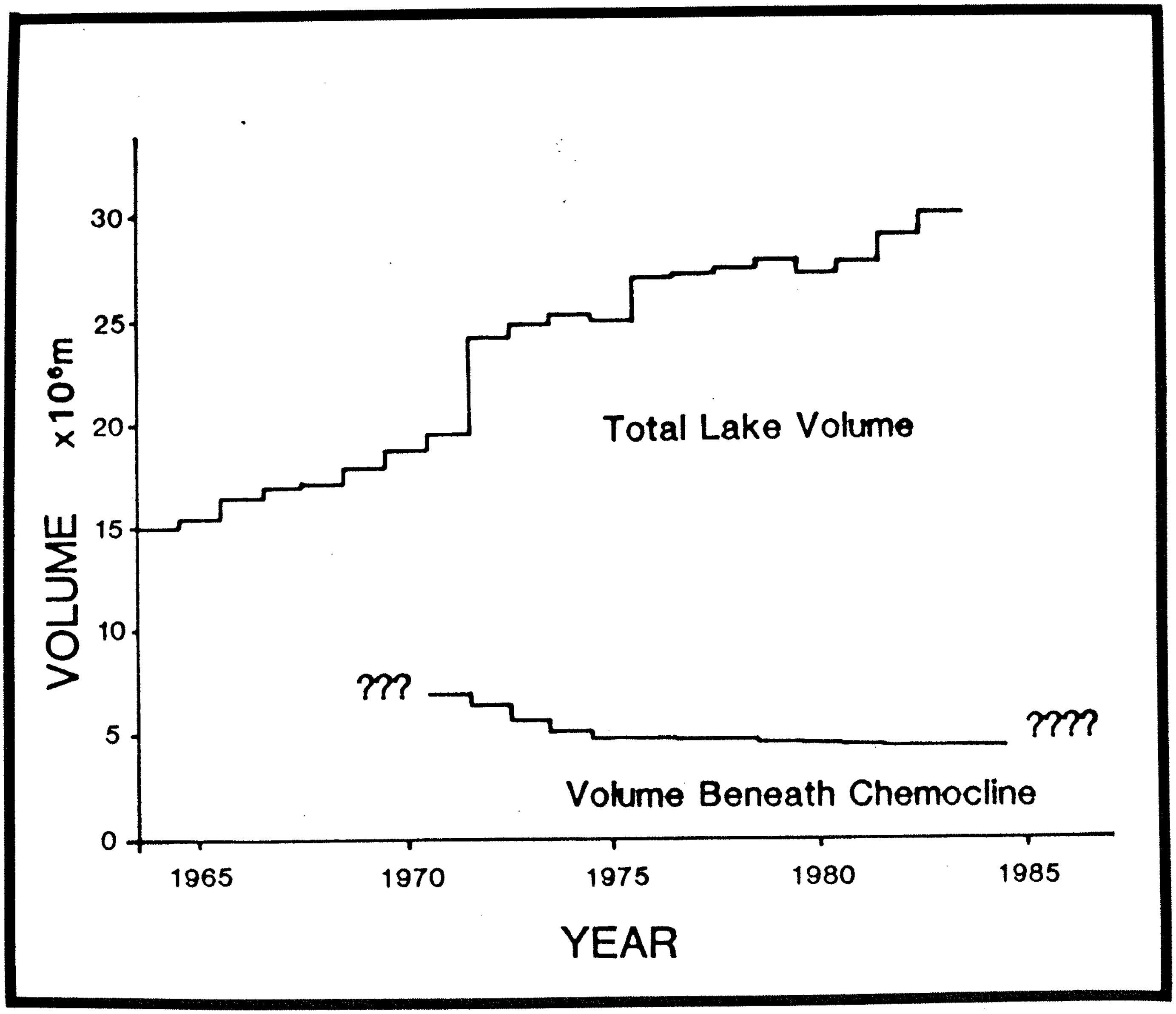


Figure 10: Volumes of the strata of Waldsea Lake

3.2.4 <u>Morphology</u>

Various morphometric parameters of Waldsea Lake were measured in accordance with the methods of Cole (1979) and Häkanson (1981) using the bathymetric map produced by Swanson (1978, Figure 11). A list of the measured parameters and their values can be found in Table 3. Two of these parameters and their changes with relative lake level warrant further discussion because they may indicate changes in the character of the lake during development.

Figure 12 shows graphically the changes in interval slope. The slope in the shallower part of the lake is interpreted to be the equilibrium lake bottom slope for the deep lake.

Relative depth is the ratio of the measure of maximum depth and the surface area of the lake in comparison to an inverted right circular cone. It is useful as an indicator of how efficiently energy may be transferred throughout the water by heat and wind. Lakes which have small relative depths (large surface areas with respect to their maximum depths) will be capable of more efficient distribution of heat by wind mixing than would lakes with large relative depths. Waldsea Lake's current relative depth is about 0.63%, which is smaller than any other previously reported relative depth of meromictic lakes (Table 4). This consequently implies a low stability of stratification, though Waldsea's current stability (about 4000 g cm/cm^2) is relatively large in comparison with some other meromictic lakes (such as those reported in Brunskill et al., 1968). Calculated values of stability of stratification are reported in section 3.2.3.

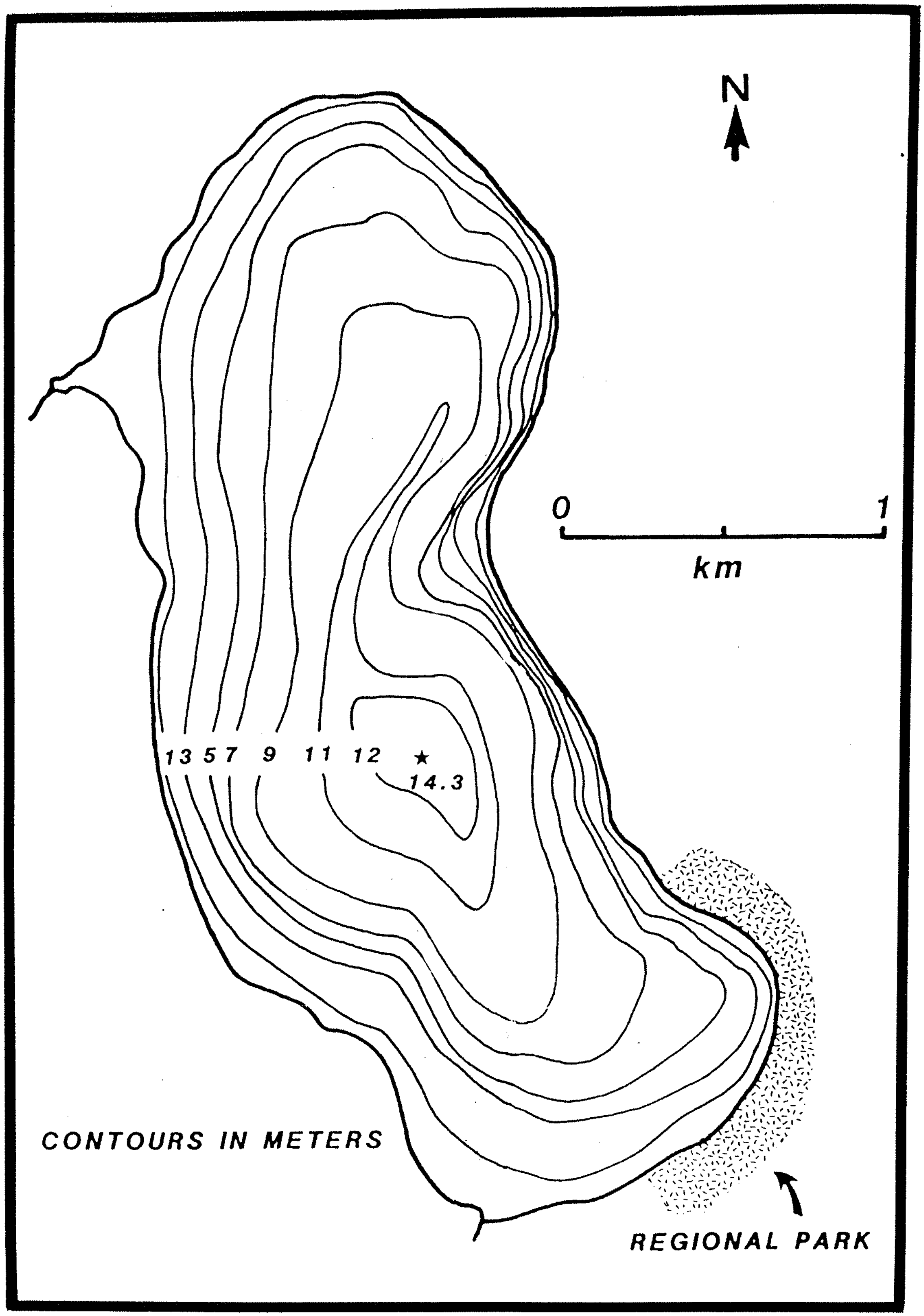


Figure 11: Bathymetric map of Waldsea Lake (after Swanson, 1978).

TABLE 3

Morphometric parameters for Waldsea Lake in 1981

Surface area	4.64 km^2
Maximum depth	14.5 m
Mean depth	8.1 m
Shoreline length	10.17 km
Shoreline development	1.30
Total volume	37.69×10^6 m^3
Volume development	1.70
Drainage basin area	47 km^2
Drainage basin area/lake area	10.0
Relative depth	0.63%
Maximum effective fetch	2.2 km
% volume in mixolimnion	88.06
% volume in monimolimnion	11.94
Total "Salt"	6.93×10^8 kg
% total salt in mixolimnion	80.08
% total salt in monimoliomnion	19.91

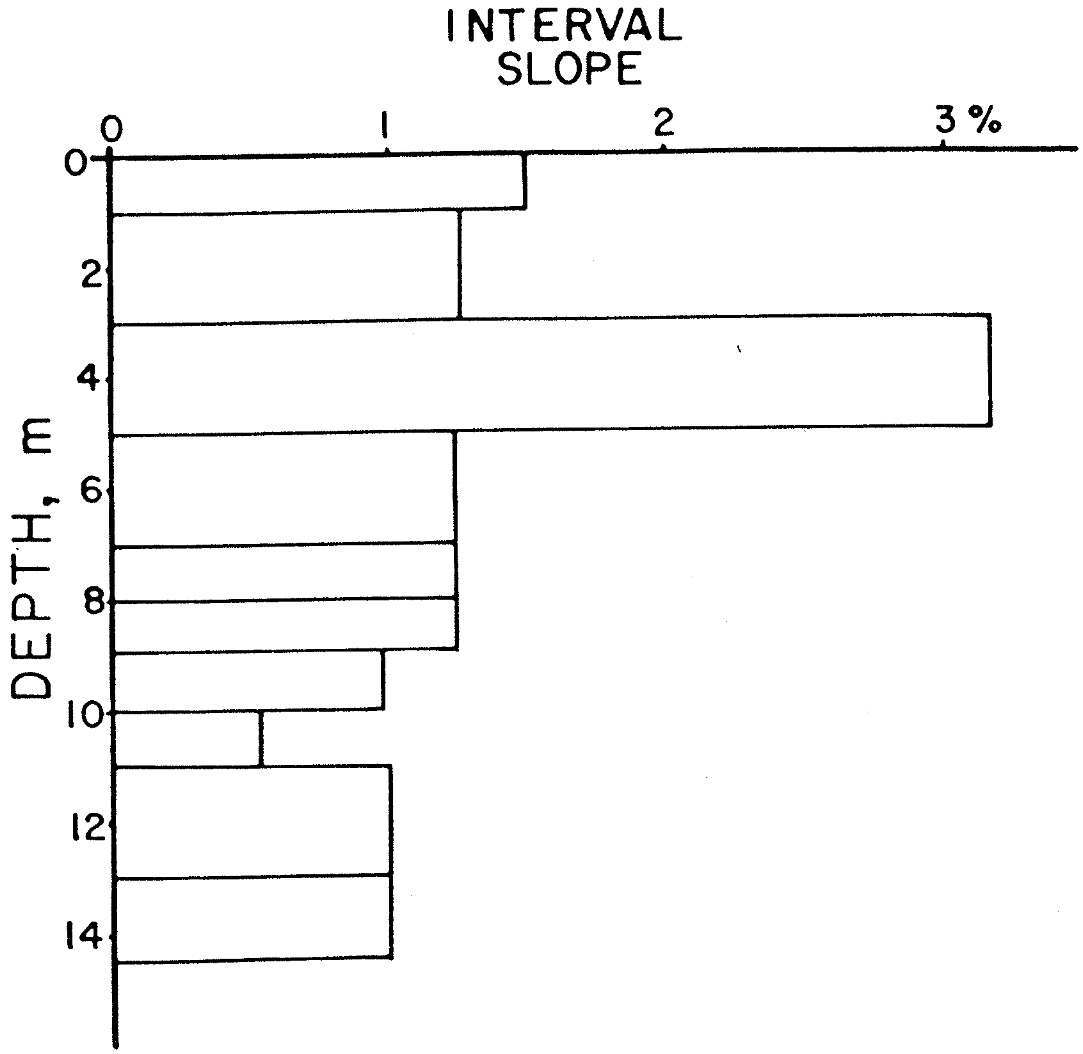


Figure 12: Graphic representation of changes in slope

TABLE 4

Relative depths for various ectogenic and crenogenic meromictic lakes

(modified from Cole, 1978)

Big Soda, Nevada	1.17%
Blue, Washington	2.90
Deadmoose, Saskatchewan	1.37
Fidler, Tasmania	5.90
Hot, Washington	2.70
Long, Alaska	2.00
Lower Goose, Alaska	3.76
Morrison, Tasmania	2.30
Nitnat, British Columbia	3.36
Ogac, Baffin Island	4.40
Pingo, Alaska	5.50
Powell, British Columbia	3.60
Sakinaw, British Columbia	4.38
Soap, Grant Co., Washington	1.16
Soap, Okanagan Co., Washington	1.29
Sulfide Pool, Tasmania	7.10
Tessiarsuk, Labrador	2.05
Vee, Alaska	0.70
Wannacut, Washington	2.77
Waldsea, Saskatchewan	0.63
West Basin, Australia	9.16%

3.3 WATER CHEMISTRY

3.3.1 Comparison with other saline lakes in the region

Last and Schweyen (1983) discussed the variability in the saline and hypersaline lakes of the northern Great Plains both in terms of character and brine chemistry. Hammer (1978b) presents chemical data from sixty of these lakes. Tables 5 and 6 and Figure 13 are included for comparison with the numerous published chemical results available in the literature.

TABLE 5

Concentrations of some major ions (mmol/l) of Waldsea Lake water

SAMPLE	Na	Mg	Ca	K	Cl
June 12, 1982					
9-Mix	281.39	214.08	12.82	5.97	7.54
9-Mon	299.04	228.17	12.02	7.05	7.54
11-Mix	177.78	143.75	8.48	3.38	10.11
11-Mon	260.99	203.04	11.20	4.90	---
12-Mix	173.26	141.71	9.08	3.56	---
12-Mon	258.04	213.08	11.92	5.01	7.11
June 13, 1982					
14-Mix	178.04	147.75	8.70	3.46	4.89
14-Mon	291.69	225.21	13.45	6.05	8.14
15-Mix	152.74	124.62	5.22	2.90	4.03
February 10, 1983					
83W2-Mix	189.48	159.83	9.08	3.77	---
83W2-Mon	312.74	234.21	12.38	5.82	---

Numbers indicate core locations at which the water samples were taken.

'Mix' indicates sample from 1 m above the chemocline
'Mon' indicates sample from 1 m below the chemocline
--- not analyzed

TABLE 6

Reported chemical results of other studies used for saturation indices calculations

SAMPLE	Eh (V)	pH	Na	Mg	Ca	K	Cl	SO_4	TA*	Fe	SiO_2
Lawrence, 1978											
August 4, 1972											
Mixolimnion	-.01	8.60	95.70	69.12	2.60	4.09	77.95	88.49	4.2	---	---
Monimolimnion	-.20	7.85	347.98	246.86	6.99	14.32	239.75	316.48	13.93	---	---
May 8, 1973											
Mixolimnion	-.10	8.60	52.63	44.85	0.54	25.06	46.26	62.46	3.8	---	---
Monimolimnion	-.20	7.85	351.46	253.03	2.20	13.30	233.55	312.31	18.85	---	---
April 13, 1974											
Mixolimnion	-.01	8.60	178.34	137.83	2.64	7.67	133.98	166.57	2.0	---	0.005
Monimolimnion	-.20	7.85	339.28	248.92	4.42	14.71	243.98	312.31	2.0	---	0.50
Heseltine, 1976											
August 19, 1971											
Surface	-.10	8.5	156.59	109.10	9.98	7.93	115.65	132.20	286.0	0.006	0.030
June 12, 1973											
Surface	-.10	8.2	139.19	106.97	14.97	6.52	106.62	133.25	283.0	0.005	0.015
July 21, 1976											
Bacterial plate	---	8.0	260.11	197.90	10.63	12.10	186.44	249.85	---	0.002	0.138
February 3, 1977											
Bacterial Plate	-.34	8.0	244.02	192.96	10.90	11.38	176.01	239.44	---	0.001	0.130

* Titration Alkalinity, reported in milliequivalents per litre.
--- indicates analyses not published.

Note: all ions are reported in millimoles per litre.

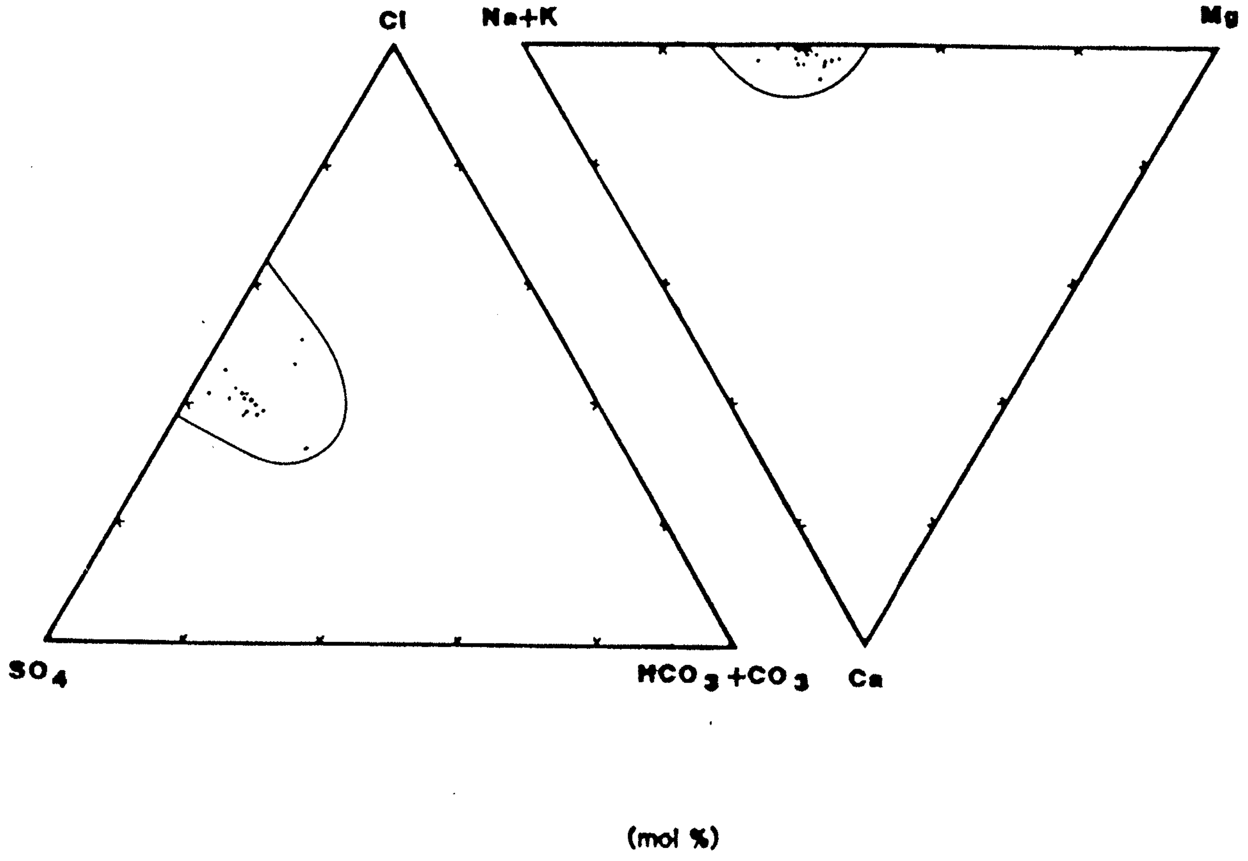


Figure 13: Ionic composition of Waldsea Lake water samples (Data taken from Lawrence (1978) and Heseltine (1976))

3.3.2 Waldsea Water Chemistry

Saturation indices, activities and molalities of complexes and ions were calculated using the computer program WATSPEC (Wigley, 1977). Table 7 gives values of calculated saturation indices (log(IAP/Ksp))[3] for selected minerals for various Waldsea Lake water samples quoted in the literature. Table 8 gives the log(Ksp) values used by WATSPEC for the calculations. Several artificial "data" ("Hypothetical Overturn") are also included in Table 7 in an attempt to determine whether mineral saturation indices would increase if the lake were mixed. These values were generated by calculating the total ion concentrations which would exist under holomictic conditions. They are based on concentrations of the ions and volumes of the strata.

Vertical profiles of the saturation indices (Figure 14) show that seasonal fluctuations occur; according to these calculated values, some chemical reactions could occur below the chemocline but not above. Gypsum's saturation index, for example, fluctuates near 0 (saturation), and dissolution might occur above the chemocline, though precipitation may be able to take place both at the surface of the lake and below the chemocline.

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[3] This is the log of the ratio of the ion activity product to the solubility product of the mineral species in question.

Other minerals for which WATSPEC calculates saturation indices are not included in this discussion because they are extremely soluble and perennially undersaturated (mirabilite, bloedite, epsomite, and halite).

TABLE 7

Calculated saturation indices for various minerals

Sample	pE	pH	Temp	Dens (C)	I[1]	IBE[2] (g/cm³)	aH2O[3]	log(IAP/Ksp)†							
								Cal-cite	Mirab-ilite	Gypsum	Thenar-dite	Arago-nite	Halite	Dolo-mite	Quartz
Lawrence (1978)															
August 4, 1972															
Mixolimnion	4.39	8.60	10.0	1.020	0.390	-45.33	0.9912	2.12	-2.43	-0.75	-4.09	1.81	-4.04	5.56	---
Monimolimnion	1.17	7.88	2.0	1.200	0.853	-18.37	0.9817	1.56	-0.81	-0.07	-2.86	1.20	-3.13	4.40	---
May 8, 1973															
Mixolimnion	4.39	8.60	10.0	1.020	0.316	-52.33	0.9926	1.47	-3.02	-1.51	-4.68	1.17	-4.51	4.47	---
Monimolimnion	1.17	7.85	2.0	1.200	0.847	-17.04	0.9818	1.03	-0.81	-0.58	-2.86	0.67	-3.14	3.85	---
April 13, 1974															
Mixolimnion	4.39	8.60	10.0	1.020	0.608	-30.33	0.9868	2.06	-4.51	-0.62	-6.15	1.76	-4.92	5.75	---
Monimolimnion	1.17	7.85	20.	1.200	0.852	-19.47	0.9817	1.35	-0.84	-0.28	-2.89	0.99	-3.13	4.18	---
Heseltine (1976)															
August 19, 1971															
Surface	4.24	8.50	15.0	1.020	0.534	-34.03	0.9879	2.65	-2.21	-0.14	-3.59	2.37	-3.69	6.33	-1.00
June 12, 1973															
Surface	4.23	8.20	15.0	1.020	0.529	-34.83	0.9882	2.59	-2.31	0.07	-3.69	2.31	-3.77	6.00	-1.60
February 3, 1977															
Bacterial Plate	-1.42	8.00	4.00	1.150	0.698	-24.24	0.9878	1.96	-1.31	0.08	-3.26	1.61	-3.42	4.94	0.50
July 21, 1976															
Bacterial Plate	2.95	8.00	4.0	1.150	0.730	-21.65	0.9844	1.94	-1.17	0.07	-3.13	1.60	-3.33	4.92	0.54
Hypothetical Overturn															
August 4, 1972	5.35	8.46	8.0	1.056	0.498	-35.03	0.9891	2.04	-1.91	-0.52	-3.66	1.72	-3.74	5.42	---
May 8, 1973	5.34	8.45	8.40	1.056	0.439	-37.47	0.9902	1.46	-2.19	-1.16	-3.93	1.14	-3.97	4.79	---
April 13, 1974	5.34	8.45	8.40	1.056	0.654	-26.62	0.9859	1.92	-1.55	-0.52	-3.27	1.60	-3.44	5.43	1.36

[1] Ionic strength.
[2] Ion Balance Error.
[3] Activity of water.
† Saturation Indices (log(IAP/Ksp)).
--- indicates that chemical data were not available for calculation of this parameter.
The above parameters were calculated by the computer program
WATSPEC (Wigley, 1977) using data given in Table 6.

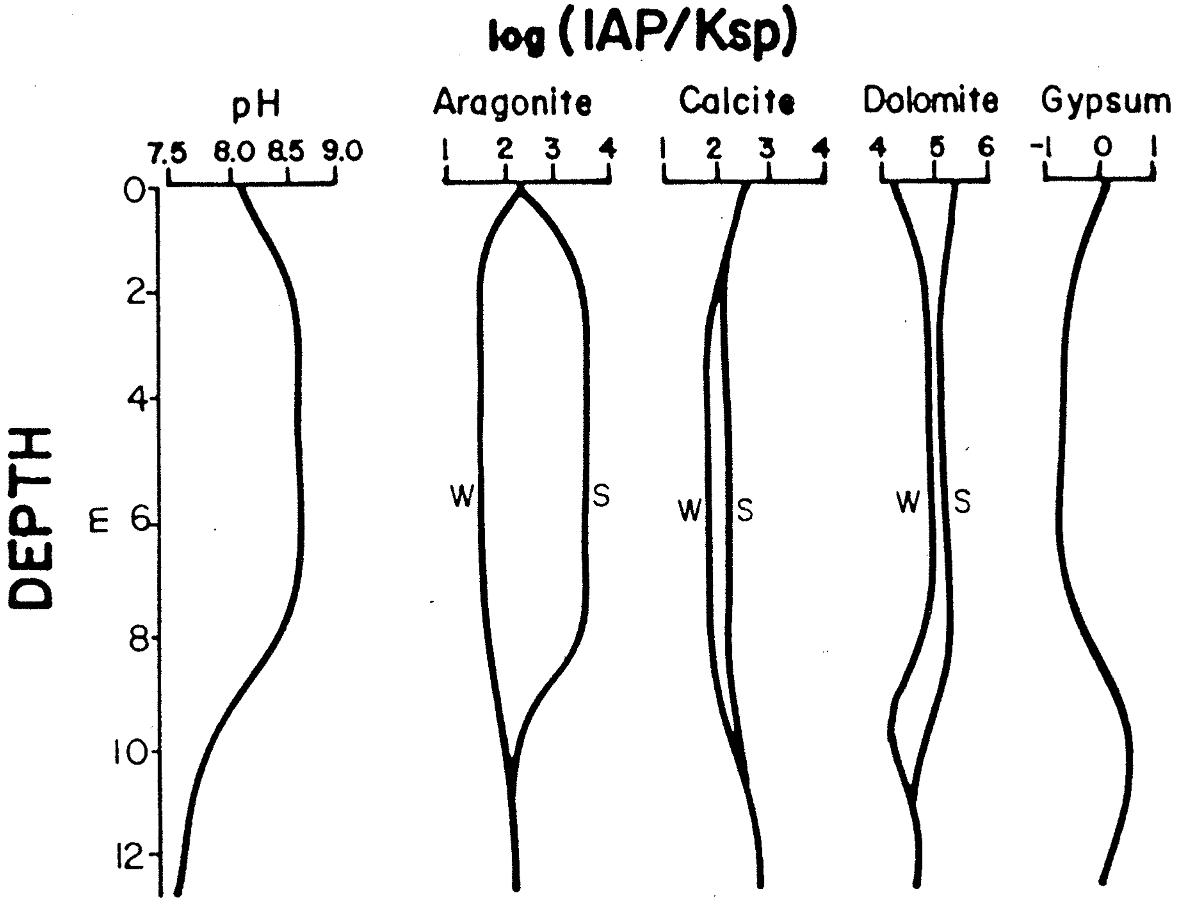

Figure 14: Vertical profile of saturation indices for summer (S) and winter (W)' (data from Table 7)

TABLE 8

Log Ksp values used in saturation indices calculations by WATSPEC

(From Truesdell and Jones, 1974)

MINERAL	log(Ksp)	SOURCE
Dolomite	-17.000	Berner, 1967
Calcite	-8.370	do
Gypsum	-4.848	Robie and Waldbaum, 1968
Aragonite	-8.305	do
Halite	1.582	do
Thenardite	-0.179	do
Mirabilite	-1.114	do
Quartz	-4.006	do
Pyrite	-18.479	do

3.3.3 Carbonate Stability

Carbonate saturometry curves are shown in Figure 15. The water samples were collected under ice cover in February 1982. In all cases, an increase in pH indicated undersaturated conditions with respect to the carbonate phase used (calcite or aragonite). This is in conflict with the results of WATSPEC calculations of saturation indices of winter 1977 samples, which showed supersaturation with respect to both calcite and aragonite (Table 7). Several possible explanations for this discrepancy can be suggested. These include:

1. The chemical system of Waldsea Lake may not be adequately modeled by the log(Ksp) values and the extended form of the Debye-Huckel equation which WATSPEC uses for its calculations. This could be related to the relatively high salinity (25-70 parts per thousand total dissolved solids) and abundance of sulfate and other ions which are available for complexing.
2. The reported analyses may have been incorrect.
3. Waldsea Lake's water chemistry may have changed since the reported results (1977).
4. The carbonate saturometry results may be incorrect.

Because no chemical analyses were run on the samples which were used for saturometry, it is difficult to determine which of the previously mentioned reasons caused this discrepancy. Further sampling and complete analyses would be able to clear up whether or not WATSPEC can be used to adequately model saturation conditions in the lake. Laboratory simulations and experimental procedure on the dissolution or precipitation of the specific mineral phases under controlled conditions would also be useful in this regard.

DeBoer (1977a) proposed a stability diagram for the carbonates upon which is plotted $(Ca^{2+})^{0.5}.(Mg^{2+})^{0.5}.(CO_3^{2-})$ versus $(Mg^{2+})/(Ca^{2+})$ ratio. Figure 16 shows values from Waldsea Lake brines plotted on this diagram. Their positions indicate that all phases of calcium and magnesium carbonates (and solid solutions) are "stable" (a phase is stable above its given line). In reality, this means those phases will not dissolve; no implications of precipitation are inferred.

In terms of Eh and pH, aragonite crystals or other precipitates formed at the surface of the lake and settled through the chemocline will be exposed to dramatic changes in chemical conditions. Figure 17 shows paths plotted from Lawrence (1978) on an Eh-pH diagram. Values for the carbonate fields are taken from Garrels and Christ (1975).

That aragonite is precipitated periodically is undisputable; its absence in the sediment provenance area and its presence in the sediment both in fine-grained disseminated form and as distinct, nearly pure laminae up to 1 mm in thickness is unequivocal evidence. A single lamina 1 mm

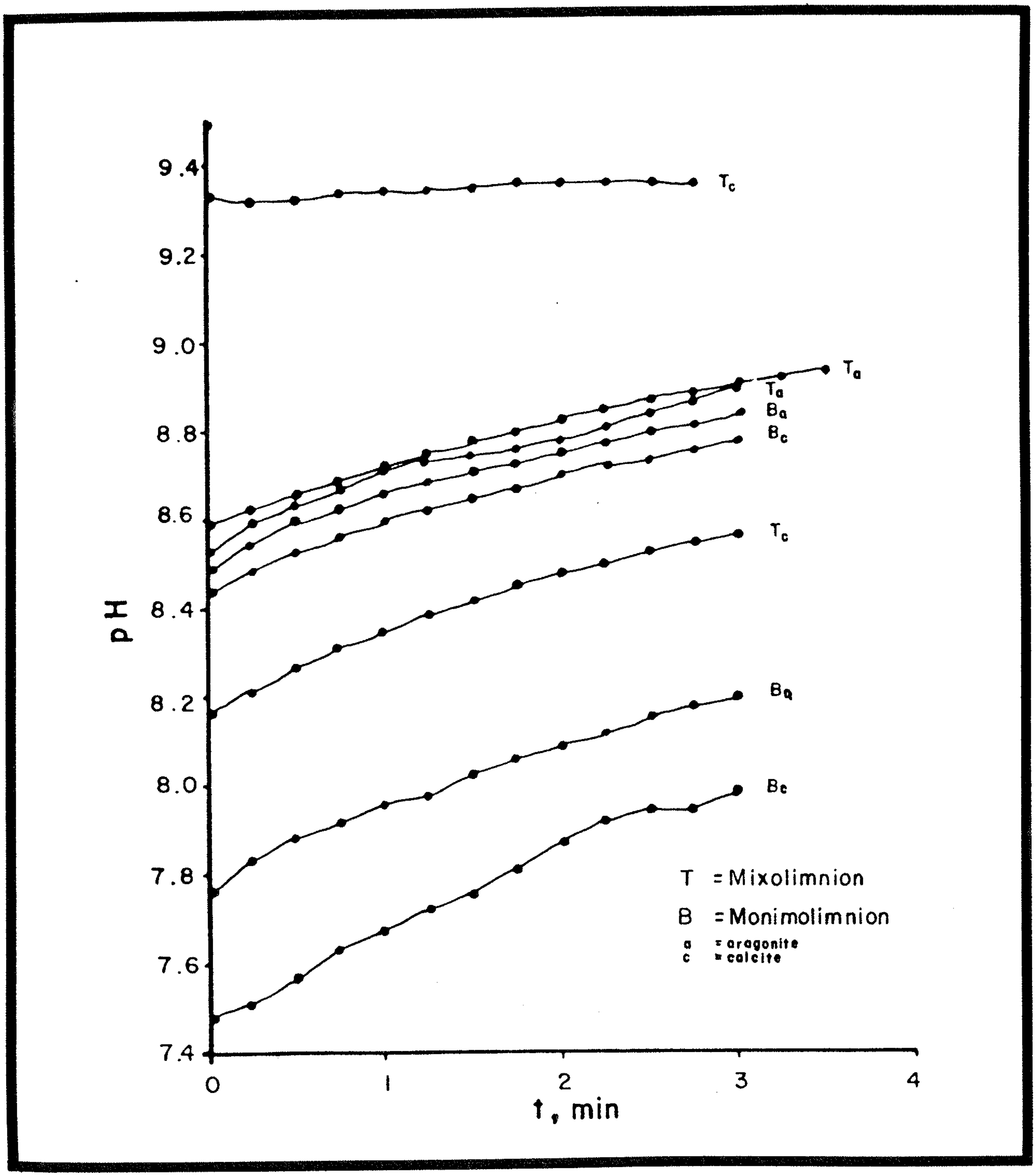

Figure 15: Carbonate saturometry curves for Waldsea Lake brines

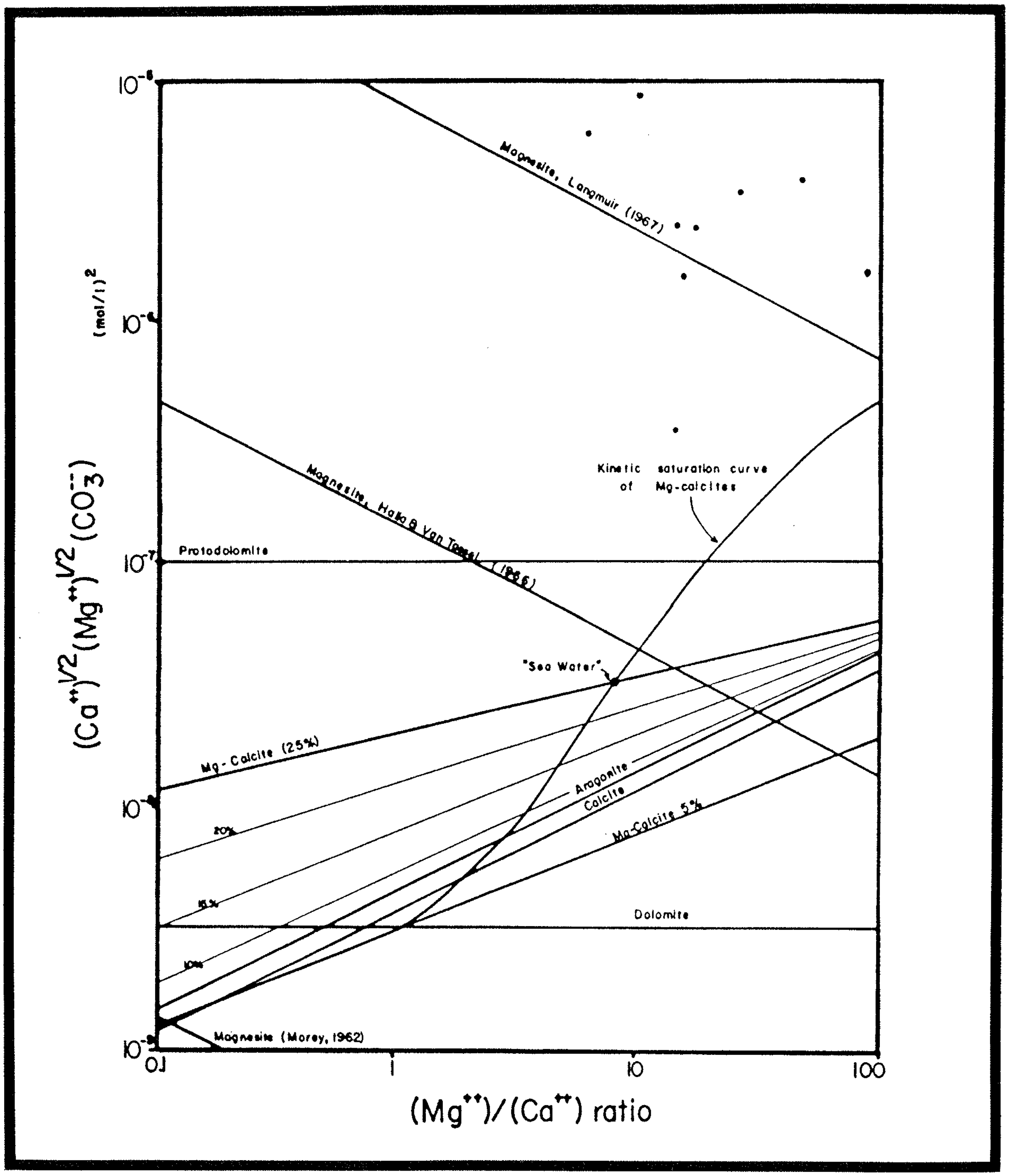

Figure 16: DeBoer's carbonate stability diagram
The lines plotted on this diagram separate the conditions under which Ca-Mg-CO_3 solid phases will be stable from those in which they will not. A solid phase will be "stable" with respect to solution phases (will not dissolve) if it occurs in a solution which plots above the mineral's "line". Samples which occur below a given line will not be stable, and should dissolve that solid phase if it is present.

thick and covering half the lake bottom area would constitute 50,000 kg of aragonite (382,000 moles). Depending on the carbonate concentrations encountered during sedimentation, the aragonite crystals (approximate size 5X5X20 μm) may become partially or totally dissolved. The finer the crystals are, the slower their descent, and subsequently the greater the chance of dissolution. Figure 23 shows aragonite needles which may have been etched during their descent. Degens and Stoffer (1976) describe this process on calcite crystals in the Dead Sea. Further dissolution may occur after the precipitate is deposited.

Though it would seem that there is overwhelming evidence that the water column is perennially supersaturated with respect to the calcium-magnesium carbonate phases, a word of caution is in order. All of the evidence which indicates that Waldsea Lake is supersaturated is based upon water samples which were collected before 1977. Carbonate saturometry samples were collected and analyzed during winter 1982. The lake could have become undersaturated during the period between the samplings. During this period the lake level rose less than 1 m, but the volume of the lake increased by approximately $2X10^6$ m^3. Though this increase would only have a major impact on conditions above the chemocline because of the dimictic annual circulation (Swanson, 1981), the initial low pH values and high salinity beneath the chemocline (Figure 17) could be responsible for undersa-

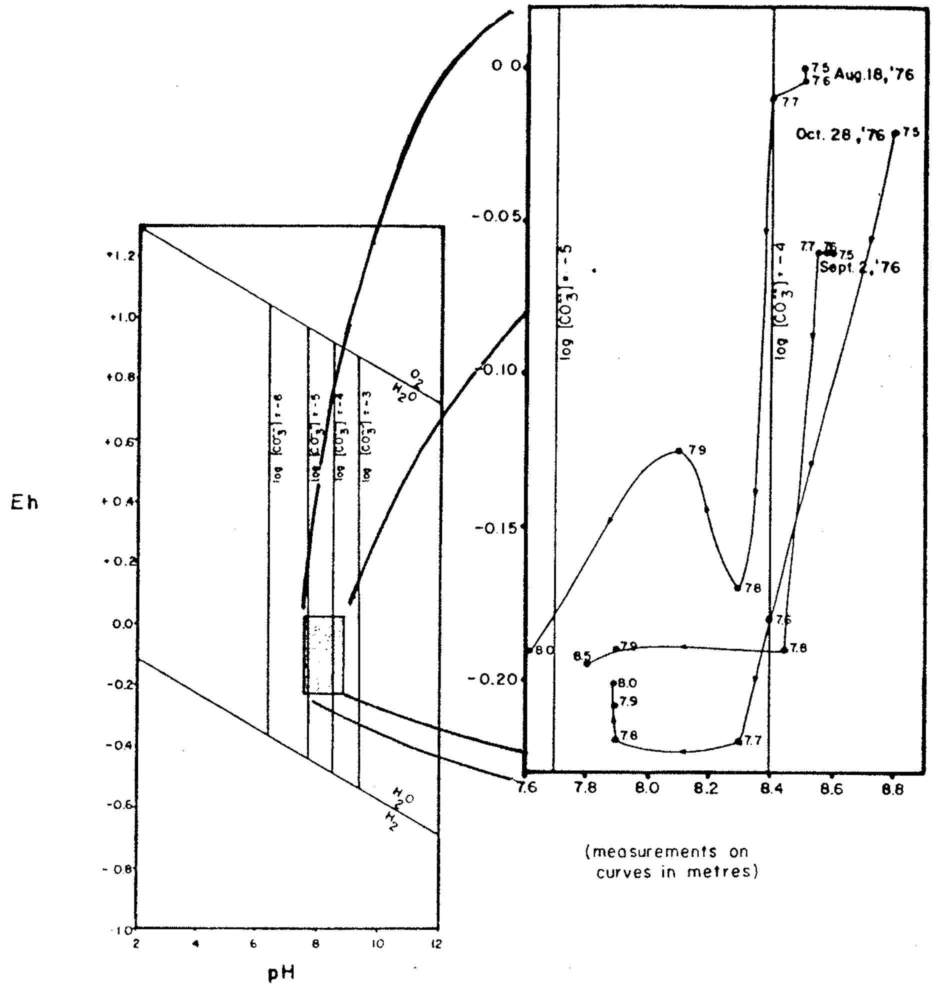

Figure 17: Changes in Eh-pH during sedimentation of precipitates

Dissolution of carbonate minerals is controlled solely by pH (hence the vertical lines) which is directly related to carbonate concentration. The conditions signified by the area to the right of each carbonate isopleth (to the higher pH value) should not cause dissolution of carbonate mineral phases. The inevitable decrease in pH during descent may or may not cause dissolution, depending on carbonate concentrations. The diagonal lines indicate the conditions under which water is stable; above the upper line, water is oxidized to H_2O_2, and it is reduced to H_3O below the lower line.

turation. In light of this situation, it does not seem unreasonable that Waldsea Lake's water column has become undersaturated with respect to most carbonate phases since 1977.

3.3.4 Preliminary Salt Budget Calculations

In a preliminary attempt at salt budget calculations, several hypotheses have been generated.

1. Waldsea Lake's total salt has not been acquired during the time interval represented in the cores.
2. Waldsea Lake's total solute load has been accumulated since deglaciation of the region (in the last 9500 years).
3. Waldsea Lake's annual salt flux is dominated by influx of salts related to groundwater.

Several major assumptions have been made to attempt to test these hypotheses. These include:

1. Evaporation exceeds precipitation by a factor of 2.
2. Groundwater influx contains 1.5 g l^{-1} TDS (based on Meneley, 1967).
3. Though no annual water budget has been calculated, it is assumed that total annual water influx is $9X10^{6}$ m^{3}.

Simple calculation of the amount of annual flux gives $3X10^{6}$ m^{3} water of 4.5 g l^{-1} salinity. This water would contain approximately 30,000 kg of salt, or 0.004% of the total salt currently in the lake. By assuming a uniform annual input over the last 9500 years, this accounts for $4.28X10^7$ kg, or about 6.3% of the total salt in the lake. Therefore, salt influx must be higher than those assumed, or must have been much higher during the period before deposition of the cored sediments to account for this discrepancy. Longer cores and more detailed analyses and calculations are required for refinement.

The presence of mirabilite ($Na_2SO_4 \cdot 10\ H_2O$) in some of the sediment (see Chapter 4) suggests hypersaline conditions in the lake basin during its deposition.

The total salt currently in the lake (based on average salinities and volumes of mixolimnion and monimolimnion) is 6.93×10^8 kg. If the average density of the "salt" which would be precipitated by complete evaporation of the lake is 2.0, the volume of that salt would be approximately $4 \times 10^4\ m^3$, which would fill the lake basin roughly 2 m. Table 9 shows these hypothetical changes in salinity. It is also interesting to note that by hypothetically "evaporating" the lake to approximately 1/2 its current volume (roughly 4 m), the resulting density would be the same as the current density of the monimolimnion.

Therefore, hypersaline conditions as indicated by sedimentary features will likely indicate lake levels lower than those today.

TABLE 9

Hypothetical salinities of Waldsea Lake

Lake depth (m)	Stratum volume (m^3)	Cumulative volume (m^3)	"Hypothetical salinity" (parts per thousand)
14.3	-----	24,240,000	28.10
14	3,910,000	20,330,000	34.10
13	3,290,000	17,040,000	40.69
12	3,000,000	14,040,000	49.38
11	2,540,000	11,500,000	60.29
10	2,360,000	9,140,000	75.85
9	2,260,000	6,880,000	100.77
8	1,900,000	4,980,000	139.21
7	1,590,000	3,390,000	204.51
6	1,260,000	2,130,000	325.49
5	950,000	1,180,000	587.53
4	730,000	450,000	1540.64
3	260,000	190,000	3648.89
2	62,500	117,500	5437.57
1	20,000	107,500	6449.21
0	7500	100,000	6932.90

The values of the "hypothetical salinity" is based on the calculation of the total dissolved solids in the lake, and would be the approximate salinity of the lake under holomictic conditions if the lake's depth was as indicated in the column on the left. This does not include annual salt flux, as no time change is taken into account.

Chapter IV

THE SEDIMENTS OF WALDSEA LAKE

4.1 GENERAL DESCRIPTION OF SEDIMENT COMPONENTS

The sediments are composed of a diverse suite of materials, including organic and both clastic and nonclastic inorganic components. Table 10 summarizes these components and their likely provenances. Because the main focus of this research is the inorganic components, the organic sediments will only be described briefly.

TABLE 10

Components of Waldsea Lake sediments

TYPE	ALLOGENIC	ENDOGENIC	AUTHIGENIC
INORGANIC			
SILICATES	Quartz		Quartz[2]
	Feldspars		
	Clay		
	Garnet		
	Amphiboles		
CARBONATES	Low-Mg Calcite	Aragonite	Aragonite[2]
	(limestone)	High-Mg Calcite	High-Mg Calcite[2]
	Dolomite		Dolomite
		Protodolomite[2]	Protodolomite
		Magnesite[2]	Magnesite[2]
SULFATES		Gypsum	Gypsum
		Mirabilite[2]	Mirabilite
SULFIDES			Pyrite
SULFUR	Sulfur		
ORGANIC			
Particulate Organic Matter			
	Insect remains	Insect remains	
	Plant fragments	Plant fragments	
		Algal fragments	
	Spores	Spores	
	Pollen	Pollen	
		Diatoms	
		Fungi	
		Ostracods	
		Artemia oogonia	
Dissolved Organic Matter			
	Pigments[1]	Pigments[1]	Pigment derivatives[1]
	Soluble organic compounds[1]		

[1] denotes material is suspected but has not been specifically identified in the sediments.

[2] denotes materials which have been identified but not precisely interpreted.

4.2 MODERN SEDIMENTS

The modern sediments (uppermost 2 cm) of Waldsea Lake can best be divided into three "facies", or zones, on the basis of physical, chemical, and biological parameters. These parameters include:

1. texture,
2. organic content,
3. colour,
4. presence or absence of biological remains.

The shoreline facies consists of sand, silt and coarse-grained material rich in low-Mg calcite, dolomite, quartz, and other silicates. Though reducing conditions are found within millimetres of the sediment-water interface, sticks and roots are the only obvious macroscopic organic material that is preserved. The nature and distribution of this material is very similar to that which would likely be found around freshwater lakes of similar morphometry and orientation. Sly (1978) gives an excellent description of processes and products associated with shoreline sedimentation in lakes.

The second facies is distinct from the first in that it is fine-grained, organic rich sediment and is found in deeper water. This facies is dominated by deposition from the mixolimnion, and grades laterally upslope into the offshore sediment of the shoreline facies. The sediment is dominantly anoxic[4] and is black (2.5YR2.5/0) to dark brown (10YR4/1). Water content ranges from 66 to 77%; organic content averages 27%. This "mixolimnion facies" also is distinct in that it supports submerged macrophytes, benthic algal mats, and is capable of supporting both macrobenthos and aufwuchs. Small insect remains, algal filaments and other plant fragments are ubiquitous in the sediment of this facies. The studies of Swanson (1978), Tones (1976), and Heseltine (1976) are based on quantification of these biological occurrences.

The third facies is found beneath the chemocline; conditions are highly anoxic, and do not support macrobenthos, aufwuchs, algal mats, or macrophytes. Organic remains are few, and are likely detrital.[5] The sediment found in this "monimolimnion facies" is black (2.5Y2.5/0) and highly reduced, and has similar texture, water content, and organic content as in the mixolimnion facies. The monimolimnion facies grades laterally into the mixolimnion facies upslope.

Because of the similarity of the mixolimnion facies and the monimolimnion facies sediments and their lateral gradation, their extent is difficult to map. The decrease

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[4] The sediment is considered anoxic due to the presence of H_2S.

[5] Detrital organic remains, in this sense, are any organic materials which were not formed <u>in situ</u> (aufwuchs, infauna, benthic microbial mats, macrophytes, etc.), but rather have been sedimented either from outside of the lake, or produced endogenically (within the water column), and deposited somewhere other than where they grew.

in chemocline elevation reported in Chapter 3 decreases the area of the lake bottom in which the monimolimnion facies is deposited. The modern sediment will record this change, but on an extremely small scale. The main distinction between these two facies will be paleolimnological; further studies are needed to delineate their boundaries both laterally and vertically in the sediment.

4.3 OLDER SEDIMENTS

The basinal sediments of Waldsea Lake can be divided into stratigraphic units on the basis of several sediment characteristics (Figure 18). These characteristics include water content, colour, sediment texture, mineralogy, endogenic[6] sediment component, and abundance and general type of biological remains. Table 11 gives relative abundances and values of these specific parameters for each stratigraphic unit. The sediment parameters which have been quantified for core 13 are shown in Figures 19 and 20 and Appendices D and E. A pollen diagram (Figure 21) for one of the longer cores (83W6) proved useful in interpreting changes in paleoclimatic conditions.

Though quantification of these various parameter was not done on all of the cores which were collected, gross similarities in sediment character (colour, carbonate con-

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[6] The term endogenic is used to indicate materials (both organic and inorganic) which were formed within the water column and were sedimented.

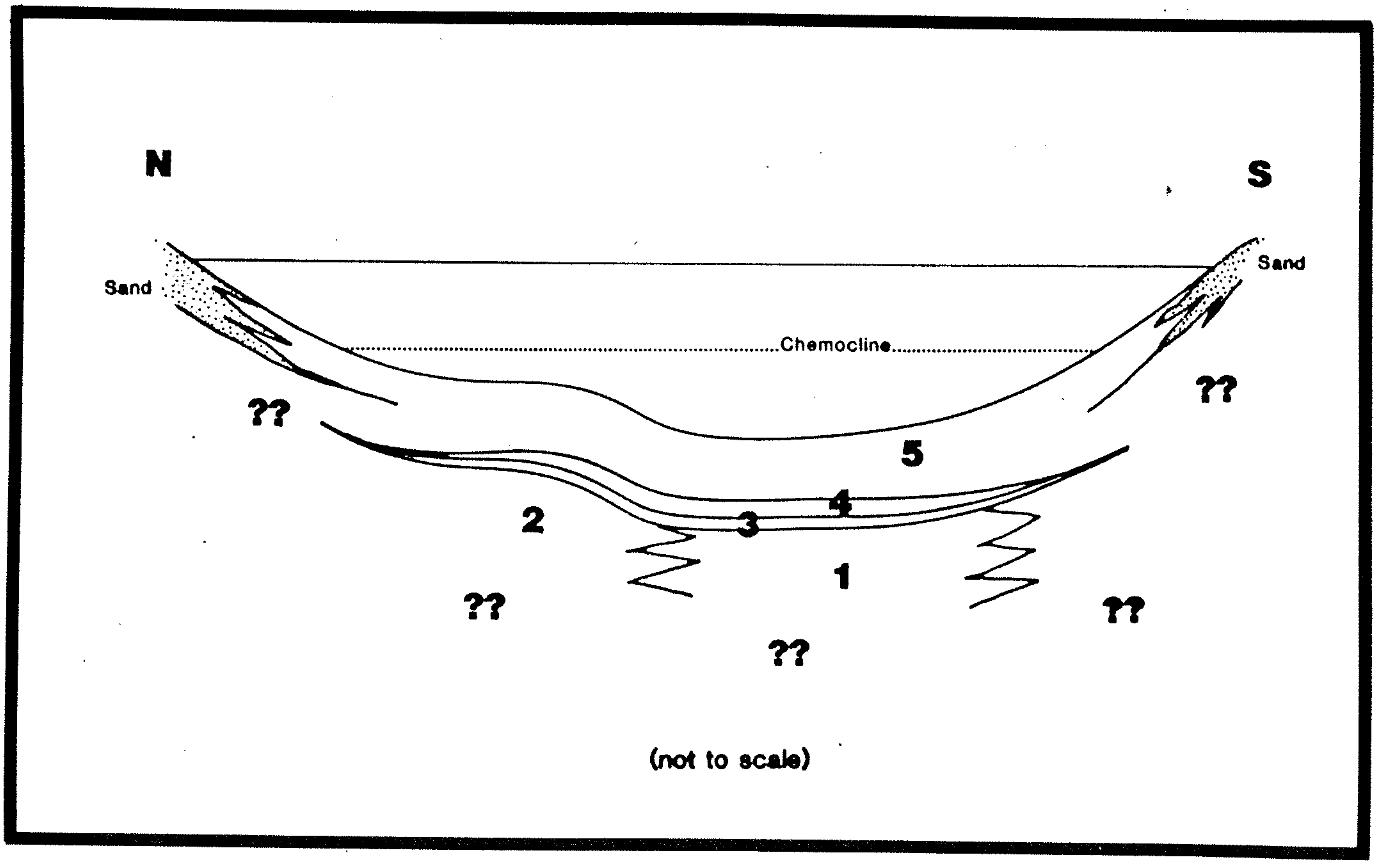

Figure 18: Diagrammatic cross-section of Waldsea Lake sediments showing the stratigraphic relationships of the units

TABLE 11

Parameters used in stratigraphic interpretation

COMPONENT	STRATIGRAPHIC UNIT 1	2	3	4	5	SAND
CARBONATES (LOC)	M	H	H	H	H	M
ORGANICS (LOI)	M	M	H	M	H	ND
WATER CONTENT	L	L	L	M	H	M
COLOUR	BLACK	GREY-GREEN TO BUFF	BLACK TO BROWN	BUFF TO GREY-GREEN	BLACK TO BROWN	GREY
LAMINATION CHARACTER	C	F	F	C	F	B
ARAGONITE LAMINAE	R	R	A	O	A	NO
DOLOMITE-CEMENTED LAMINAE	NO	O	NO	O	NO	NO
GYPSUM LAMINAE	O	A	NO	A	O	NO
ORGANIC FIBRE MATS	A	O	NO	A	O	NO
MINERAL COMPONENTS*						
QUARTZ	ND	M	L	M	L	H
DOLOMITE	ND	M	L	M	L	M
CALCITE	M[1]	M	L	M	L	M
MAGNESIAN CALCITE	ND	M	L	M	L	NO
ARAGONITE	ND	M	H	M	H	NO
PYRITE	ND	L	L	L	NO	NO
GYPSUM	ND[2]	M	L	M	L	NO
PROTODOLOMITE	ND	M	L	M	L	NO
MIRABILITE	M	NO	NO	NO	NO	NO
ORGANIC REMAINS						
PLANT						
VASCULAR HYDROPHYTES	A	R	O	R	A	NO
ALGAL FIBRES	A	A	O	O	A	NO
TERRESTRIAL SEEDS	R	O	O	R	O	NO
ANIMAL						
OSTRACODS	A	A	O	A	O	R
COPEPOD NAUPLII	A	O	R	O	R	NO
ARTEMIA OOGONIA	A	A	R	O	R	NO
INSECTS	O	R	R	R	R	R

*	on the basis of X-ray diffraction.
[1]	on the basis of dilute HCl acid effervescence
[2]	on the basis of visual observation
L	low concentration
M	medium concentration
H	high concentration
R	rare
O	occasional
A	abundant
C	coarse (laminations generally greater than 2 mm in thickness)
F	fine (laminations generally 1 mm or less in thickness)
B	cross-bedded in core
ND	not determined
NO	not observed

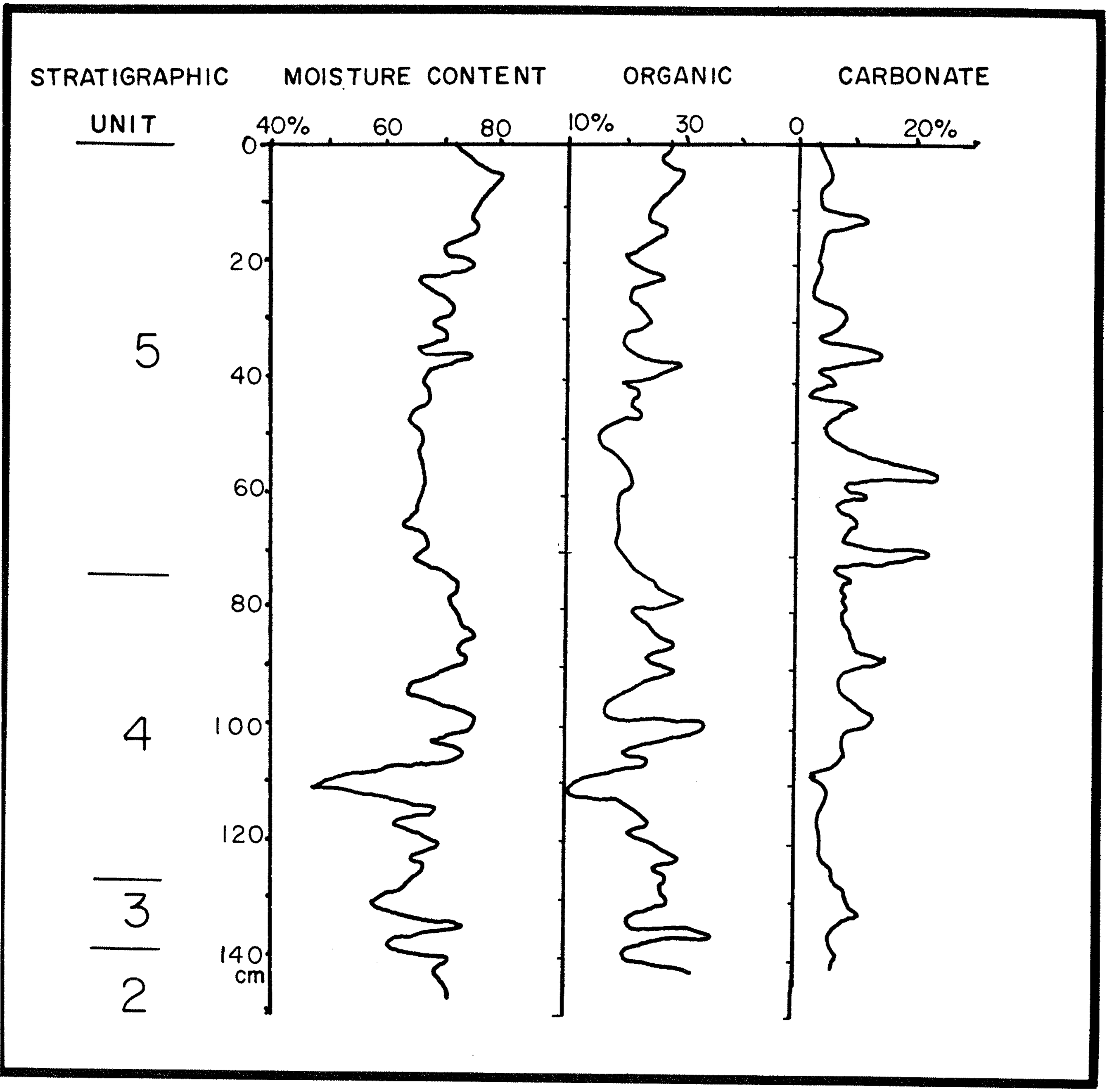

Figure 19: Moisture, organic, and carbonate content of Core 13

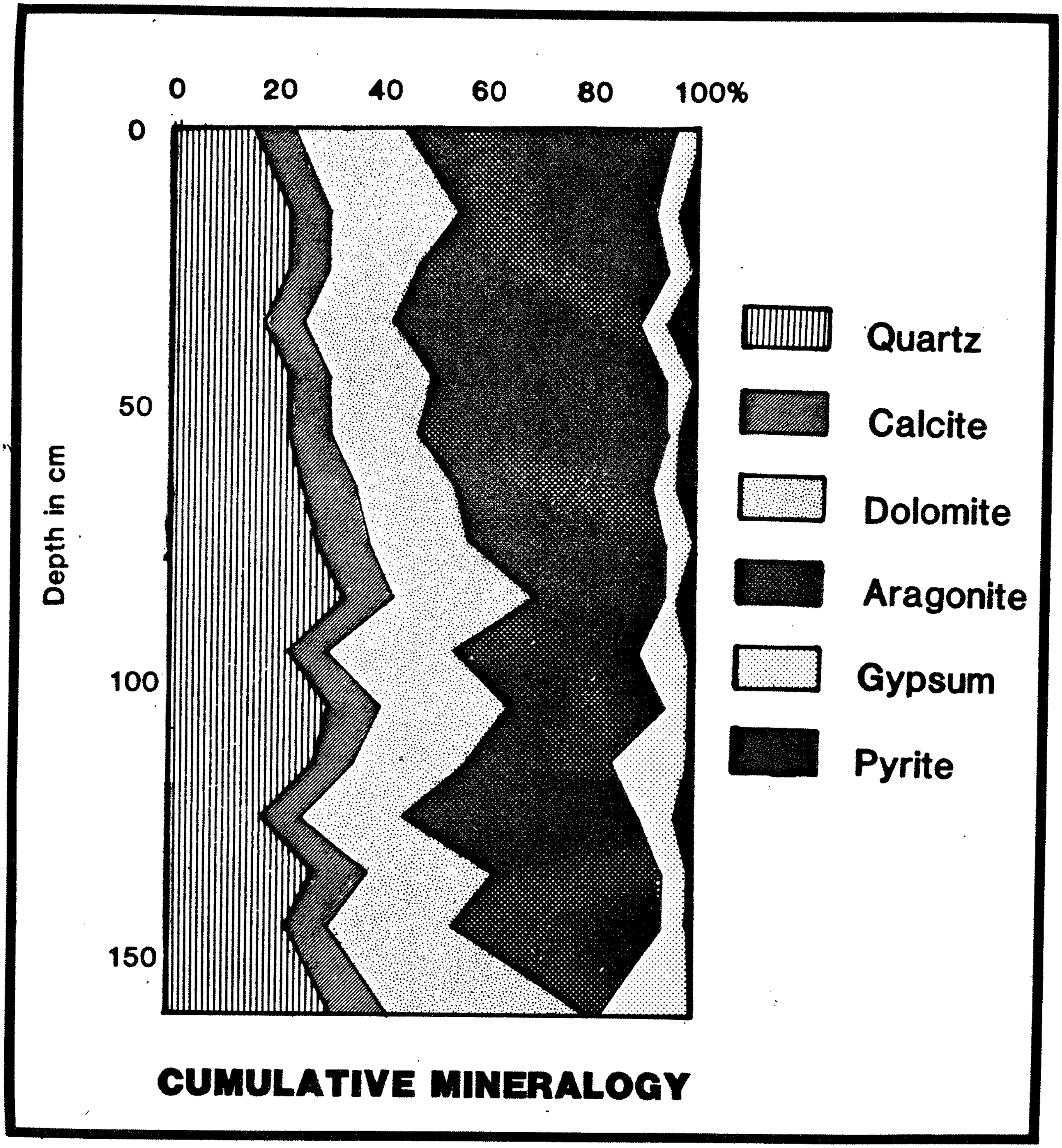

Figure 20: Relative changes in mineralogy in Core 13. (Data are smoothed on 10 cm intervals)

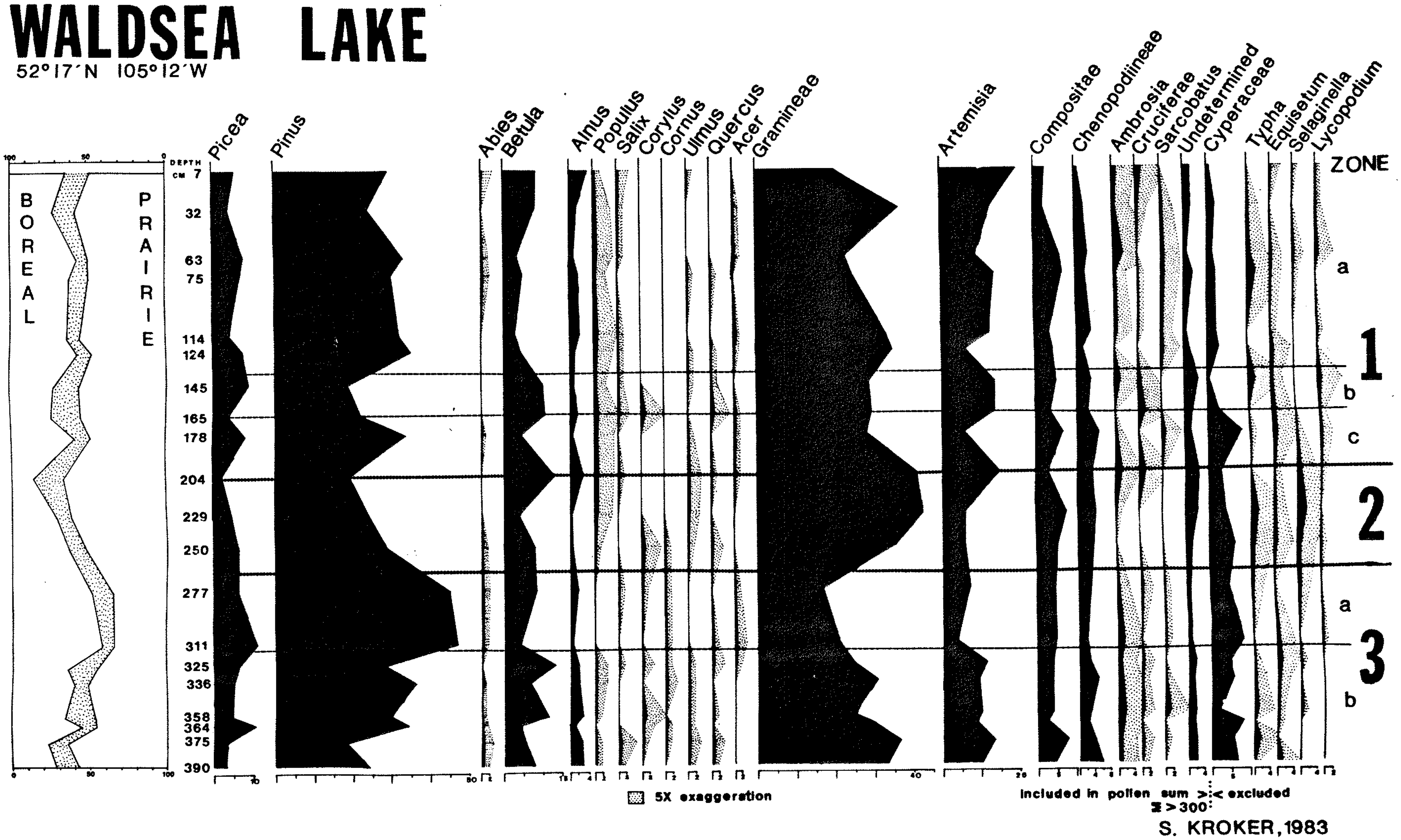

Figure 21: Waldsea Lake pollen diagram, core 83W8
(S. Kroker, pers. comm.)

tent by acidification during description, general lamination character, and macroscopic and microscopic organic and mineralogic features) made possible the identification and delineation of the lateral extent of the sedimentary units with the use of the other cores.

The upper 4 metres of lacustrine fill in the Waldsea Lake basin consists mainly of organic-rich, well-laminated silty clay and clayey silt. Moisture content decreases from about 80% in the youngest sediment to 35% at the base of the cores. Organic matter content ranges from 5 to 45% but does not exhibit any specific trend with depth. Organic fibre mats occur within the lower 2 metres of section. Sediment colours are generally dark grey (2.5Y2.5/1) to dark greenish grey (5Y2.5/1) with abundant lighter laminae (10YR4/1) throughout.

4.3.1 General Stratigraphy

The basinal Waldsea Lake sediments can be divided into five major stratigraphic units. Each unit likely represents a major change in the water level, chemistry, and trophic state of the lake. The lowermost unit (Unit 1) is a black silty mud with plant fibre mats and mirabilite crystals. Overlying Unit 1 is Unit 2, which is a grey to green gypsum-rich silt containing calcite coated twigs and algal fibres. Unit 3 is a dark brown to black sapropel with abundant aragonite laminae. Overlying this are Unit 4 (similar to Unit 2) and Unit 5 (similar to Unit 3).

4.3.2 Unit 1

Description:

Unit 1, the oldest unit recovered, is a black silty mud with numerous unidentified plant fibre remains and sparse but recognizable *Artemia* spp. oogonia. The plant fibres occur both as individual fibres and as interwoven mats, some of which contain obvious pigments. Within this sediment are mirabilite crystals (Figure 28) which are commonly transparent and mud-free and show syntaxial overgrowths and gas-phase fluid inclusions.

Interpretation:

Vugs the size of the mirabilite crystals are also found in parts of Unit 1. These likely represent mirabilite crystals which have been removed by dissolution and transported by diffusion into the lake water. The mirabilite crystals may not be original primary sediment, but rather may possibly represent intrasedimentary displacive growth by "freezeout" precipitation during the cooler months. In either case, the presence of mirabilite indicates hypersaline conditions within the lake basin at the time of deposition, and probably much lower lake levels.

4.3.3 Units 2 and 4

Description:

Units 2 and 4 are quite similar to each other, but each varies greatly in texture and composition on a small scale. Both rounded, silt-sized clastic gypsum laminae and lensoid gypsum plates and rosettes occur within several millimetres of each other in the section (Figure 27). The carbonates within these units show even more eclectic textures and structures (Figure 22). These range from finely crystalline buff (10YR5/1) dolomite cemented laminae to calcite-coated plant fragments and fine algal filaments. In addition, these units commonly contain intraclasts of carbonate material. The very fine-grained aragonite laminae which are characteristic of Units 3 and 5 are rare.

The predominant minerals in Units 2 and 4 are disseminated aragonite, gypsum, dolomite and quartz. Some of the dolomite is actually a cation-disordered form of the mineral termed protodolomite.

Interpretation:

The rounded gypsum silt is interpreted as being primary gypsum undergoing dissolution, whereas the lensoid gypsum is a product of very early diagenesis. The variety of gypsum ocurrences is described in Section 4.4.2.

Carbonate intraclasts were probably partially consolidated before being ripped up by storm-derived currents or waves and redeposited. Protodolomite may be a penecontemporaneous alteration product of pre-existing calcium carbonate (see Section 4.4). Although the genesis of this dolomite in Waldsea Lake has not yet been fully resolved, both formative

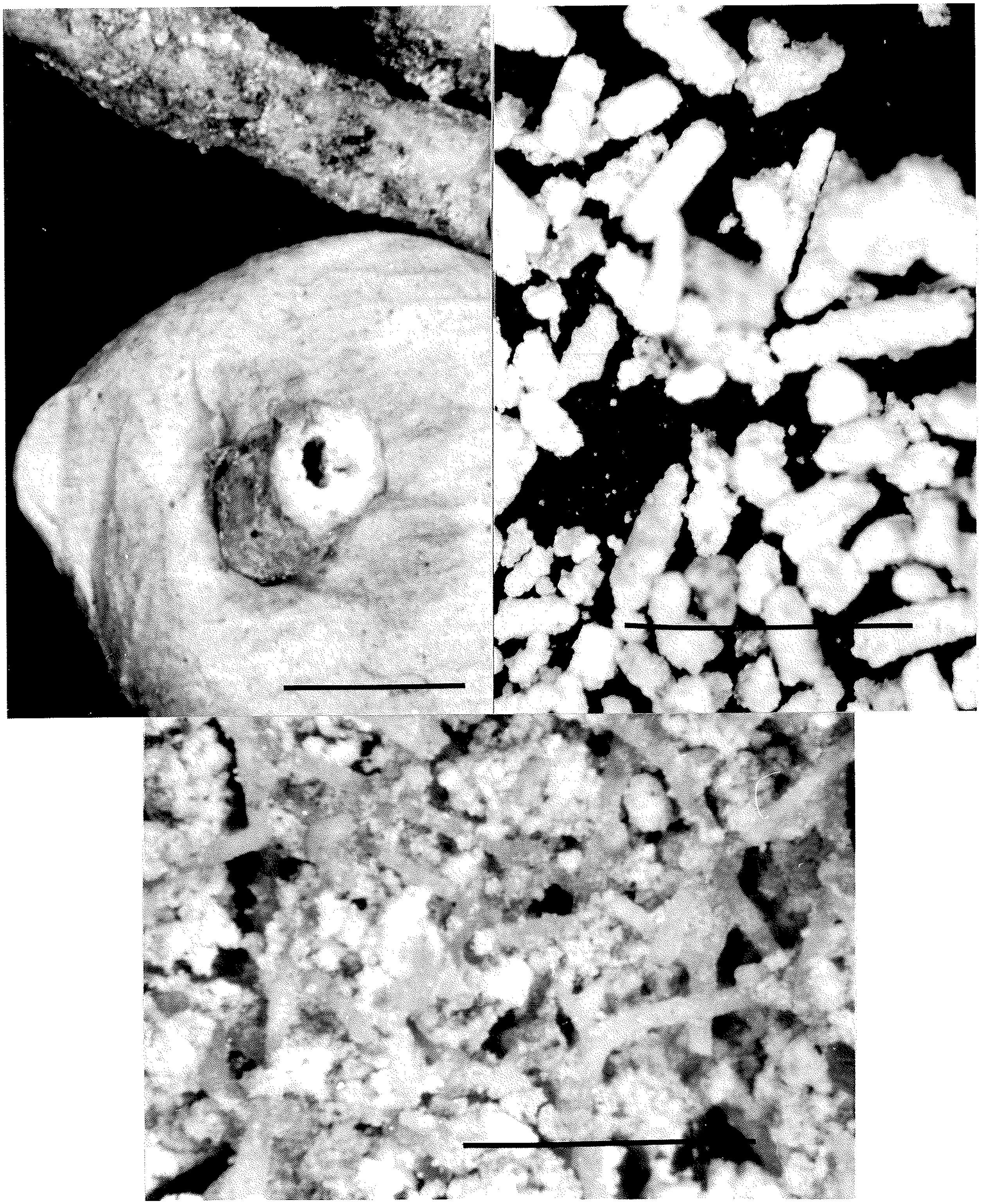

Figure 22: Textures and structures of carbonate occurrences in Units 2 and 4
These photographs show carbonate coated plant stems, a pelleted zone, and an unidentified carbonate structure. In each case, the scale bar is 5 mm.

modes (endogenic and authigenic[7]) imply elevated Mg:Ca ratios and possibly schizohaline[8] conditions.

Unit 2 may be, in part, time-correlative with Unit 1, as Unit 1 occurs only in the southern part of the lake, and both units appear to be overlain by Unit 3. The paleomorphometry interpreted from this (Figure 32) is complicated by isostatic rebound (see Section 3.1.6).

4.3.4 Units 3 and 5

Description:

Units 3 and 5 consist of dark brown to black, silty, aragonite-rich sapropel[9] to silty sapropelic mud with irregularly spaced, very fine-grained aragonite laminae (Figure 23). The colour of these laminae range from white

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[7] Authigenic materials (specifically inorganic) are those which are "formed or generated in place; specifically said of rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found, and of minerals that came into existence at the same time as, or subsequently to, the formation of the rock of which they consitute a part. The term, as used, often refers to a mineral . . . formed after deposition of the original sediment." (Bates and Jackson, 1980). The term is used in this context even though the sediments have not been lithified.

[8] "Said of an environment characterized by extreme variation from hypersaline to brackish or fresh conditions" (Bates and Jackson, 1980).

[9] The word "sapropel" is used to describe the organic rich sediments of Units 3 and 5. The actual definition of sapropel is "an unconsolidated, jelly-like ooze or sludge composed of plant remains, most often algae, macerating and putrefying in an anaerobic environment on the shallow bottoms of lakes and seas" (Bates and Jackson, 1980). The organic component of these units is probably predominantly bacterial in its source. The term sapropelic is defined

(7.5YR8/8) to buff (10YR5/1) with some showing a distinct red (5R5/6) colouration.

Interpretation:

This latter colour is attributed to organic pigments, such as carotenoids and chlorophylls, sedimented with or immediately before or after the aragonite precipitation.

4.4 ENDOGENIC MINERAL PHASES

4.4.1 The Carbonates

There are six main carbonate phases in the Waldsea Lake sediments which are identifiable by X-ray diffraction. These include:

1. Aragonite
2. High-Mg Calcite
3. Low-Mg Calcite
4. Dolomite
5. Protodolomite (non-stoichiometric and poorly ordered).
6. Magnesite

Dolomite which is stoichiometric and ordered, and low-magnesium calcite are the only carbonate phases which have been identified in the tills of the region (Meneley, 1964). Therefore the occurrence of other carbonate minerals in the lake sediments indicates that they are endogenic or

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as "pertaining to or derived from sapropel; indicating a high sulfate or reducing environment".

authigenic.

4.4.1.1 Aragonite

Occurrence:

Aragonite is the most abundant carbonate mineral in Waldsea Lake sediments (up to 60% of the sediment mass). It occurs as fine-grained (20 X 5 X 5 μm) crystals both disseminated and concentrated in laminae up to 1.5 mm in thickness (Figure 23; Frontispiece).

Interpretation:

These laminae are abundant in the upper metre of sediments, and are likely the products of mass nucleation and inorganic precipitation events ("whitings"). These events are known to occur in other lakes (both fresh and saline), but the precipitates are usually calcite rather than aragonite.

Spontaneous nucleation and precipitation of the calcium carbonate may take place because of:

1. supersaturation of a specific mineral phase due to biological CO_2 uptake and consequent increase in pH (Kelts and Hsü, 1978),
2. supersaturation caused by increase in pH or concentration due to evaporation or dilution (Krumgalz, 1977),
3. supersaturation due to temperature change (Brunskill, 1969),

4. supersaturation due to mixing of two water bodies with differing chemistries (Raup, 1982).

In Waldsea Lake, any one of these mechanisms could be responsible for whiting events, but none have ever been documented in process.

Several mechanisms have been suggested by which aragonite may form preferentially rather than calcite by inorganic precipitation. These include:

1. inhibition of calcite nucleation and/or precipitation by the presence of organic acids or cations (such as Sr^{2+} or Mg^{2+}) which are preferrentially adsorbed to crystal surfaces (Bathurst, 1979; Jackson and Bischoff, 1971);
2. availability of seed crystals (deBoer, 1977b);
3. Mg^{2+} and the Mg/Ca ratio (Müller et al., 1972; Folk and Land, 1975; Müller, 1971; Katz, 1973; Berner, 1975; deBoer, 1977a,b).

Müller et al. (1972) suggested an empirical relationship between Mg:Ca ratios of a solution and mol% Mg within the primary carbonate minerals precipitated from that solution (Table 12).

Waldsea Lake water currently varies in molar Mg:Ca ratio from about 10 to 25 (Table 5), making aragonite the most likely carbonate phase to be precipitated.

Several mechanisms may be suggested to explain the presence of the disseminated aragonite. These are:

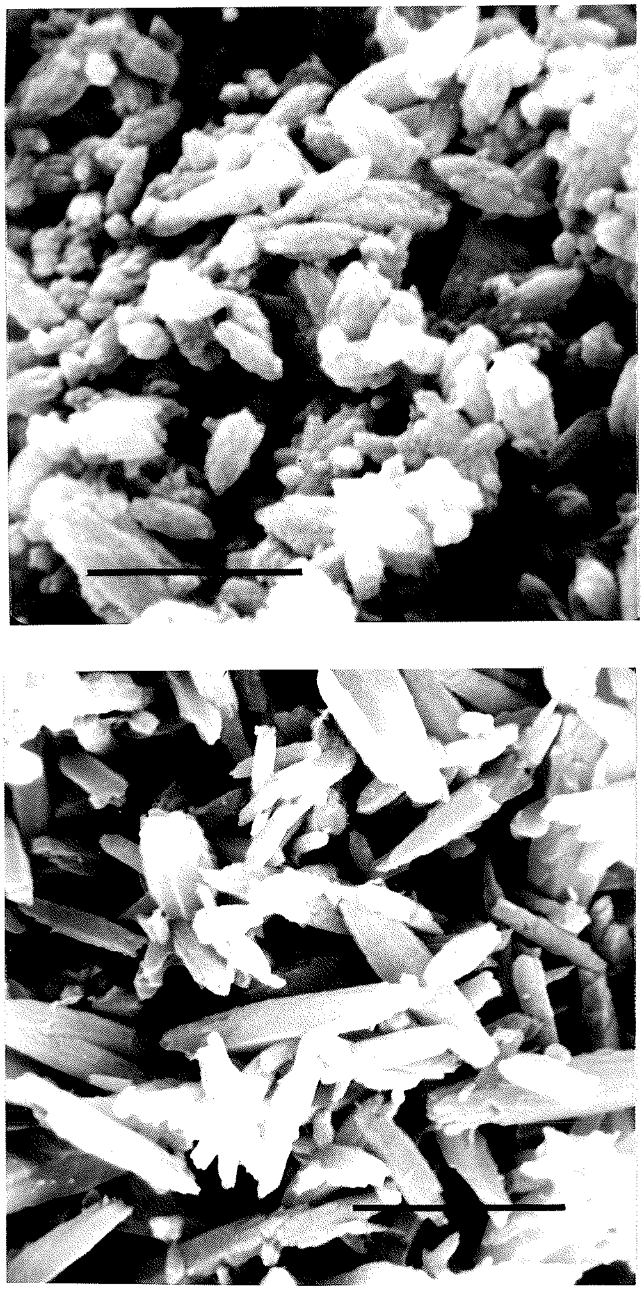

Figure 23: Scanning Electron Micrograph of aragonite crystals from Waldsea Lake
Scale bar represents 20μm. Upper photograph shows dissolution features.

TABLE 12

Primary minerals vs. Mg:Ca ratios

(After Müller et al., 1972)

Mg/Ca	Primary Precipitate	Sediments
<2	Calcite	Calcite
2-12	Mg Calcite, Aragonite	Dolomite, Mg Calcite
>12+	Aragonite	Aragonite

1. Continuous supersaturation of the water column with respect to aragonite and consequent 'rain' of small crystals.
2. Bioturbation on an extremely fine scale, which could mix minor amounts of aragonite from the distinct laminae without destroying the fine structures.
3. Mixing of sediment rich in aragonite on the upper slopes of the lake bottom by wave action, and remobilizing and dispersing the sediment by turbidity currents.

Long term field studies would be required to substantiate which of these processes would be most likely.

4.4.1.2 Calcite

Occurrence:

Low-Mg calcite makes up about 8% of the sediment. Meneley (1964) reported that the tills of the area range from 5 to 15% calcite.

Interpretation:

Previous work (Kelts and Hsü, 1978; Folk and Land, 1975) indicates that the magnesium content of calcium carbonates will be related to the magnesium content of the solution from which they are precipitated. Therefore, the low-Mg calcite content which is found in the lake sediment is probably all allogenic.[10]

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[10] Allogenic in this sense is "formed or generated else-

4.4.1.3 Magnesian Calcite

Occurrence:

Magnesian calcite (High-Mg calcite) contains more than 7 mol% $MgCO_3$ in solid solution with calcium carbonate (Kelts and Hsü, 1978; Goldsmith et al., 1955). It is found in greatest abundance in Waldsea Lake below the upper metre of sediment and disseminated in very minor amounts above this.

Interpretation:

As discussed above, the presence of elevated levels of Mg in calcite implies that the Mg:Ca ratio during its formation (either by endogenic precipitation or authigenesis) was less than about 12. Because the magnesian calcite does not occur in distinct laminae, it is interpreted to be primarily authigenic (possibly from the recrystallization of aragonite).

4.4.1.4 Protodolomite

Occurrrence:

Protodolomite, or nonstoichiometric disordered dolomite occurs throughout the sediment, though concentrations in the uppermost metre are minor. Its X-ray diffraction peaks

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where, usually at a distant place; specifically said of rock constituents and minerals that were derived from pre-existing rocks and transported to their present depositional site, or that came into existence before the rock of which they now constitute a part and at some place other than where now found" (Bates and Jackson, 1980).

are short and stubby (Figure 24). The average of six protodolomites from Waldsea Lake sediments is 34.8 mol% $MgCO_3$ (66.2 mol% $CaCO_3$, range 32.0-38.5 mol% $MgCO_3$).

Interpretation:

Graf and Goldsmith (1958), and Goldsmith et al.(1955) describe the various occurrences and properties of both natural and synthetic protodolomite. Müller et al. (1972) defines protodolomite as a disordered carbonate mineral with compositions ranging from $Ca_{0.7}Mg_{0.3}CO_3$ to $Ca_{0.45}Mg_{0.55}CO_3$.

A possible explanation of this extreme non-stoichiometry may lie in the experimentation of Müller and Fischbeck (1973). They synthesized an amorphous Ca-Mg-carbonate gel of approximate dolomite stoichiometry by freeze-drying carbonate-bicarbonate solutions. They also suggested that subsequent wetting and drying of this material might allow it to crystallize. This mechanism may have been (or still may be) at work in the saline lakes during annual freezing cycles (Egan, 1984; Last, 1984).

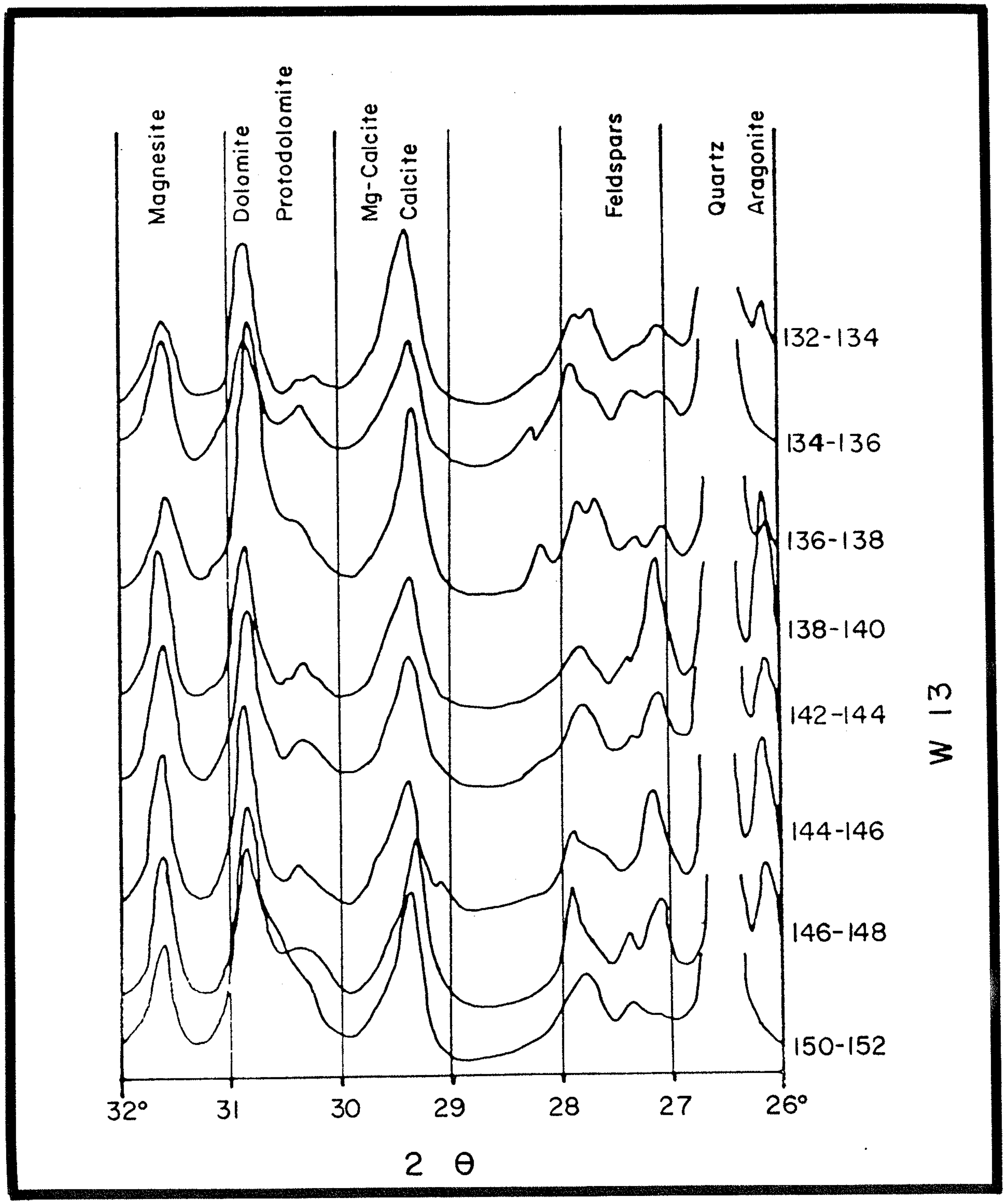


Figure 24: Selected detailed X-ray diffractograms of the carbonates

4.4.1.5 Dolomite

Occurrence:

The amount of dolomite in Waldsea Lake sediments ranges from 20 to 35%. It occurs as both finely disseminated and cemented horizons.

Interpretation:

Christiansen (1979) found a mean value of 10% dolomite and 4% calcite in the tills of the Saskatoon area; Meneley (1964) found slightly higher values of both dolomite and calcite in the tills of the Melfort Region.

Despite the likely detrital origin of most of the dolomite in the sediment, the occurrence of horizons cemented by stoichiometric ordered dolomite is unequivocal evidence of its very early authigenesis or primary precipitation. The dolomite in these horizons consists of poorly-formed equant crystals or clusters of fine crystals (Figure 25). The early diagenetic dolomite-cemented laminae occur in Unit 2 (Figure 26).

Alderman (1965) and vonderBorch (1976) found stoichiometric dolomite in the modern sediment of the Coorong (Australia), along with protodolomite, aragonite, magnesite, and hydromagnesite. They attributed the occurrence of the different mineral species to the difference in Mg:Ca ratio and pH of the environments. Stoichiometric, ordered dolomite occurred at higher values of pH and Mg:Ca ratio. Such a mechanism likely occurs in the Waldsea sediments as well.

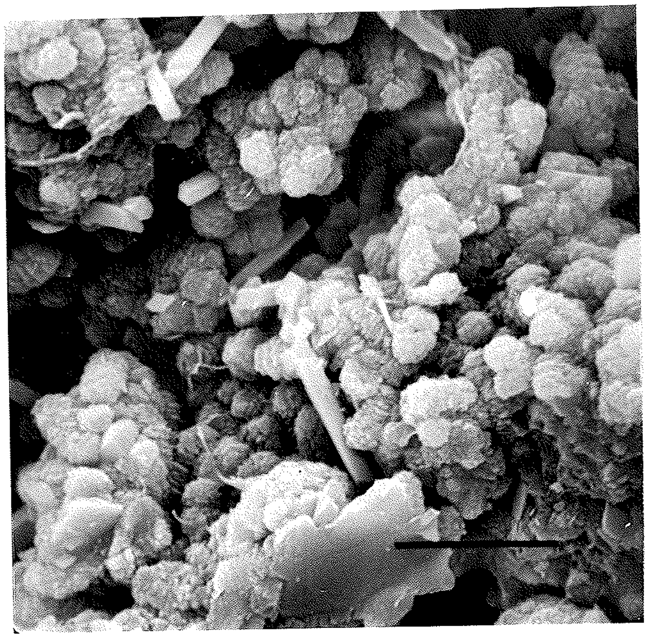


Figure 25: Dolomite crystals in Waldsea Lake cemented laminae
Acicular crystals have not been identified.
Scale bar is 5μm.

List of Symbols

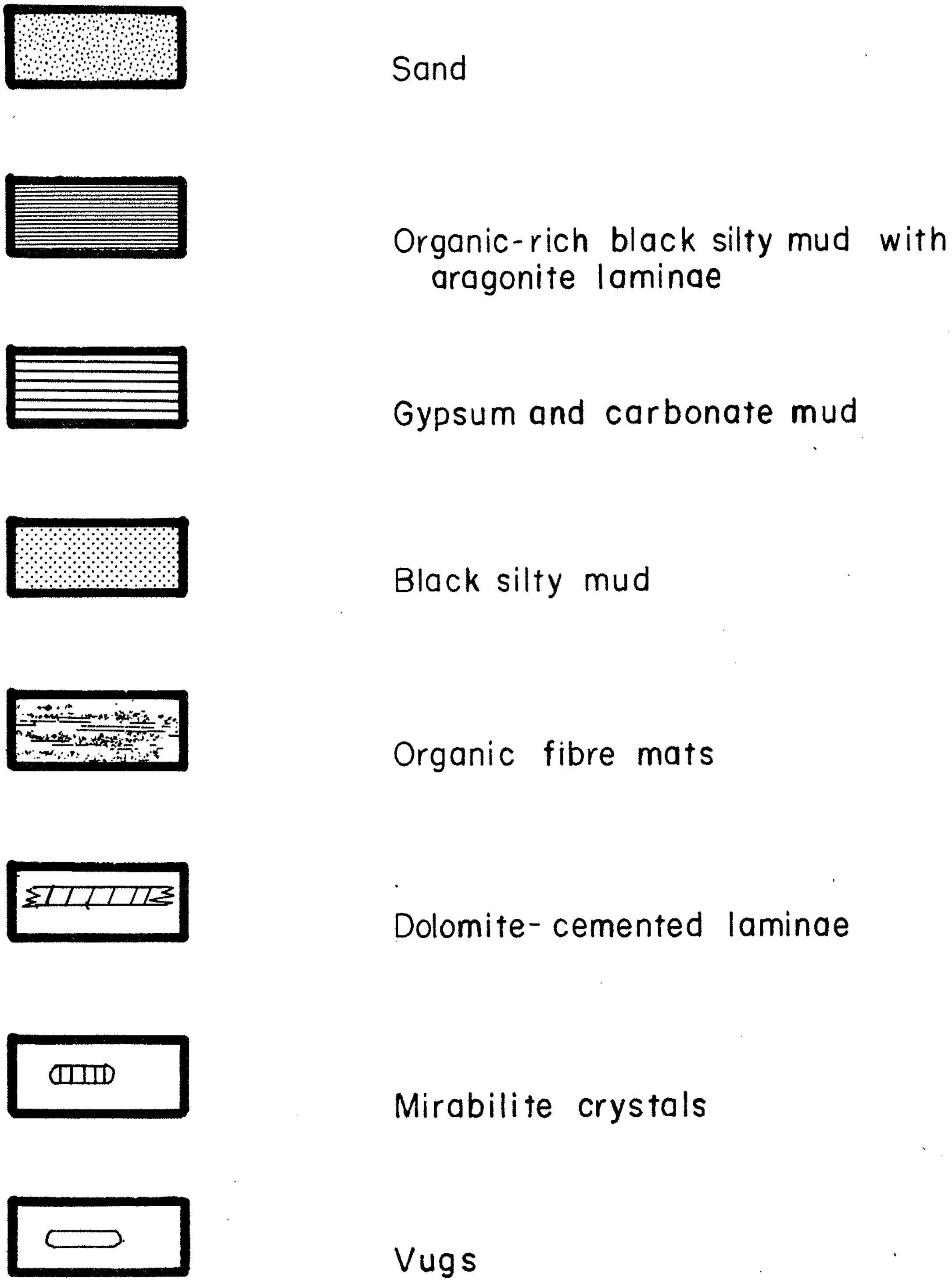
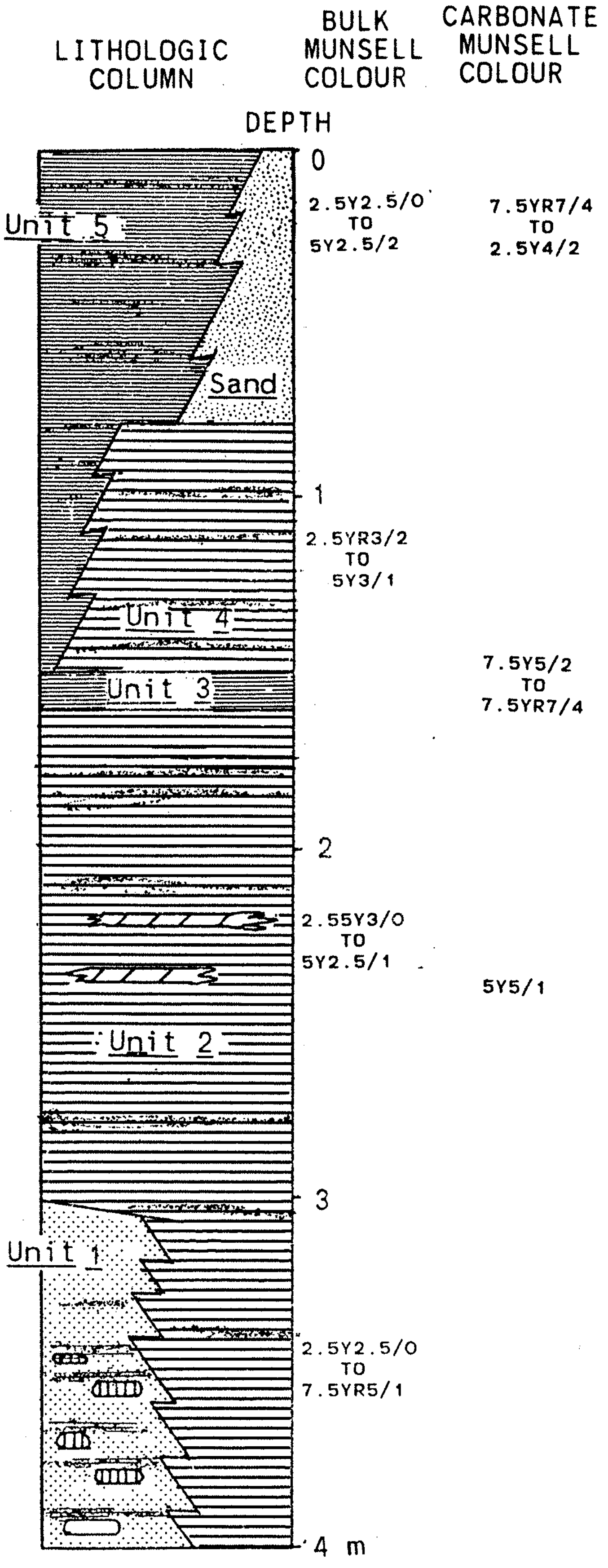


Figure 26: Composite stratigraphic column for Waldsea Lake



COMPOSITE DESCRIPTION

Unit 5: Black to brown silty organic-rich clay to sapropel. Quartz sand and silt grains abundant. Occasional ostracods (Cypridineae ?); generally concentrated in laminae. Aragonite laminae are abundant (some with pink or orange pigments); thin sand laminae found interspersed. Numerous organic fibres of various types.

Sand: Quartz, feldspars, and carbonate clasts predominate, but some mafic minerals and rock fragments are present. Pebbly in part (carbonate pebbles show reduction staining). Most clasts are coarse sand, some frosting is evident. Grades upward.

Unit 4: Brown to green silty clay and clayey silt. Few aragonite laminae, but overall laminated. Ostracods (as above), in laminae. Fibre mats (Ruppia-Potamogeton?) gypsum silt laminae composed of rounded crystals, 0.25-0.5 mm diameter.

Unit 3: Black to brown silty organic-rich clay with aragonite laminae as above. Ranges from 7 to 28 visible aragonite laminae, each approximately 0.5-1.0 mm thick.

Unit 2: Dark green to dark grey silty carbonate- and gypsum-rich clay. Laminae of gypsum (both as above and as lensoidal crystals 0.5-2.0 mm diameter, some as rosettes or twins) abundant. Algal fibres in mats (Rhizoclonium ?) carbonate intraclasts in some zones, and dolomite-cemented laminae occur. Ostracods occur in laminae. Some thin zones appear granular; some carbonate laminae are pelleted.

Unit 1: Black silty clay, coarsely laminated. Gypsum silt, gypsum lensoidal crystals occur in laminations. Artemia oogonia are concentrated in some laminae; ostracods are also concentrated, predominantly under the abundant organic fibre mats. Clear mirabilite crystals in the middle of the unit; At the base of the section, vugs the size of these crystals occur (approximately 2 cm X 2 cm X 1 cm).

4.4.1.6 Magnesite

Occurrence and Interpretation:

Magnesite occurs in small amounts in Waldsea Lake sediments, but has not yet been quantified. Its origin is not known.

4.4.2 The Sulfates

Two sulfate minerals have been identified in Waldsea Lake sediments: gypsum and mirabilite. Both occur macroscopically; gypsum also occurs microscopically.

4.4.2.1 Gypsum

Occurrence:

Last and Schweyen (1983) describe the occurrence of gypsum in the sediments (Table 13). Three main types of gypsum crystals are found.

Interpretation:

Crystal habit and size is thought to be dependent upon specific physical and chemical conditions.

4.4.2.2 Lensoidal Gypsum

Cody (1979), Barcellona and Atwood (1978,1979), and Edinger (1973) discuss the interactions of gypsum crystal growth mechanisms and available organic components to form lensoidal gypsum crystals. They found that certain organic compounds (specifically organic acids) were preferentially

TABLE 13

Gypsum occurrences in Waldsea Lake sediments

(from Last and Schweyen, 1983)

BEDDED GYPSUM

Pure or mixed with carbonates, quartz

Beds 0.5-4 mm thick

Composed of

a. Platy or lensoid crystals	0.005-1 mm diameter
b. Equant crystals	0.01-0.06 mm
c. Rounded grains	0.05-0.5 mm

INTRASEDIMENTARY

Macroscopic; isolated euhedral crystals up to 0.5 mm

Microscopic, disseminated.

adsorbed onto some of the crystal faces, effectively inhibiting crystal growth in that specific direction. These gypsum crystals occur as diagenetic products rather than as primary precipitates.

Waldsea Lake sediments are organic rich; the intimate association of organic material with the gypsum lenses in some of the sediment is very similar to those described by Krumbein et al. (1977) and Arakel (1980). Shallow water evaporitic conditions are conducive to algal or microbial mat growth. The crystals formed under these conditions tend to be lensoidal because of the inhibition of growth in the C-axis direction caused by organic compounds adsorbed on specific crystallographic planes (Cody, 1979; Barcelona and Atwood, 1978,1979; Edinger, 1973).

Though a few laminae of lensoidal gypsum crystals have been found in the sediments, most of the crystals are disseminated, suggesting diagenetic growth. The pore water of the sediments is likely near saturation with respect to gypsum, as shown by growth of 2 to 3 mm lensoidal gypsum crystals on the outside of the cores after a month or so of slow drying. Diagenetic crystal growth may also have occurred during lower water phases of the lake.

4.4.2.3 Equant Crystals

Equant crystals are rare, and may indicate growth at the sediment-water interface or precipitation at the air-water interface and sinking as shown by Teller et al. (1982) in Lake Tyrrell, Australia.

4.4.2.4 Rounded Grains

Rounded gypsum grains are probably produced by one of three processes:

1. Abrasion. Abraded gypsum crystals have been described in Australian dry lakes (Teller et al., 1982; Bowler, 1981) and also have been identified in shallow hypersaline lakes of the northern Great Plains (Lockhart, 1983; Last, pers. comm.). Two processes are thought to be associated with abrasion--wind and water reworking. Concentrations of abraded lensoid gypsum crystals 1 to 4 mm in diameter have been found at Patience Lake (approximately 50 km west) washed into shoreline sediments approximately 25 cm above current water levels.
2. Biological action. Teller et al. (1982) describe the destruction of primary gypsum crystals sedimented in Lake Tyrrell, Australia, by *Desulfovibrio desulfuricans*, a sulfate-reducing bacterium. This process did not likely occur on a large scale throughout deposition of Waldsea Lake sediment because much gypsum is preserved. This would indicate that either conditions were not suitable for *Desulfovibrio* or that the species is not present.

3. Dissolution. Berner (1980) describes two types of morphologies of surfaces undergoing dissolution based on the kinetics of the processes involved. The first, transport-controlled dissolution, generally rounds the grains involved as the dissolution is not confined to molecular dislocations. The second is surface-reaction controlled dissolution; it generally creates angular, crystallographically-controlled surfaces by etching. Berner (1980) also lists gypsum as a substance which will dissolve via transport-controlled dissolution.

In view of the remnant morphology and grain size (Figure 27), the pitted, rounded gypsum found in the sediments of Waldsea Lake was probably precipitated at or near the sediment-water interface and was later partially dissolved by undersaturated waters, either within the sediment or under schizohaline conditions at the surface. Some of the material may also have been reworked and abraded by either water (by swash) or wind (during low water levels).

4.4.2.5 Mirabilite

Occurrence:

The other sulfate mineral identified in the sediment cores is mirabilite ($Na_2SO_4 \cdot 10\ H_2O$). It occurs in the lowermost sediment and has been identified in only three of the cores. The crystals of mirabilite are relatively large (2

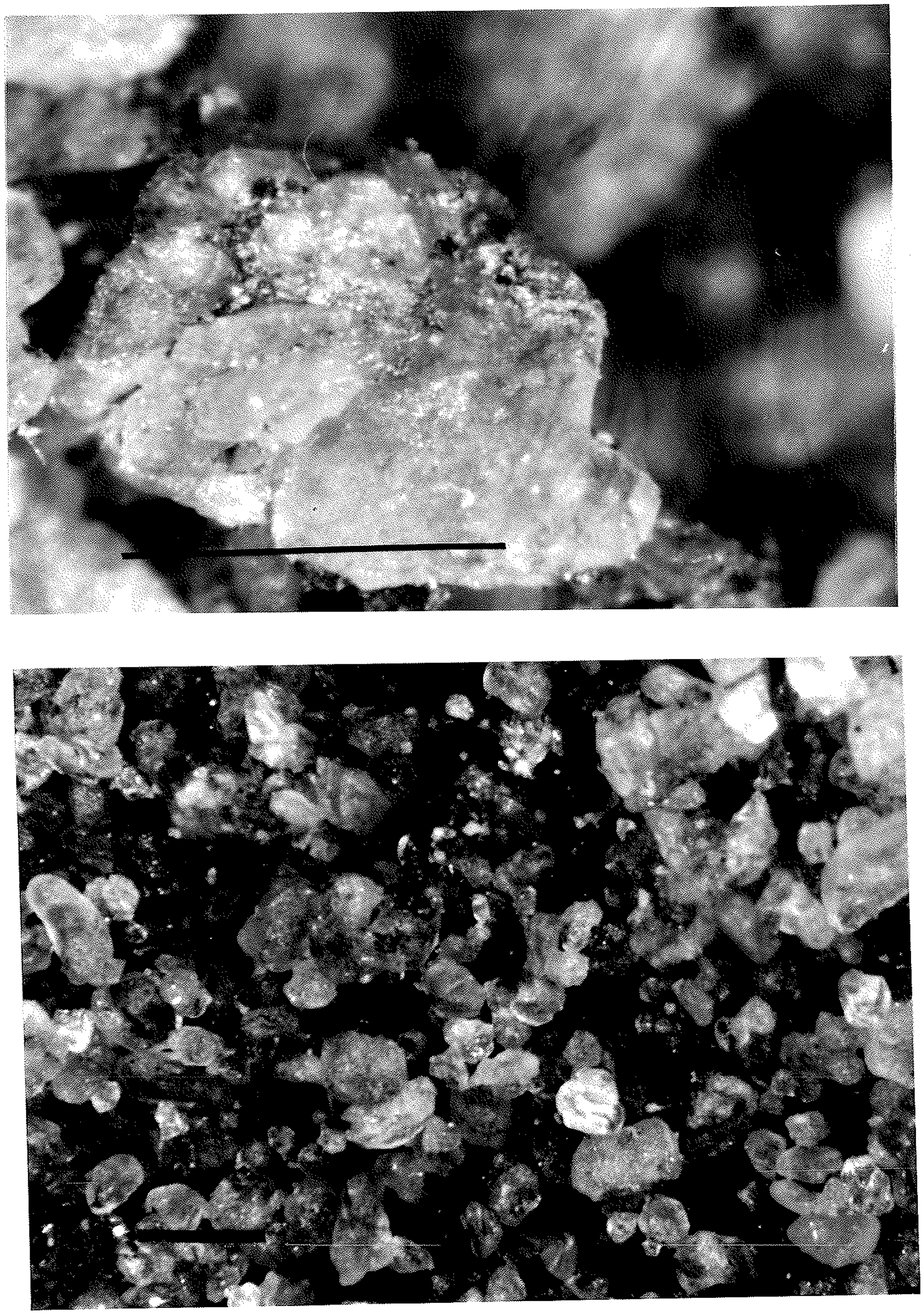


Figure 27: Gypsum crystal morphologies in Waldsea Lake sediments
Upper photograph shows lensoidal crystals and rosettes; lower photograph shows rounded gypsum silt. Scale bars are each 2 mm.

cm X 2 cm X 1 cm) and generally have rounded outer surfaces (Figure 28). All of the crystals are clear; some have very minor mud inclusions, green algal filaments and/or spherical gas bubble inclusions. They generally occur in direct association with organic fibre mats.

Interpretation:

The occurrence of mirabilite in Unit 1 probably indicates hypersaline conditions during their formation.

Figure 28: Mirabilite crystals from Waldsea Lake
Scale is in mm.

4.5 SULFIDES

4.5.1 Pyrite

Occurrence:

Pyrite is the only sulfide mineral that has been positively identified in the sediment by X-ray diffraction methods. It is absent from the upper metre of sediment, and present in small amounts (<5%) below that. It has not been identified in the soils or tills of the drainage basin.

Interpretation:

The occurrence of pyrite indicates that:

1. there was a source of iron and sulfur available,
2. reducing conditions were prevalent, and
3. burial conditions have allowed it to be preserved.

Though the source of iron has not been suggested, reducing conditions are currently found in nearly all of the basinal sediments. It is likely that the pyrite is very early diagenetic in nature (Teller et al., 1982).

4.5.2 Sulfur

Occurrence:

X-ray diffraction analysis indicates that orthorhombic sulfur is found in some of the sediment in small amounts.

Interpretation:

Chlorobium has been described as being able to deposit sulfur intracellularly (Lawrence, 1978; Pfennig, 1977). It is likely that much bacterial organic matter is sedimented upon death, and the sulfur granules are sedimented as well.

4.5.3 Organic Sediments

The organic material is derived from within the lake and from outside sources. Fragments and pollen of agricultural plants, wild grasses and flowers may be washed or blown into the lake.

The nature and amount of organic sediment vary dramatically throughout the cores. Most of the younger sediment contains only extremely fine-grained organic matter, possibly of bacterial and algal origin. The organic content of this sediment ranges from about 15 to 35%.

The sediment also contains abundant dispersed plant fragments (see core descriptions in Appendix D). Some of these plant fragment fibre mats are shown in Figure 29. These mats are similar in nature to those found forming along the shoreline of Dana Salt Lake, approximately 30 km southwest of Waldsea Lake (Figure 29), and likely indicate similar chemical and biological conditions.

Figure 29: Organic fibre mats from Waldsea Lake sediments and Dana Salt Lake shoreline.
Scale on upper photo is 5mm.

4.6 RADIOCARBON DATES AND SEDIMENTATION RATES

Four radiocarbon dates of the organic fibre-rich sediments were used to estimate ages of the sediment units as well as interval sedimentation rates. Table 14 gives the estimates for the ages. Figure 30 shows the interval sedimentation rates (between radiocarbon samples) and sediment deposition versus time. Sedimentation rates were calculated on the basis of a four metre continuous core (i.e. assuming no overlap of core segments). These rates are expressed in terms of thickness of wet sediment deposited per year.

The changes in sedimentation rates most probably reflect changes in the relative predominance of the processes which transport or create the sediment. The total amount of sedimented material for any given year is related by the equation:

$$S_{total} = S_{wind} + S_{water} + S_{precip} + S_{organic} - S_{loss}$$

where:

S_{total} is the total amount of sediment deposited,

S_{wind} is the amount of sediment blown into the lake,

S_{water} is the amount of sediment washed in,

S_{precip} is the amount of endogenic inorganic material,

$S_{organic}$ is the total amount of organic sediment,

S_{loss} is the total amount of sediment lost by erosion.

TABLE 14

Radiocarbon Ages of Waldsea Lake sediment

Sample	Age (YBP)	Depth (cm)	Stratigraphic Unit
1	1230±50	80-90	5
2	2340±70	190-199	4
3	2920±70	283.5-290	2
4	3970±90	375-390	1

Samples taken from Core 83W8

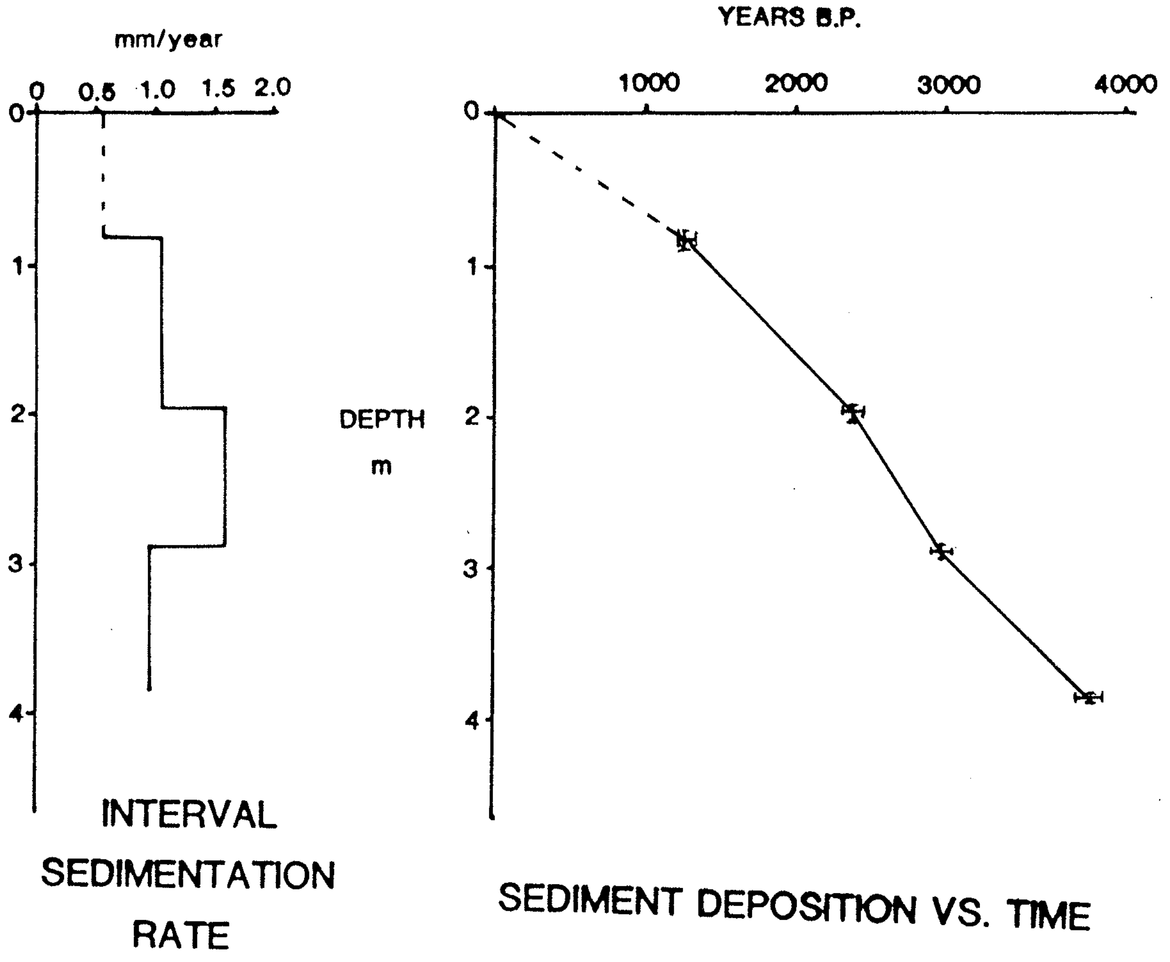


Figure 30: Sedimentation rate in Waldsea Lake sediments

The calculation of sedimentation rates based solely on the thickness of sediment between dated samples in a core may lead to the misinterpretation of the actual processes and conditions which produce the sediment record. In relatively small lakes, sedimentation rates vary from place to place within the lake due to the process of "sediment focussing" (Likens and Davis, 1975; Davis and Ford, 1982). This process produces thicker sediment (and consequently greater interpreted sedimentation rates) in the deeper portions of the basin relative to rates calculated for more peripheral areas. This effect is shown in Waldsea Lake's Unit 3, where a thickness of 10 cm in the peripheral areas of the lake is in contrast to twice that in the deepest portion of the basin.

Other problems may result from too rigorous an application of interval sedimentation rates. In Waldsea Lake sediments, for example, the sedimentation rates appear to be relatively high between 4000 years ago and 3000 B.P. and then lower until the present. This does not necessarily relate to the actual change in the amount of sediment being transported to the lake and deposited. Compaction of the sediments after deposition has decreased water contents from an average of 70% (observed in the surface sediments) to less than 40% (at 3 to 4 metres depth in the sediment in Unit 1); this compaction should be taken into account in rate calculations. Along with this, lake levels and area have changed with time. Consequently, if the same sediment load is delivered to the lake each year, that amount of sediment must be "spread out" when the lake level is high and the bottom surface area is large. When the lake was small (for example, 25% of its current area), sedimentation rates could appear to be 4 times that of today with the same amount of annual sediment.

Other factors may also influence sedimentation rates. An increase in the frequency of inorganic precipitation could increase overall sedimentation rates, though actual allogenic input may have decreased during that time. The upper metre of sediment contains 10 to 15% millimetre-thick aragonite laminae; this, plus the disseminated aragonite can make up 45% or more of the total dry sediment mass (Figure 20).

Wind is also an important contributor of sediment to Waldsea Lake. Much of the lake sediment could be transported by wind. Schweyen and Last (1983) reported dust storms in the Waldsea Lake basin which would contribute silt- and clay-sized sediment to the lake. This process would be active all year long. The lake is covered with ice during most of the winter, but still receives a large amount of blown-in sediment (Figure 31).

Other chemical sediments cannot be easily included in the sedimentation rate. Soluble salts, such as mirabilite, which had to have been precipitated when the lake was at

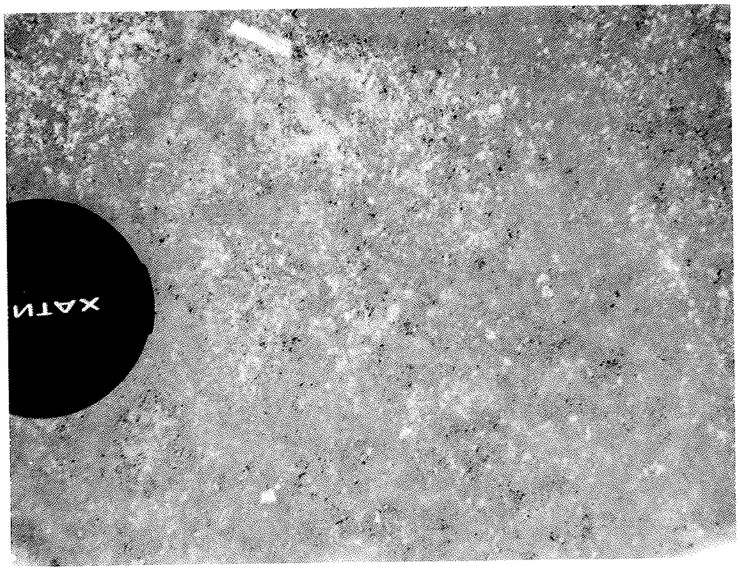


Figure 31: Windblown sediment in Waldsea Lake ice Lens cap is approximately 40 mm diameter.

lower levels, have been dissolved and added to the lake during its "freshening". This may have at one time produced a "negative" sedimentation rate by actually decreasing the thickness of sediments.

4.7 STRATIGRAPHIC INTERPRETATION

Units 1 and 2 were probably deposited contemporaneously as separate facies of a small hypersaline lake with broad mudflats between about 4000 and 2800 YBP. Unit 1 sediment, a reduced, non-laminated silty mud has numerous fibre mats, which, for the most part, are similar in nature (and probably in origin) to those found in other small hypersaline lakes in the area today, and, as such, is named the "mirabilite facies". Mirabilite crystals which are associated with this sediment also indicate hypersaline conditions. As contemporaneous facies, Units 1 and 2 became intercalated as minor fluctuations in lake level occurred. A maximum of 1 m of sediment has been recovered from Unit 1 by Livingstone coring, but this unit may be considerably thicker.

Unit 2, on the other hand, has been measured to be 2 m thick; this measurement may be anomalous due to overlap in core sections. Unit 2 overlies Unit 1 in several cores, but whether Unit 1 is completely covered by Unit 2 or this is just a function of the intercalation is not clear.

The deposition of the gypsum-carbonate sediments of Units 2 and 4 (in the "mudflat facies") probably occurred on broad hypersaline mudflats (Figure 32). Evidence for this interpretation includes the relatively extensive evaporitic and carbonate features. Intermittent inundation and evaporation along with freezing and runoff (perhaps on an annual basis) provided schizohaline conditions under which precipitation and diagenesis of the carbonate and sulfate minerals could occur. This very early diagenesis includes cementation of some carbonate laminae by dolomite, and also some gypsum dissolution and/or precipitation. Further diagenesis (partial dissolution of mineral phases, oxidation of organic phases with reduction of inorganic chemical species, bacterial reduction of sulfate, etc.) is also recorded in the sediment.

The deep water units, 3 and 5, were probably deposited under conditions similar to that of today's lake. These units are notable in the abundance of the irregularly-spaced aragonite laminae (see Frontispiece). These laminae have been interpreted to represent acyclic inorganic precipitation by chemical supersaturation of the lakewater. This supersaturation could occur by a variety of means (see Section 4.4) including evaporation, dilution, biological uptake of CO_2, heating of the water column, freeze concentration, or overturn of a chemically or thermally stratified water column.

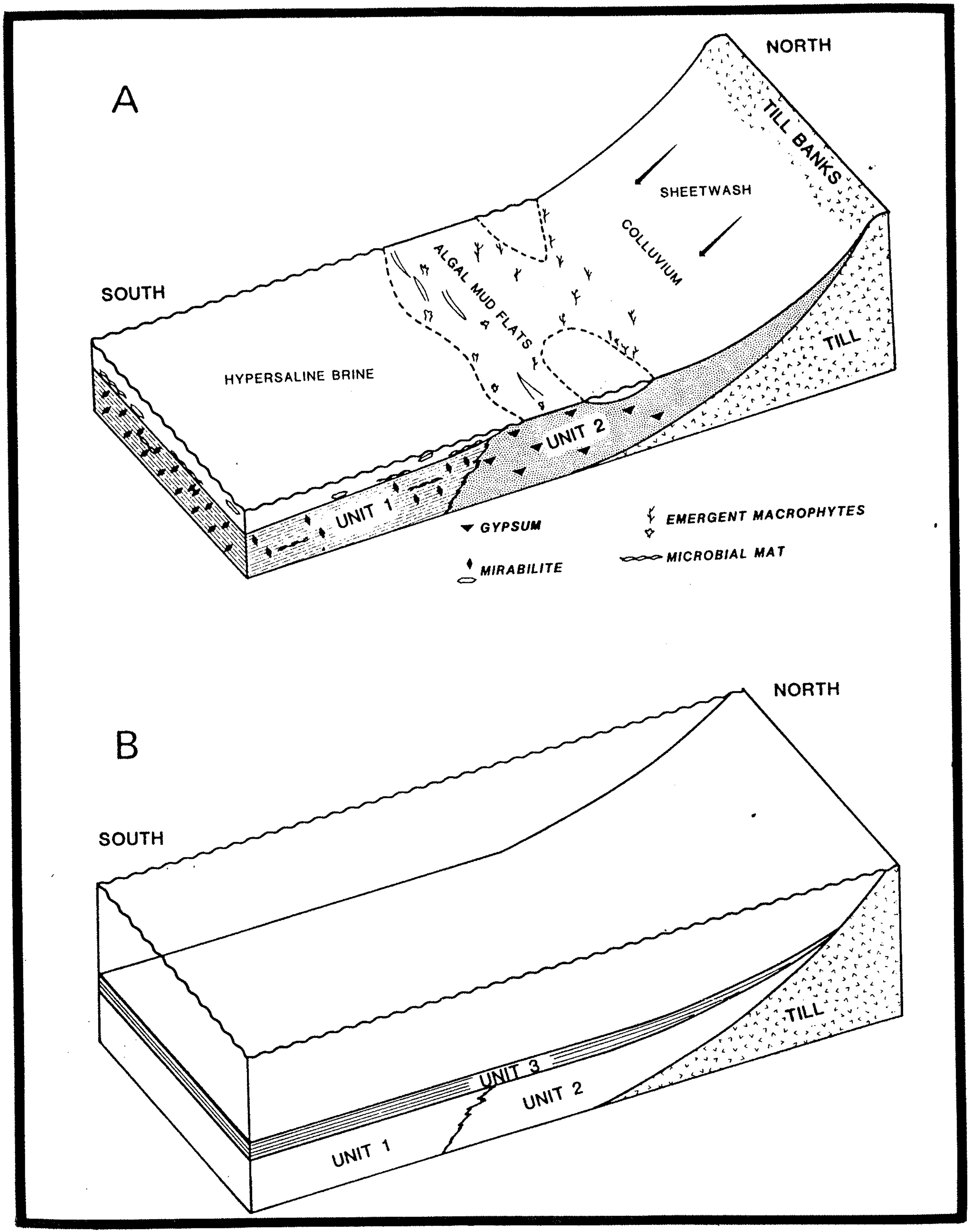


Figure 32: Paleohydrologic model of the early sediment deposition

4.7.1 Paleohydrologic Interpretation

The paleohydrologic history of Waldsea Lake has been interpreted using the mineralogical, biological, and chemical parameters which have been measured on the specific cores previously discussed, and the gross sediment character of the cores which were not analyzed in detail. This model of the variation in lake level in time is also based on aerial extent and distribution of the stratigraphic units as indicated by coring. Figure 33 shows this qualitative curve.

The low lake level at the bottom of the curve is meant to indicate conditions which were hypersaline and capable of producing mirabilite, as found in many small hypersaline lakes in the region today. Since the oldest sediment which has been dated is only 4000 years old, a substantial portion of the post-Glacial lake sediment is not available for interpretation. It is assumed that, during the time between deglaciation and 4000 years before present, Waldsea Lake acquired much of its total solute content. This assumption is accompanied by another: that since then, Waldsea Lake's annual salt influx is minor.

The curve is drawn to indicate an increased lake level around 3300 YBP[11] to about 3100 YBP; this interpretation is based upon the occurrence and age of Unit 3. This unit is interpreted as having been deposited under relatively

---

[11] Years before present.

deep (and possibly intermittent temporary meromictic) conditions because of its similarity to the sediment deposited in Unit 5. The mineralogical and textural similarities of Units 2 and 4 is invoked to draw the curve back to the "Low" water levels to represent the time during which Unit 4 was deposited. The curve returns to the "High" level phase from about 2400 YBP to the present, because the lake is relatively deep at present, and the sediment deposited during this time is very similar in most respects to that which is being deposited today.

Waldsea Lake's paleohydrology can be compared graphically with that of Devil's Lake, North Dakota (Callender, 1968). Both lakes have a similar history of lake level changes over the last 4000 years (Figure 33), though more minor fluctuations during the last 1000 years have been interpreted for Devil's Lake. This is probably a function of minor climatic changes and their influence on the hydrology of the region.

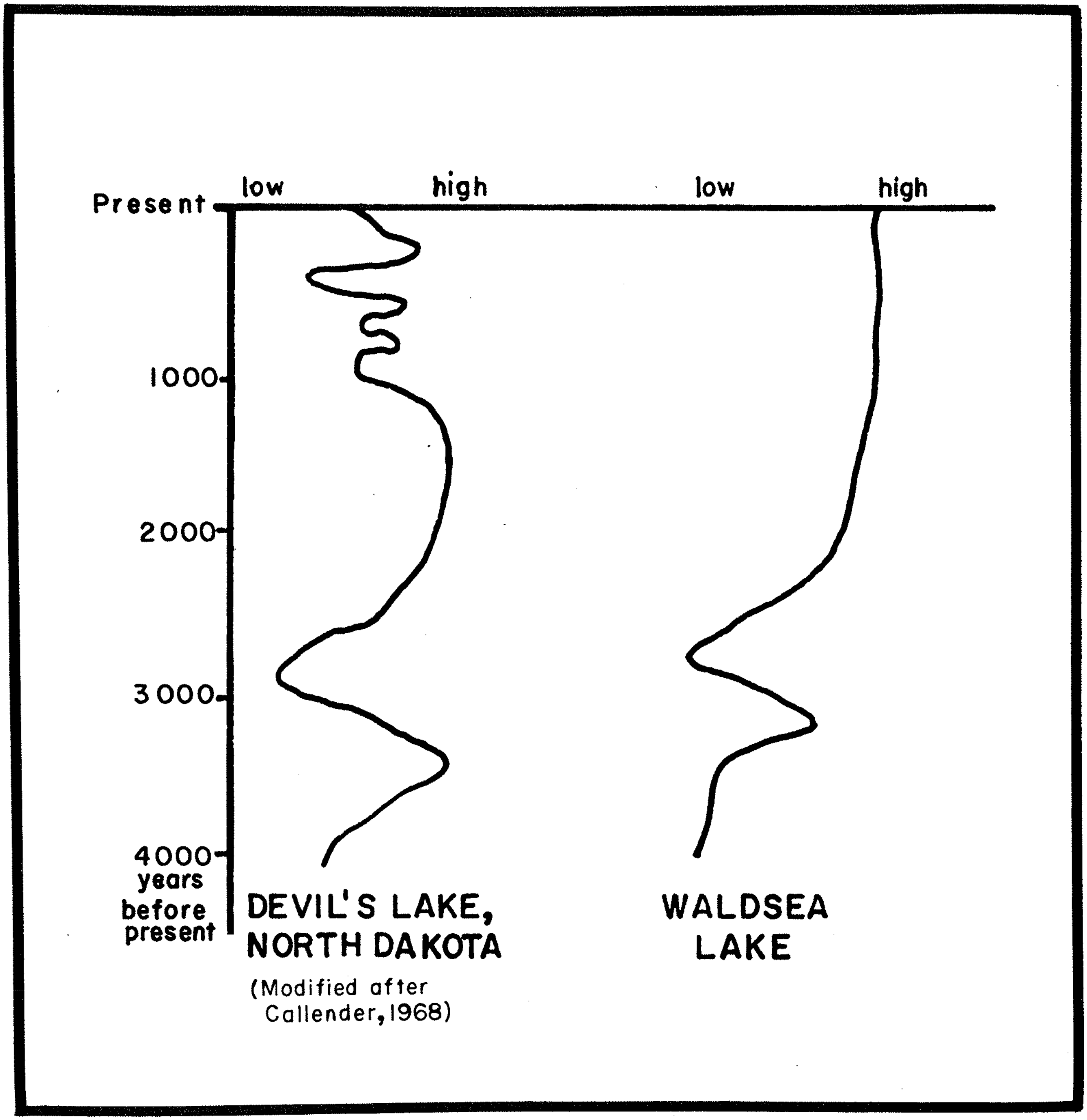


Figure 33: Comparative paleohydrology of Waldsea Lake and Devil's Lake, North Dakota (The Devil's Lake curve is modified from Callendar (1968).)

4.8 HISTORY AND PALEOCLIMATOLOGY

On the basis of the radiocarbon dates and palynology, the lowermost sediment recovered from Waldsea Lake was deposited at the end of the "Hypsithermal" (Altithermal, or thermal maximum). This time is the sub-Boreal episode of Wendland and Bryson (1974). The uppermost part of Unit 2 is near the boundary of the sub-Boreal and sub-Atlantic episodes, at about 2920 YBP. The change in depositional style (from a chemical sediment-dominated to a detrital-dominated system) probably reflects changes in temperature, evaporation conditions, and groundwater level.

In terms of trophic state, pre-sub-Atlantic Waldsea Lake was too hypersaline to support much biota, or at least not a diversified biota, as few biological remains have been preserved. During this time, the basin was probably floored by solid salts of sodium and magnesium sulfates (mirabilite, thenardite, bloedite, and epsomite) and possibly chlorides (NaCl), which were later dissolved and added to the lake brine. Most of the organic mats deposited in this sediment are allogenic in origin, likely being derived from plants surrounding the lake, as indicated by a relatively large proportion of plant fragments which were derived from grasses (T. Stevens, pers. comm.). The deposition of Unit 2 was probably occurring at the same time as Unit 1, with the lake area expanding and contracting in response to minor climatic variations. Carbonate and sulfate chemical sedimentation occurred as brine within the shallow lake evaporated and cooled annually. Rounded gypsum silt laminae in Units 1 and 2 likely represent rapid supersaturation of the brine with respect to gypsum by cooling, evaporation, or brine mixing.

Unit 3 represents a deepening of the lake, possibly at the end of the sub-Atlantic episode (approximately 2500 YBP.). A "colder, moister phase", based on the increase in Pinus and Picea pollen (Kroker, pers. comm.; Figure 21), allowed a substantial increase in lake level and attendant decrease in salinity. The presence of aragonite in laminae indicate a high Mg-Ca ratio (probably over 12:1, Müller, 1972), and the possibility of chemical stratification of the brine system. It is likely that this sediment was formed under similar conditions as those of the more recent sediments (discussed later).

The lake brine was probably nearly saturated with respect to the minerals in the "salt", and freshwater influx would easily create density stratification. Periods of mixing could form aragonite laminations by the process of brine mixing described by Raup (1982) or by evaporation. In either case, preservation of the laminated sediment was accomplished by an initial high salinity, and reducing conditions. These conditions decrease biological diversity and effectively eliminate bioturbators from the system. A similar situation has been described in the Black Sea (Degens and Stoffers, 1976). Virtually all of the aragonite seen in

SEM photos of Waldsea Lake sediments show dissolution features, which are likely due to intrasedimentary dissolution after deposition. This relatively cool period warmed (Kroker, pers. comm.), and the lake became shallower and more saline through increased evaporation.

Unit 4 (2300 to 1200 years B.P.) deposition has been interpreted on the basis of the similarity of the sediment to have been deposited under similar conditions to Unit 2. Since no present-day analogues have been found in Saskatchewan, a detailed definition of the chemical and physical conditions of the lake at that time is not possible. Paleolimnological investigation of the biological remains may offer more information. Once again, chemical sedimentation of sparingly-soluble mineral compounds increased, and very early diagenesis was accelerated. Protodolomite may have been formed by the recrystallization of aragonite under excess magnesium conditions, or possibly by the "freeze-dry" method proposed by Müller and Fischbeck (1973). Dolomite cementation could occur on the sediment surface or below, under schizohaline conditions caused by intermittent flooding and evaporation.

Unit 5 sedimentation began about 1200 YBP, near the end of the sub-Atlantic. Cooling and a decrease in evaporation coupled with an elevating groundwater table caused an increase in lake level, and a return to the sedimentation pattern of Unit 3. Salinity decreased as lake levels rose due to freshening of the brine by mixing of fresher influx. Sedimentation rates also apparrently decreased, but this may be due to the change in lake area with increases in lake level, rather than real increases in sediment load. This pattern of sedimentation has continued with little change since then.

Chapter V

SUMMARY AND CONCLUSIONS

1. Waldsea Lake's basin occurs on a glacial lake plain. The material available to wash into the lake contains carbonates (calcite and dolomite) and other clastic minerals (quartz, feldspars, and clays).
2. The soil contains salts which can be washed into the lake.
3. The groundwater is generally of low salinity, and may be a major source of salts for the lake.
4. Waldsea is chemically stratified and meromictic at present. The meromixis is primarily ectogenic in its origin, but cryogenesis and diffusion of salts from the sediment may be important processes in maintaining stratification and increasing its stability.
5. The chemocline is decreasing in elevation, but stability calculations do not indicate any systematic decrease or increase.
6. Chemically, Waldsea Lake water is a $Mg-Na-SO_4-Cl$ brine.
7. Precipitation of aragonite occurs on an irregular basis. Aragonite is the precipitated carbonate phase because of the high Mg:Ca ratio, pH, salinity, and alkalinity.

8. The inorganic sediment is of three origins--
   a) Allogenic
   b) Endogenic
   c) Authigenic (diagenetic).
9. Aragonite occurs in the sediment as both disseminated grains and laminae.
10. Low-Mg calcite occurs only as detrital (allogenic) material.
11. High-Mg calcite probably occurs as an authigenic phase replacing aragonite.
12. Protodolomite may occur as a primary precipitate, or as a diagenetic phase replacing aragonite.
13. Dolomite (stoichiometric and ordered) occurs as clastic material and also as a very early diagenetic product cementing silty laminae.
14. Gypsum is the major sulfate mineral in Waldsea Lake sediments. Several morphologies of crystals may indicate changes in conditions of formation or preservation.
15. Mirabilite occurs in the lowermost sediments and indicates hypersaline conditions during deposition.
16. Native sulfur is found as a disseminated mineral in the sediment.
17. The sediment recovered from Waldsea Lake has a maximum radiocarbon age of about 4000 years.

18. Sedimentation rates calculated on the basis of ^{14}C radiochronology vary from 0.5 to 1.5 mm/yr. There is a general decrease over the last 3000 years.
19. Sediment character varies due to changes in physical, chemical, and biological conditions within the lake. These changes in sediment character can be used to interpret the history and climatology of the lake basin.

Chapter VI

SUGGESTIONS FOR FURTHER STUDIES

Waldsea Lake and its sediments could provide a wealth of information which would be useful in understanding both its present physical/chemical and biological and sedimentological regimes. Despite the abundance of previous studies (see Appendix A), many more will be needed in order to adequately understand the lake and its changes in time. Several suggestions for further studies are hereby put forth:

1. Detailed chemical studies of the lake water, groundwater, and runoff would be useful in establishing both water and salinity budgets.
2. Measurements and calculation of heat and energy budgets would shed light on the stratification stability.
3. Suggested paleolimnological studies include:
    a) Diatom stratigraphy,
    b) Pigment and pigment derivative stratigraphy,
    c) Stratigraphy of botanical remains, and
    d) Stratigraphy of zoological remains.
4. Recovery of core samples which represent the entire post-Glacial record to define the early developmental history of the lake and its watershed could also include studies as previously suggested.

5. Detailed chemical and mineralogical analyses would be useful in delineating both changes in chemical conditions during deposition, and also changes incurred during diagenesis.
6. Stable isotope analyses (carbon, sulfur, and oxygen) would be helpful in the interpretation of changes in temperature, salinity, and other conditions, which are recorded in the sediment.
7. Pore water studies would provide information useful in characterizing diagenetic changes in the sediment.
8. Detailed trace metal analyses (both "whole rock" and specific mineral and organic fractions) would prove useful in evaluating recent anthropogenic influences on the lake system.
9. Comparison studies of the previously suggested studies and similar studies on nearby Deadmoose Lake (the only other reported meromictic lake in Saskatchewan) would provide an excellent opportunity to evaluate the chemical/biological/sedimentological responses of two lakes of different morphometries and chemistries only 3 km apart which probably have undergone similar developmental histories.
10. Laboratory-oriented studies of lakewater-mineral interactions and changes due to evaporation will be able to clarify problems encountered while comparing calculated saturation indices and saturometry.

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Parker, R. D., J. R. Lawrence, and U. T. Hammer, 1983. A comparison of phototropic bacteria in two adjacent saline meromictic lakes. Hydrobiologia, volume 105, pages 53-62.

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Schweyen, T. H., and W. M. Last, 1983. Sedimentology and Paleohydrology of Waldsea Lake, Saskatchewan, pages 45:59 in: Scott, M. D. (ed.), 1983. Third Biennial Plains Aquatic Research Conference: Proceedings, Canadian Plains Research Center, Regina, Saskatchewan, Canada, 243 pages.

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Spyker, J. W., 1981. Desalination of brackish water by spray freezing, Saskatchewan Research Council Technical Report 126, 114 pages.

Spyker, J. W., 1982a. Desalination of brackish water by spray freezing, Saskatchewan Research Council Technical Report 134, 69 pages.

Spyker, J. W., 1982b. Desalination of brackish water by spray freezing, Saskatchewan Research Council Technical Report 140, 59 pages.

Swanson, S. M., 1978. Ecology and production of macrobenthos of Waldsea Lake, Saskatchewan, with emphasis on Cricotopus Ornatus (Diptera:Chironomidae), Ph.D. thesis, University of Saskatchewan, 238 pages.

Swanson, S. M., and U. T. Hammer, 1983. Production of Cricotopus ornatus (Meigen) (Diptera: Chironomidae) in Waldsea Lake, Saskatchewan. Hydrobiologia, volume 105, pages 155-164.

Teller, J. T., J. M. Bowler, and P.G. Macumber, 1982. Modern sedimentation and hydrology in Lake Tyrrell, Victoria, Journal of the Geological Society of Australia, volume 29, pages 159-175.

Tones, P. I., 1976. Factors influencing selected littoral fauna in saline lakes in Saskatchewan, Ph.D. thesis, University of Saskatchewan, 185 pages.

Tones, P. I., 1978. Osmoregulation in adults and larvae of Hygrotus Salinarum Wallis (Coleoptera:Dytiscidae), Comp. Biochem. Physiol., volume 60, pages 247-250.

Tones, P. I., 1983. Megalocypris ingens Delorme (Ostracoda) in Saskatchewan saline lakes: osmoregulation and abundance, Hydrobiologia, volume 105, pages 133-136.

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Appendix A

ANNOTATED BIBLIOGRAPHY OF PREVIOUS STUDIES

The following is an annotated bibliography of the published and unpublished material pertaining to Waldsea Lake.

Hammer, U. T., R. C. Haynes, J. M. Heseltine and S. M. Swanson, 1975. The Saline lakes of Saskatchewan. Verh. Internat. Verein Limnol. volume 19, pages 589-598.

This article was presented as an interim report on the research being done on saline lakes at the University of Saskatchewan.

Hammer, U. T., 1978a. The saline lakes of Saskatchewan: I. Background and rationale for saline lake research, Int. Rev. ges. Hydrobiol. v. 63, pages 173-177.

Though this is not specifically a reference on Waldsea Lake, it is the first article in a series on saline lakes research which gives the uninitiated reader a background on the hydrographic, chemical and biological setting in the saline lakes of Saskatchewan.

Hammer, U. T., R. C. Haynes, J. R. Lawrence and M. C. Swift, 1978. The saline lakes of Saskatchewan: II. Locale, hydrography and other physical aspects. Int. Rev. ges. Hydrobiol. volume 63, pages 179-203.

This article discusses the physical and hydrological setting of the Saskatchewan saline lakes. Waldsea Lake is one of sixty lakes which are included in the study, and one of eleven which are presented in detail. The morphometry and physical setting is discussed and related to other lakes.

Hammer, U. T., 1978b. The saline lakes of Saskatchewan: III. Chemical characterization. Int. Rev. ges. Hydrobiol. volume 63, pages 179-203.

The chemistry of sixty saline lakes in Saskatchewan is compared and contrasted. Some trace constituent analyses for Waldsea Lake are also reported.

Hammer, U. T., J. Shamess, and R. C. Haynes, 1983. The distribution and abundance of algae in saline lakes of Saskatchewan, Canada. Hydrobiologia, volume 105, pages 1-26.

This article is an excellent review and documentation of algae in the Saskatchewan saline lakes, including Waldsea Lake. Species lists are given.

Haynes, R. C. and U. T. Hammer, 1978. The saline lakes of Saskatchewan: IV. Primary production of phytoplankton in selected saline ecosystems. Int. Rev. ges. Hydrobiol. volume 63, pages 337-351.

Primary production figures are given for some of the lakes presented in the previous articles in the series. Waldsea Lake is one of the lakes which is discussed.

Heseltine, J. M., 1976. A study of environmental influence on the distribution of submerged vascular hydrophytes in three Saskatchewan saline lakes (including Waldsea Lake), with emphasis on substrate factors., M.Sc. thesis, Department of Biology, University of Saskatchewan, 75 pages.

Heseltine relates surficial 'sediment type' to the distribution of the aquatic plant life found in three lakes. The 'sediment types' include sand, silt, and clay, as well as mixtures of the three.

Last, W. M., and Schweyen, T. H., 1983. Sedimentology and geochemistry of saline lakes of the Great Plains, Hydrobiologia, volume 105, pages 245-263.

A general overview of the sedimentology and geochemistry of some of the saline lakes found strewn hither and yon across the Great Plains. Waldsea Lake sediment photographs are presented, as well as other data on Waldsea Lake.

Lawrence, J. R., 1978. Factors influencing the contribution of Chlorobacteriaceae to primary production in a saline meromictic lake., M.Sc. thesis, Department of Biology, University of Saskatchewan, 103 pages.

Lawrence studies the changes in primary production of green sulfur bacteria living in the chemocline of Waldsea Lake relative to environmental factors, including temperature, oxygen and hydrogen sulfide concentrations, pH, Eh, and light transmittance of the overlying waters.

Lawrence, J. R., R. C. Haynes and U. T. Hammer, 1978. Contribution of photosynthetic green sulfur bacteria to total primary production in a meromictic lake. Verh. Internat. Verein. Limnol. volume 20, pages 201-207.

This is a concise presentation of the data collected by Lawrence and his colleagues during the course of his M.Sc. work.

Parker, R. D., 1980. The ecology and primary production of limnetic phytoplankton, with emphasis on the chromatiaceae in a saline meromictic lake. M.Sc. Thesis, Department of Biology, University of Saskatchewan, 134 pages.

Though this thesis is actually on Deadmoose Lake (the only other reported meromictic saline lake in Saskatchewan, located approximately 2 km northeast of Waldsea Lake), it provides an interesting comparison of the two stratified systems. Physical parameters of Deadmoose Lake are measured, and primary production estimates are given.

Parker, R. D., J. R. Lawrence, and U. T. Hammer, 1983. A comparison of phototropic bacteria in two adjacent saline meromictic lakes. Hydrobiologia, volume 105, pages 53-62.

Waldsea and Deadmoose Lakes are compared physically, chemically, and biologically. Some possible explanations are given as to why the chemoclines of the two lakes support two different populations of phototrophic bacteria.

Schweyen, T. H., and Last, W. M., 1983. Sedimentology and paleohydrology of Waldsea Lake, Saskatchewan. Proceedings of the Second Biennial Plains Aquatic Research Conference, M. D. Scott, (ed.).

Most of the material in this article is presented in this thesis.

Swanson, S. M., 1978. Ecology and production of macrobenthos of Waldsea Lake, Saskatchewan, with emphasis on _Cricotopus ornatus_ (Diptera:Chironomidae). Ph.D. thesis, Department of Biology, University of Saskatchewan, 238 pages.

This thesis discusses the biomass of the chironomids of Waldsea Lake and gives an indication of the amount of bioturbation on a fine scale which is occurring because of them. She also presents the bathymetric map upon which the morphometric measurements for this thesis are based.

Swanson, S. M., and U. T. Hammer, 1983. Production of _Cricotopus ornatus_ (Meigen) (Diptera: Chironomidae) in Waldsea Lake, Saskatchewan. Hydrobiologia, volume 105, pages 155-164.

Production figures are given for these chironomids in Waldsea Lake.

Tones, P. I., 1976. Factors influencing selected littoral fauna in saline lakes in Saskatchewan, Ph.D. thesis, Department of Biology, University of Saskatchewan, 185 pages.

Six fauna are discussed in four different saline lakes of which Waldsea Lake is one. She discusses the processes by which these insects and crustaceans regulate the salinity within their bodies in contrast to the salinity of their environment.

Tones, P. I., 1978. Osmoregulation in *Trichocorixa Verticalis* interiores Sailer (Hemiptera:corixidae), an inhabitant of Saskatchewan saline lakes, Canadian Journal of Zoology, volume 53, pages 1207-1212.

This is the published results of part of Tones' Ph.D. research. Only the information about the corixid (an insect) is presented.

Tones, P. I., 1983. *Megalocypris ingens* Delorme (Ostracoda) in Saskatchewan saline lakes: osmoregulation and abundance, Hydrobiologia, volume 105, pages 133:136.

Data collected during Tones' Ph.D. studies on the ostracod *Megalocypris* are discussed.

Appendix B

CHUNG'S ADIABATIC PRINCIPLE OF MATRIX-FLUSHING SYSTEMS

The following WATFIV program calculates percentages of mineral phases in a mixture by using Chung's (1974b) adiabatic principle of matrix-flushing systems. The calculations are rather simple, but the results will be valid only for materials in the sample that have the same degree of crystallinity. The well-crystalline materials (quartz, aragonite, dolomite, pyrite, and low-Mg calcite) were chosen because of their abundance. Bassanite was measured because the samples had been heated to 105°, and some of the gypsum had been dehydrated. Reference intensities were calculated by measuring peak intensities of prepared samples of 50% mineral - 50% quartz and dividing (quartz was used as the internal standard because of its ubiquity). The resulting ratios were used to calculate relative percentages of these specific mineral phases in the sample.

FLUSH, the first program, does the basic mineral calculations. FLUSH2 calculates the minerals and prepares the data for plotting as in Figure 19. FLUSH3 calculates ratios of mineral specific mineral pairs.

```
 JOB WATFIV FLUSH,NOEXT
      CHARACTER IDENT*20,IEND*4
      DATA IEND/'9999'/
C
C             PROGRAM:   FLUSH    BY T.SCHWEYEN        1983
C
C     THIS PROGRAM CALCULATES THE RELATIVE PERCENTAGES OF SEVEN MINERALS
C     IN A LAKE SAMPLE SEDIMENT. CALCULATIONS ARE BASED ON FRANK CHUNG'S
C     (1974) ADIABATIC PRINCIPLE OF X-RAY DIFFRACTION MATRIX FLUSHING
C     SYSTEM. REFERENCE INTENSITIES ARE CALCULATED FROM THE RELATIONSHIP
C     OF AN UNAMBIGUOUS PEAK OF THE MINERAL IN QUESTION AND THE HIGHEST
C     PEAK OF QUARTZ.  THE REFERENCE INTENSITY, II/IQ, IS USED TO CALCU
C     LATE THE CONCENTRATION OF THE MINERAL BASED ON THE INTENSITIES OF
C     ALL OF THE MATERIALS IN THE SAMPLE. THUS RESULTS ARE RELATIVE ONLY
C     TO THE OTHER MINERALS ALSO CALCULATED WITH THE ADIABATIC PRINCIPLE.
C
C
      PRINT,'       IDENTIFICATION       QUARTZ        GYPSUM      CALCIT
     1E       DOLOMITE       ARAGONITE    BASSANITE    PYRITE    TOTAL'
      DO 100 I=1,1000
      READ(5,2)IDENT,QZ,ARAG,DOL,CALC,GYP,BAS,PYR
  2   FORMAT(A19,7F5.0)
      IF (IDENT.EQ.IEND)GO TO 110
C   REFERENCE INTENSITIES FOR EACH MINERAL BASED ON QUARTZ
      QA=.17
      QC=.69
      QD=.28
      QG=.14
      QB=.35
      QP=.32
C  INITIALIZE CONCENTRATIONS TO 0 PERCENT
      XQZ=0.
      XGYP=0.
      XARAG=0.
      XDOL=0.
      XCALC=0.
      XBAS=0.
      XPYR=0.
C   CHECK FOR INTENSITIES OF 0, AND SKIP CALCULATION OF CONCENTRATION
C    IF SO.
      IF (QZ.EQ.0)GO TO 20
      XQZ=1./(1.+((1./QZ)*((ARAG/QA)+(CALC/QC)+(DOL/QD)+(GYP/QG)+(BAS/QB
     1)+(PYR/QP))))
 20   IF(GYP.EQ.0)GO TO 30
      XGYP=1./(1.+((QG/GYP)*(QZ+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(BAS/QB)+(
     1PYR/QP))))
 30   IF(ARAG.EQ.0)GO TO 40
      XARAG=1./(1.+((QA/ARAG)*(QZ+(GYP/QG)+(CALC/QC)+(DOL/QD)+(BAS/QB)     1(PYR/QP))))
 40   IF(CALC.EQ.0)GO TO 50
      XCALC=1./(1.+((QC/CALC)*(QZ+(GYP/QG)+(ARAG/QA)+(DOL/QD)+(BAS/QB)     1(PYR/QP))))
 50   IF(DOL.EQ.0)GO TO 60
      XDOL=1./(1.+((QD/DOL)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(BAS/QB)+(
     1PYR/QP))))
 60   IF(BAS.EQ.0.)GO TO 70
```

```
      XBAS=1./(1.+((QB/BAS)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(
     1PYR/QP))))
 70   IF(PYR.EQ.O.)GO TO 80
      XPYR=1./(1.+((QP/PYR)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(
     1BAS/QB))))
C    RUN TOTAL AS A MATHEMATICAL CHECK
 80   XTOT=XQZ+XDOL+XARAG+XCALC+XGYP+XBAS+XPYR
C    CONVERT TO PERCENTAGES.
      XQZ=XQZ*100.
      XGYP=XGYP*100.
      XARAG=XARAG*100.
      XCALC=XCALC*100.
      XDOL=XDOL*100.
      XTOT=XTOT*100.
      XBAS=XBAS*100.
      XPYR=XPYR*100.
      XGYP=XGYP+XBAS
      WRITE(6,90)IDENT,XQZ,XGYP,XCALC,XDOL,XARAG,XPYR,XTOT
 90   FORMAT(3X,A20,6X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,6X,F
     16.2,6X,F6.2)
 100  CONTINUE
 110  CONTINUE
      STOP
      END
 ENTRY
```

```
 JOB WATFIV FLUSH,NOEXT
      CHARACTER IDENT*20,IEND*4
      DATA IEND/’9999’/
C
C              PROGRAM:   FLUSH2    BY T.SCHWEYEN        1983
C
C     THIS PROGRAM CALCULATES THE RELATIVE PERCENTAGES OF SEVEN MINERALS
C     IN A LAKE SAMPLE SEDIMENT. CALCULATIONS ARE BASED ON FRANK CHUNG’S
C     (1974) ADIABATIC PRINCIPLE OF X-RAY DIFFRACTION MATRIX FLUSHING
C     SYSTEM. REFERENCE INTENSITIES ARE CALCULATED FROM THE RELATIONSHIP
C     OF AN UNAMBIGUOUS PEAK OF THE MINERAL IN QUESTION AND THE HIGHEST
C     PEAK OF QUARTZ.  THE REFERENCE INTENSITY, II/IQ, IS USED TO CALCU
C     LATE THE CONCENTRATION OF THE MINERAL BASED ON THE INTENSITIES OF
C     ALL OF THE MATERIALS IN THE SAMPLE. THUS RESULTS ARE RELATIVE ONLY
C     TO THE OTHER MINERALS ALSO CALCULATED WITH THE ADIABATIC PRINCIPLE.
C     SUMMATION RESULTS ARE THEN RECALCULATED FOR PLOTTING ON 100 PER
C     CENT DIAGRAMS.
C
C
C
      PRINT,’      IDENTIFICATION       QUARTZ        GYPSUM      CALCIT
     1E      DOLOMITE      ARAGONITE    BASSANITE   PYRITE    TOTAL’
      DO 100 I=1,1000
      READ(5,2)IDENT,QZ,ARAG,DOL,CALC,GYP,BAS,PYR
    2 FORMAT(A19,7F5.0)
      IF (IDENT.EQ.IEND)GO TO 110
C   REFERENCE INTENSITIES FOR EACH MINERAL BASED ON QUARTZ
      QA=.17
      QC=.69
      QD=.28
      QG=.14
      QB=.35
      QP=.32
C  INITIALIZE CONCENTRATIONS TO 0 PERCENT
      XQZ=0.
      XGYP=0.
      XARAG=0.
      XDOL=0.
      XCALC=0.
      XBAS=0.
      XPYR=0.
C   CHECK FOR INTENSITIES OF 0, AND SKIP CALCULATION OF CONCENTRATION
C    IF SO.
      IF (QZ.EQ.0)GO TO 20
      XQZ=1./(1.+((1./QZ)*((ARAG/QA)+(CALC/QC)+(DOL/QD)+(GYP/QG)+(BAS/QB
     1)+(PYR/QP))))
   20 IF(GYP.EQ.0)GO TO 30
      XGYP=1./(1.+((QG/GYP)*(QZ+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(BAS/QB)+(
     1PYR/QP))))
   30 IF(ARAG.EQ.0)GO TO 40
      XARAG=1./(1.+((QA/ARAG)*(QZ+(GYP/QG)+(CALC/QC)+(DOL/QD)+(BAS/QB)      1(PYR/QP))))
   40 IF(CALC.EQ.0)GO TO 50
      XCALC=1./(1.+((QC/CALC)*(QZ+(GYP/QG)+(ARAG/QA)+(DOL/QD)+(BAS/QB)      1(PYR/QP))))
   50 IF(DOL.EQ.0)GO TO 60
```

```
      XDOL=1./(1.+((QD/DOL)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(BAS/QB)+(
     1PYR/QP))))
 60   IF(BAS.EQ.0.)GO TO 70
      XBAS=1./(1.+((QB/BAS)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(
     1PYR/QP))))
 70   IF(PYR.EQ.0.)GO TO 80
      XPYR=1./(1.+((QP/PYR)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(
     1BAS/QB))))
C    RUN TOTAL AS A MATHEMATICAL CHECK
 80   XTOT=XQZ+XDOL+XARAG+XCALC+XGYP+XBAS+XPYR
C    CONVERT TO PERCENTAGES.
      XQZ=XQZ*100.
      XGYP=XGYP*100.
      XARAG=XARAG*100.
      XCALC=XCALC*100.
      XDOL=XDOL*100.
      XTOT=XTOT*100.
      XBAS=XBAS*100.
      XPYR=XPYR*100.
C    ADD FOR 100 PERCENT DIAGRAM
      XARAG=XARAG+XQZ
      XCALC=XCALC+XARAG
      XDOL=XDOL+XCALC
      XGYP=XGYP+XDOL+XBAS
      XPYR=XPYR+XGYP
      WRITE(6,90)IDENT,XQZ,XGYP,XCALC,XDOL,XARAG,XBAS,XPYR,XTOT
 90   FORMAT(3X,A20,6X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,6X,F
     16.2,6X,F6.2,6X,F6.2)
 100  CONTINUE
 110  CONTINUE
      STOP
      END
 ENTRY
```

```
 JOB WATFIV FLUSH,NOEXT
      CHARACTER IDENT*20,IEND*4
      DATA IEND/'9999'/
C
C              PROGRAM:   FLUSH3   BY T.SCHWEYEN        1983
C
C     THIS PROGRAM CALCULATES THE RELATIVE PERCENTAGES OF SEVEN MINERALS
C     IN A LAKE SAMPLE SEDIMENT. CALCULATIONS ARE BASED ON FRANK CHUNG'S
C     (1974) ADIABATIC PRINCIPLE OF X-RAY DIFFRACTION MATRIX FLUSHING
C     SYSTEM. REFERENCE INTENSITIES ARE CALCULATED FROM THE RELATIONSHIP
C     OF AN UNAMBIGUOUS PEAK OF THE MINERAL IN QUESTION AND THE HIGHEST
C     PEAK OF QUARTZ.  THE REFERENCE INTENSITY, II/IQ, IS USED TO CALCU
C     LATE THE CONCENTRATION OF THE MINERAL BASED ON THE INTENSITIES OF
C     ALL OF THE MATERIALS IN THE SAMPLE. THUS RESULTS ARE RELATIVE ONLY
C     TO THE OTHER MINERALS ALSO CALCULATED WITH THE ADIABATIC PRINCIPLE.
C     RESULTS OF FLUSH3 ARE RATIOS OF SPECIFIC MINERAL PAIRS.
C
C
C
      PRINT,'      IDENTIFICATION       XQA            XQD          XDC
     1       XAD            XAG           XAC          XQG        XAE   '
      DO 100 I=1,1000
      READ(5,2)IDENT,QZ,ARAG,DOL,CALC,GYP,BAS,PYR
  2   FORMAT(A19,7F5.0)
      IF (IDENT.EQ.IEND)GO TO 110
C    REFERENCE INTENSITIES FOR EACH MINERAL BASED ON QUARTZ
      QA=.17
      QC=.69
      QD=.28
      QG=.14
      QB=.35
      QP=.32
C   INITIALIZE CONCENTRATIONS TO 0 PERCENT
      XQZ=0.
      XGYP=0.
      XARAG=0.
      XDOL=0.
      XCALC=0.
      XBAS=0.
      XPYR=0.
C    CHECK FOR INTENSITIES OF 0, AND SKIP CALCULATION OF CONCENTRATION
C     IF SO.
      IF (QZ.EQ.0)GO TO 20
      XQZ=1./(1.+((1./QZ)*((ARAG/QA)+(CALC/QC)+(DOL/QD)+(GYP/QG)+(BAS/QB
     1)+(PYR/QP))))
 20   IF(GYP.EQ.0)GO TO 30
      XGYP=1./(1.+((QG/GYP)*(QZ+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(BAS/QB)+(
     1PYR/QP))))
 30   IF(ARAG.EQ.0)GO TO 40
      XARAG=1./(1.+((QA/ARAG)*(QZ+(GYP/QG)+(CALC/QC)+(DOL/QD)+(BAS/QB)     1(PYR/QP))))
 40   IF(CALC.EQ.0)GO TO 50
      XCALC=1./(1.+((QC/CALC)*(QZ+(GYP/QG)+(ARAG/QA)+(DOL/QD)+(BAS/QB)     1(PYR/QP))))
 50   IF(DOL.EQ.0)GO TO 60
      XDOL=1./(1.+((QD/DOL)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(BAS/QB)+(
```

```
     1PYR/QP))))
 60   IF(BAS.EQ.O.)GO TO 70
      XBAS=1./(1.+((QB/BAS)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(
     1PYR/QP))))
 70   IF(PYR.EQ.O.)GO TO 80
      XPYR=1./(1.+((QP/PYR)*(QZ+(GYP/QG)+(ARAG/QA)+(CALC/QC)+(DOL/QD)+(
     1BAS/QB))))
C    RUN TOTAL AS A MATHEMATICAL CHECK
 80   XTOT=XQZ+XDOL+XARAG+XCALC+XGYP+XBAS+XPYR
C    CONVERT TO PERCENTAGES.
      XQZ=XQZ*100.
      XGYP=(XGYP+XBAS)*100.
      XARAG=XARAG*100.
      XCALC=XCALC*100.
      XDOL=XDOL*100.
      XTOT=XTOT*100.
      XPYR=XPYR*100.
C CALCULATE RATIOS OF PERCENTAGES
      XQA=XQZ/XARAG
      XQD=XQZ/XDOL
      XDC=XDOL/XCALC
      XAD=XARAG/XDOL
      XAG=XARAG/XGYP
      XAC=XARAG/XCALC
      XQG=XQZ/XGYP
      XAE=(XARAG+XGYP+XPYR)/(XDOL+XCALC+XQZ)
      WRITE(6,90)IDENT,XQA,XQD,XDC,XAD,XAG,XAC,XQG,XAE
 90   FORMAT(3X,A20,6X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,7X,F6.2,6X,F
     16.2,6X,F6.2,6X,F6.2)
 100  CONTINUE
 110  CONTINUE
      STOP
      END
 ENTRY
```

Appendix C

IDSO'S METHOD OF CALCULATION OF STABILITY OF STRATIFICATION

Idso (1973) proposed a method of calculating the stability of stratification (the amount of work hypothetically needed to mix a lake to uniform temperature and density). The following WATFIV program, modified from a prototype written by Doug Bell (University of Manitoba), does the calculations and prints out various parameters in tabular form.

```
 JOB  WATFIV  SCHWEY,NOEXT C PROGRAM TO  CALCULATE STABILITY
OF STRATIFICATION
      REAL
Z(50),AZ(59),RHOZ(50),RHOBAR,ZRHO,ZMAX,S,VSTRAT(50),VOL,
     +VTOT(50),ATOT(50),GRAD,INCR
      READ,(Z(I),AZ(I),RHOZ(I),I=1,50)
      AT END DO
          I=I-1
          ZMAX=Z(I)
      END AT END C CALCULATION OF VOLUME OF STRATUM
      VOL=0
      DELTAZ=Z(2)-Z(1)
      N=I
      WHILE(N.GE.1)DO
         VSTRAT(N)=DELTAZ*AZ(N)
         VOL=VOL+VSTRAT(N)
         VTOT(N)=VOL
         N=N-1
      END WHILE C CALCULATION OF % TOTAL AREA
      J=1
      WHILE(J.LE.I)DO
         ATOT(I)=AZ(I)/AZ(1)
         J=J+1
      END WHILE C CALCULATION OF MEAN DENSITY;RHOBAR
      RHOBAR=0
      K=I-1
      J=1
      WHILE(J.LE.K)DO
         RHOBAR=RHOBAR+((1/VOL)*RHOZ(J)*AZ(J)*DELTAZ)
         J=J+1
      END WHILE C CALCULATION OF CENTER OF GRAVITY, ZRHO
      J=1
      WHILE(J.LT.I)DO
      IF(RHOZ(J).LE.RHOBAR .AND. RHOBAR.LE.RHOZ(J+1))THEN DO
         GRAD=(RHOZ(J+1)-RHOZ(J))/100
         INCR=(RHOBAR-RHOZ(J))/GRAD
         ZRHO=Z(J)+INCR
      END IF
         J=J+1
      END WHILE C CALCULATION OF STABILITY OF STRATIFICATION
      S=0
      J=1
      WHILE(J.LE.I)DO
         S=S+((1/AZ(1)*(RHOZ(J)-RHOBAR)*AZ(J)*(Z(J)-ZRHO))*100)
         J=J+1
      END WHILE
      PRINT 100
      K=1
      WHILE(K.LE.I)DO
         PRINT 200,Z(K),AZ(K),VTOT(K)
         K=K+1
      END WHILE
      PRINT 300
      PRINT 400,RHOBAR,ZRHO,S
```

```
 100         FORMAT('1',15X,'DEPTH(CM)',10X,'AREA         OF
STRATUM(SQ.CM)',10X,
     +'% TOTAL AREA',10X,'VOLUME SUM(CUBIC CM)'/)
 200  FORMAT(' ',T17,F10.0,T42,E10.4,T72,E10.4)
 300     FORMAT('-',32X,'MEAN     DENSITY',10X,'CENTER    OF
GRAVITY',10X,
     +'STABILITY',/)
 400  FORMAT(' ',T38,F6.4,T60,F7.2,T74,F10.4)
      STOP
      END  ENTRY
```

```
250.,2.44E8,1.025
350.,2.34E8,1.025
450.,1.98E8,1.025
550.,1.67E8,1.025
650.,1.34E8,1.025
750.,1.04E8,1.025
850.,7.2E7,1.169
950.,2.6E7,1.125
1050.,9.0E6,1.169
1150.,1.0E6,1.169
1250.,5.0E5,1.169
1350.,2.0E5,1.169
1450.,0.,1.169
//
/*
'Sample data set for stability calculations, 1974'
```

```
DEPTH(CM)   AREA OF STRATUM(SQ.CM)   VOLUME SUM(CUBIC CM)

  250.          0.2440E09                 0.1190E12
  350.          0.2340E09                 0.9457E11
  450.          0.1980E09                 0.7117E11
  550.          0.1670E09                 0.5137E11
  650.          0.1340E09                 0.3467E11
  750.          0.1040E09                 0.2127E11
  850.          0.7200E08                 0.1087E11
  950.          0.2600E08                 0.3670E10
 1050.          0.9000E07                 0.1070E10
 1150.          0.1000E07                 0.1700E09
 1250.          0.5000E06                 0.7000E08
 1350.          0.2000E06                 0.2000E08
 1450.          0.0000E00                 0.0000E00

   MEAN DENSITY   CENTER OF GRAVITY   STABILITY

       1.0372       758.47            2371.6660
```

Sample output of stability calculations

Appendix D

CORE DESCRIPTIONS

The following core descriptions were chosen for presentation because they are representative of the widest range of sediment types found in Waldsea Lake. The descriptions contain numerous abbreviations; these are formulated in accordance with the Colorado School of Mines (Low, 1951) standard usage.

CORE SITE W1A Collected: February 82

Recovery: 0-1 78cm; 1-2 82cm.

General Notes:

Cores deformed by extrusion due to partial freezing.

Laminae stretched and folded.

Upper 25 cm (?) finely laminated, carbonate laminae pink to grey.

Nondistinct throughout upper metre.

Second carbonate laminae series @ 153-158; grey at base, 179-182 cm.

fin

CORE SITE W1B

Date collected WINTER 82

Recovery:1-2 53cm.

General Notes:

Core site to replace W1A cores deformed by extrusion (10 m west of W1A).

Second carbonate laminated series @ 145 cm; organic fibre zone @ 140-144cm.

Very thin sand @ 142.5 cm.

* * *

DEPTH	DESCRIPTION
100-112.4	Core disturbed by extrusion due to partial freezing. Black 5YR2.5/1 clay, slightly silty, moderately firm. Two carbonate laminae @ 102.5, 104.5--10YR8/1, 5YR8/2. Disseminated carbonate throughout.
110-112.4	Grey-green 5Y3/1; gypsum-silty clay, with indistinct contacts. Gypsum silt laminae and carbonate-poor throughout.
112.4-114.2	Black 10YR2.5/1, slightly silty in part. Fine fibres from 110 on, with some ostracod shells interspersed.
114.2-124.7	Clay, 5Y3/2, 5YR2.5/1, with some organic fibres; carbonate in part, increasing downward.
124.7-138	Clayey silt to silty clay, 7.5YR4/0; massive to subtly laminated in parts (Gypsum silt lamina @ 135, 7.5YR6/0); strongly to moderately carbonate-rich. Clayey fine sand in part, 133-134, 136-137.

138-141	Organic Zone, Radiocarbon sample 141-1431; Quartz sand on bedding plane @ 141; gypsum silt lamina @ 138.7.
141-143.7	Clay, black, silty in part, 10YR2.5/1; carbonate-rich.
143.7-149	Carbonate Serises, about 16 carbonate laminae; pink, 5YR7/3, others, 10YR8/2 to 10YR8/1; Carbonate-rich between some laminae, some associated "dark-light" carbonate transitions.
149-152.5	Clay, 10YR2.5/1. silty in part; subtly laminated, carbonate-rich overall. Organic fibres--fine, not straight, "root-like".

fin

CORE W2 Date collected February 1982

General Notes:

Core 0-1 destroyed by extrusion.

1-2 generally good recovery, 89cm; several fibre-rich zones; good carbonate laminae from 133-141, orange lam @147; generally firmly gelatinous to moderately firm and subtly laminated.

2-3m 93.5 cm recovery ; 5 zones of mirabilite crystals, 239,249,266,279, 282 cm; generally finely and subtly laminated; several widely-spaced gypsum silt laminae. Cores partially oxidized before description.
Many organic mats.

DEPTH	DESCRIPTION
100-106.6	10YR2.5/1 black clay, moderately fibrous throughout; very slightly silty, increasing downward; no carbonate; grading to 5Y3/2, and then 7.5YR 2.5/2.
106.6-110.8	Clay, 10YR2.5/1, 5Y2.5/1,5Y2.5/2 black, very dark grey-black; silty, much orgainc fibres; Slightly carb, subty laminated.
110.8-112.8	Clay, 10YR2.5/1, to silt, subtly laminated, grading to 5Y2.5/1; very slightly carb.
112.8-114.7	Clay, 5Y2.5/1; silty, slightly carb, subtly laminated.
114.7-118.5	Clay, 7.5YR2.5/0 black, silty, slightly carb. grading to silty clay, 7.5YR4/0 through 5Y4/1; slightly carb.

118.5-121 Silt, 7.5YR4/0 grading to silty clay 7.5YR3/0 with fibres. Slightly to moderately carb.

121-122 Grey, 7.5YR4/0 clay, silt, organic fibres abundant; Slightly carb

122-125.5 7.5YR3/0 grey silt and clay, finely laminated. Rounded gypsum silt laminae @ 123.6,125.6,124.8,125.3; 7.5YR6/0; Slightly carb, fine textured.

125.5-127 A/A, becoming darker 7.5YR3/0, "Granular texture"; very silty, predominantly clay. Rounded Gypsum silt lamina @ 125.8, some organic fibres.

127-130 Silty clay, A/A, predominantly 7.5YR3/0 and 10YR2.5/1 and 2.5Y2.5/2 clay; very silty, carbonate in part. Rounded gypsum silt lamina @ 128.1

130-133.1 A/A, becoming 10YR2.5/1; "granular", silty, slightly carb.

133.1-141.5 Clay, 5Y2.5/1 and 10YR2.5/1; slightly silty, with carb laminae, predominantly 2.5Y8/2; "pink" laminae 10R6/3, 7.5YR8/4, 5Y7/2. Fibrous zone @ 137.3-137.5. Carb rich between laminae.

141.5-147.3 Clay, slightly silty, slightly carbonate in parat; black 10YR2.5/1 subtly laminated, misc. fibres.

147.3-153.0 Clay, slightly silty in part, slightly to moderately carb overall; 5Y3/1,5Y2.5/1,10YR2.5/1; "pink" carbonate laminae @ 147.5, 7.5YR5/4; gypsum silt lamina @ 150.5, 2.5Y8/0.

153-161.3 Clay, Slightly silty, slightly carb, subtly laminated.

10YR3/2,5Y2.5/1, black, dark grey. Much plant fibres "blades". Increasing organic content downward, base predominantly organics.

161.3-163.5 Clay, black, slightly silty, sublty laminated 10YR2.5/1, 2.5Y2.5/0. Some organics, "root hairs".

163.5-170 Clay, slightly silty to nonsilty; slightly carbonate to noncarb; grading (Subtle laminations) from 2.225YR2.5/0 to 5Y3/1.

170-172.2 Clay and silt, interlaminated, 2.25Y3/0,5Y3/1. Gypsum silt laminae @ 171.2,171.4,172.1.

172.2-174 Clay, very silty, slightly carb. "Granular" texture, Artemia oogonia.

174-176.7 Clay, subtle laminations, much organic fibres/blades. Slightly silty, slightly carb. 10YR2.5/1, 10YR3/1.

176.7-189.0 Clay, silty, lsightly carb, 2.5Y3/0; very subtle laminae in part. Rounded gypsum silt lamina @ 182.7-182.9. Mottled 10YR5/1. and @185.0,185.3,185.6, 10YR4/1. Becoming more finely laminated and more visible from 185 on; abundant plant fragments below 186.7.

2-3 m.

200-206.5 Black clay, 10YR2.5/1, slightly to moderately silty, gelatinous Moderately abundant organic fibres/blades; slightly carb, increasing downward.

206.5-211.5 Clay, 2.5Y2.5/0, moderately silty, gypsum silt laminae, contorted by extrusion; slightly to moderately carb.

211.5-216.8 Clay, 10YR2.5/1 moderatelly silty to very silty; slightly carb, firm; subtly laminated. Much fine fibrous organic material.

216.8-222.5 Clay, 7.5YR2.5/0, 7.5YR3/0; laminated, very silty, 1 mm lensoid gypsum crystal layers and dispersed; "fine" texture.

222.5-229.5 Clay, "Granular" texture, 10YR2.5/2, very silty; few organic fibres, moderately calc.

229.5-233.5 Organic rich, very fibrous, A/A.

233.5-240.5 Silt, predominantly gypsum, clayey in part, 7.5R4/0. Lensoidal gypsum crystal (1mm) lamina@233.2, of 7.5YR7/0 grey; noncarb. Becoming finer downward; dispersed lensoid gypsum 1 mm crystals; organic fibres throughout. Gypsum rosettes @ 239, Mirabilite too.

240.5-246.5 Clay, silty, black 10YR2.5/1,7.5YR2.5/0, laminated. Carb in part. Abundant organic fibres. Gypsum silt throughout.

246.5-250 Organic Fibre mat, seeds, algal filaments. Mirabilite @249.

250-254 Clay, black, 10YR2.5/1; rich in oftanic fibres. Nonsilty. Grading to 5YR2.5/1, silty; gypsum silt lamina @ 253, several different sizes. intraclasts(?) at 252.5.

254-256 Organic fibre mat A/A. no seeds and more clay.

256-267 Clay, silty, 7.5YR2.5/0 laminated with 7.5YR3/0; Gypsum silt throughout, several gypsum laminae. Slightly to moderately carb. Much fibres throughout. Mirabilite @266.

267-274 Clay 2.55Y2.5/0 silty. Gypsum silt laminae in part. Very carbonate rich throughout;"VUG" from 271.5-273.5 with very fine white precipitate in "dendritic pattern".

274-276 Organic fibres, clay rich in part.

276-280.5 Clay, silty, gypsum silt, 7.5YR2.5/0,5YR2.5/1; slightly to moderately carb, numerous organic fibres.

280.5-288 Organic material.

fin

CORE W3 Date collected February 1982

General Notes:

49 cm recovered total (0-1); predominantly white, pale yellow carb laminae irregularly spaced in dark olive grey to dark brown to black silty clay;core deformed due to partial freezing and extrusion.

1-2 m-- 100 cm recovered; both ends disturbed, core warped from extrusion because of freezing.

DEPTH	DESCRIPTION
0-5	Black 10YR2.5/1 clay, sl slty. some v fine org fibres, some carb, v irreg, bcm slty.
5-10	5Y2.5/1 clay, sl slty, carb; 6 carbonate lam, some doublets, from 5-6,7. Carb ranges form 2.5Y8/4 to 2.5Y7/2 and back; lam @ 7 is 7.5Y7/4; fibres
10-12.5	Clay, sl slty 10YR2.5/1; carbonate lam 2.5Y7/2 @ 10.2; 2 @ 10.8,10.9; sl carbonate overall.
12.5-16	Qz grains, 2.5-.5mm, sbang,sbrd,clr,om bdg pln. Dk brn 10YR2./1 Clay; carbonate lam, couplets @ 2 mm spacing, 7.5R6/4, all finely lam; more carbonate lam 5Y7/1.
16-20	10YR3/2 clay grdg to 10YR2.5/1; strongly carb, v f lam. Clay grades to 2.5Y2.5/0 w/ abnt fibres. carbonate lam 10YR7/2. Carb rich between carb lams. 12-14 lams 10YR6/2,5Y3/2,10YR6/2.
20-22	Clay, 7.5YR2.5/0, NOB, v fibrous. Grdg to f lam w/10YR7/2 @ base.

9 lam increasing in thicness.

22-23.9 Clay 7.5YR2.5/0 NOB; grdg to thinly lam,10YR5/3; f to v f gr sand
@ 23.4 on;sbanc sbrd grs. QZ.

23.9-28.5 Clay, 5Y2.5/1 w/ v f lam (18 sep lam/couples); carbonate rich;
carbonate lam @ 25.5 has red base 5R4/6.

28.5-34.5 Clay, 7.5Y2.5/0, NOB, occ fibres; grdg to clay 5Y2.5/1 w/
light carbonate lams 10YR6/3, thicker lams @ base.

34.5-41 Clay, 5Y2.5/}1 occ light carbonate lam @ 36.5,37.5,2 @ 39.0;
bcm disturbed @ base, faintly lam throughout. fibres incr near base.

41-49 remainder disturbed due to extrusion, lams vertical; gyp near base?

fin

100-110 Black 5Y2.5/1 clay, slty, frm; subtle lams.

110-112.7 Gypsum, sand-silt, fgr, carbonate in pt;grdg to clay, 5Y2.5/1,
5YR2.5/1; subtle lam; sl slty in pt; org fibres.

112.7-114.7 Clay, carb, gypsum lensoids (1mm), org fibres; 5Y2.5/1.
Grdg to clay, subtle lams A/A but no gyp plates.

114.7-121.0 Carbonate laminated cly, 5Y2.5/1 to 7.5YR8/4-5Y8/3 in
5Y2.5/1 and 10YR2.5/1 black slty clay w/ org fibres.

121-124.8 Clay, 5Y2.5/1-10YR2.5/1; sl slty, f lam, sm org fibres; ncarb.
One carbonate lam @ 124, 5Y5/1.

124.8-126.4	F lam slty clay, poos disturbed by coring; 5Y7/1, 5Y2.5/1; abrupt "erosional" contact w/ 7.5YR2.5/1 glack clay, org rich.
126.4-127.3	Dk clay, little silt, 7.5YR2.5/0; one carbonate lam, disoriented by coring?
127.3-127.4	Gypsum silt, carbonate in pt.
127.4-136.3	Clay, 5Y3/1,5Y3/2 sl slty, carb.; laminated. Much fine org fibres @ 132.5,133.8 and down. Incr slty.
136.3-139.6	Clay, v slty, grey 10YR5/1 to 5Y4/1; carbonate except in light grey 5Y7/1 to 5Y6/1 clay; gyp slt, no carb; core disturbed.
139.6-143.5	F lam clay, grdg from green to 5YR2.4/2 and 10YR2.5/1 clay, v sl slty, sl carb; much plant fibres, insect remains.
143.5-146.0	Clay, sl slty 5Y3/2 grdg to 5Y4/2 and 5Y7/1 gyp silt @ 144.8; carbonate in pt.
146-152.2	Clay, 5Y2.5/2 grdg to 5YR2.5/1 v slty, carbonate in pt; "worm"; gritty tx, pelleted? in pt. Irreg carbonate intclsts @ 150.5; repetitive sequences; bcm f lam in pt.
152.2-153.3	Clay, fine tx, gyp slty; 5Y4/1 gy, sl calc, firm.
153.3-155.5	Clay, green to 5Y3/2, "granular" tx. slty in pt; subtly lam.
155.5-160.2	Clay, A/A, fine tx. Wierd green to 5Y4/2,5Y4/1, sl slty, grdg to "Granular" tx; 5Y2.5/1 intclsts@ 157.0, .3 cmX1.5cm, coinciding w/ Carb lam (coarse granular); gyp lams @ 158.3,158.6; f lam overall, slty.

160.2-162 f lam, clay, much org fibres, sl slty, "Gran" tx; 5Y3/2-5YR2.5/2-5Y2.5/1 (2 cycles).

162-166 A/A, but 5Y3/2-5Y2/2-5Y4/1-5Y4/2; upper 2 cm "gran" tx, lower "fine"' v fibrous @ 164.5, numerous types.

166-167 A/A, "gran", carbonate (green) @ base, sl slty clay, carb throughout.

167-167.7 A/A, suubtle lams, grdg to 5Y2.5/1.

167.7-170 Clay, sl slty, 5Y4/1, lam; gyp/carbonate silt lam 5Y7/1, org fibres throughout, fine txs.

170-174 Wierd green claym, gran tx, bcm 5Y3/1, w/ gyp platelets @ 173.8-174. Carb, silt throughout; org fibres above gypsum.

174-178.3 A/A; subtle lams; 5Y3/2. Sl slty, fine tx; lighter (5Y4/3) @177, carbonate throughout, bcm v org rich @ 178.

178.3-183 A/A, bcm 5Y4/1, rd gyp silt lam @ 179.2,180,180.4. Sprs org fibres throughout; subtle lalms (coarse); fine to fine gran tx.

183-187.6 F lam clay, nslty-slslty; carbonate throughout; carb lam pink 5YR6/4 @ 183.3,185.5,186.0; lam pred 5YR2.5/2,5YR2.5/1,5Y2.5/1,10YR2.5/1 dk brn, gybrn, dk green; org fibres v sprs but even.

187.6-190 Blk Clay, 10YR2.55/1,5Y2.5/1; nslty, vsl carb, fine tx; double carbonate lams 5Y5/3, f gran tx @ 89.3, green to 5Y3/2 below to 190.

190-193 Clay, c lam, green and gy 5Y4/2; slty in pt, some org fibres; mod carbonate overall; gran tx.

193-195 Clay, slty, brkblk 5YR2.25/1,10YR2.5/1, gran tx, carb.

195-198 Clay, A/A, greens, gys 5Y4/2; carb, gyp slt. Pink 5YR6/3 gyp silt lam in disturbed part of core, @ approx. 197.8 cm.

fin

Appendix E

MINERALOGICAL, ORGANIC, MOISTURE, AND OTHER PARAMETERS MEASURED ON CORE 13.

The following table reports the measured values of various mineralogical, physical, and chemical components within the sediments of Core 13. The methodology involved is given in Chapter 2 and Appendix B.

IDENT	QUARTZ	GYPSUM	CALCITE	DOLOMITE	ARAGONIT	PYRITE	WATER	LOI	LOC
0-2	18.93	7.40	7.84	20.53	45.29	0.00	72.9	27.93	3.45
2-4	25.51	3.59	8.27	19.00	43.62	0.00	75.3	25.89	4.16
4-6	13.63	4.63	6.89	17.53	57.32	0.00	80.1	30.32	6.03
6-8	17.20	4.05	8.94	23.09	46.71	0.00	79.4	29.26	4.07
8-10	16.00	5.30	8.02	27.62	43.06	0.00	77.6	26.93	3.52
10-12	21.39	9.67	8.31	28.91	31.72	0.00	76.3	25.26	3.68
12-14	11.08	7.28	5.38	16.46	55.23	4.58	74.2	23.86	12.80
14-16	15.83	3.84	7.57	19.02	53.74	0.00	76.1	27.54	4.27
16-18	26.09	3.87	9.97	29.00	31.07	0.00	74.3	24.96	4.06
18-20	35.60	1.31	8.79	28.89	18.66	6.75	70.4	19.48	3.40
20-22	17.93	2.60	6.09	19.78	49.04	4.56	70.7	21.65	3.81
22-24	21.40	5.58	10.35	24.17	38.50	0.00	75.5	25.82	3.85
24-26	14.25	1.37	4.32	10.81	69.25	0.00	65.6	21.34	2.88
26-28	33.61	7.02	10.89	16.46	32.00	0.00	67.3	20.91	2.79
28-30	19.22	1.96	7.02	20.31	51.49	0.00	70.5	23.62	8.72
30-32	15.28	4.92	8.45	20.61	46.00	4.75	72.6	24.37	7.02
32-34	23.44	3.69	9.54	23.71	39.61	0.00	68.5	19.44	3.84
34-36	12.46	6.16	5.38	16.18	54.27	5.54	71.0	19.70	14.50
36-38	13.19	2.29	5.69	12.07	62.80	3.96	65.6	20.14	14.38
38-40	18.49	11.99	10.43	21.19	31.19	6.71	74.9	30.63	4.56
40-42	17.97	1.26	6.78	17.37	50.92	5.70	67.0	19.69	6.70
42-44	21.76	1.32	8.36	23.79	39.05	5.72	66.6	22.19	1.45
44-46	13.37	1.34	6.95	13.29	59.39	5.67	67.6	20.05	11.42
46-48	21.95	0.00	10.45	22.55	45.05	0.00	67.8	23.03	6.56
48-50	36.56	0.00	9.38	25.58	22.36	6.12	63.8	16.61	4.18
50-52	24.91	1.12	6.41	19.79	42.65	5.12	64.4	14.83	6.94
52-54	15.51	3.96	7.71	14.57	58.25	0.00	66.2	18.11	12.11
54-56	23.53	6.65	9.74	20.39	39.69	0.00	65.9	19.70	16.08
56-58	20.38	0.00	7.60	18.55	53.46	0.00	66.1	20.41	25.60
58-60	25.55	0.70	7.20	17.08	43.14	6.32	66.5	21.35	7.43
60-62	22.05	5.74	9.63	21.62	40.97	0.00	66.8	18.93	13.44
62-64	29.20	5.93	8.11	17.10	39.66	0.00	65.9	18.65	6.66
64-66	28.65	0.00	14.25	21.77	28.28	7.05	65.9	18.80	11.01
66-68	22.56	9.01	8.38	18.55	41.49	0.00	63.0	19.10	8.45
68-70	24.46	3.94	8.80	20.85	37.21	4.74	66.9	18.60	7.55
70-72	33.41	0.00	14.44	23.19	28.95	0.00	67.5	19.64	23.54
72-74	19.19	2.28	9.01	13.49	56.03	0.00	64.5	20.26	6.43
74-76	25.10	8.91	12.37	19.03	34.59	0.00	67.5	24.92	9.82
76-78	30.37	4.50	3.73	20.38	41.02	0.00	71.8	25.47	7.09
78-80	30.14	10.11	11.98	18.93	28.83	0.00	73.4	30.44	8.39
80-82	49.23	9.06	15.48	26.23	0.00	0.00	70.7	27.10	8.64
82-84	39.42	4.91	10.67	25.00	20.01	0.00	72.3	24.50	9.82
84-86	30.67	0.00	10.18	38.72	20.42	0.00	72.3	27.18	9.23
86-88	19.46	2.95	8.04	23.45	39.70	6.40	75.2	29.40	9.88
88-90	21.27	0.00	11.46	25.83	41.43	0.00	72.9	23.08	16.38
90-92	19.67	3.41	7.24	22.90	40.93	5.85	74.4	29.67	7.77
92-94	15.56	11.94	9.51	18.57	44.42	0.00	71.3	21.80	7.16
94-96	12.37	8.95	6.05	15.20	57.43	0.00	64.0	18.33	7.66
96-98	19.10	9.20	9.06	21.24	41.40	0.00	63.6	16.93	9.99
98-100	41.43	5.45	12.56	40.55	0.00	0.00	70.8	17.26	13.90
100-102	32.92	9.29	14.77	24.49	18.53	0.00	75.3	34.04	8.08
102-104	26.11	5.34	8.44	29.71	30.40	0.00	74.4	24.61	7.64
104-106	19.43	2.97	9.48	18.37	49.74	0.00	67.6	19.60	8.49

IDENT	QUARTZ	GYPSUM	CALCITE	DOLOMITE	ARAGONIT	PYRITE	WATER	LOI	LOC
106-108	24.36	0.00	11.72	33.10	30.82	0.00	73.7	24.90	7.53
108-110	45.65	6.80	7.78	21.89	17.88	0.00	68.6	18.16	2.70
110-112	29.72	7.99	8.48	25.46	28.36	0.00	52.5	10.04	5.07
112-114	21.01	18.55	8.12	25.70	26.62	0.00	47.2	12.36	5.25
114-116	28.70	17.37	13.23	22.38	18.31	0.00	59.9	20.93	4.63
116-118	21.27	8.43	8.39	23.96	33.79	4.16	68.7	24.77	4.69
118-120	35.21	12.84	3.11	17.43	31.41	0.00	61.6	20.80	4.84
120-122	24.73	13.84	2.92	27.46	31.05	0.00	64.9	24.84	4.62
122-124	28.75	4.00	10.48	29.22	27.55	0.00	69.5	30.44	4.10
124-126	13.18	11.94	6.70	13.12	50.67	4.39	64.3	25.33	6.53
126-128	13.76	9.12	6.27	14.49	52.36	3.99	66.4	28.12	6.30
128-130	13.27	4.82	7.99	17.48	56.44	0.00	64.7	26.30	8.74
130-132	18.08	2.75	7.55	19.73	51.89	0.00	63.2	28.49	8.87
132-134	15.95	1.71	6.39	12.53	59.28	4.15	56.7	21.13	11.48
134-136	34.28	0.00	11.05	26.73	27.94	0.00	62.7	21.38	7.35
136-138	38.17	13.84	13.38	34.61	0.00	0.00	73.4	35.78	5.52
138-140	29.82	3.16	10.71	32.76	23.56	0.00	61.2	20.19	6.61
140-142	23.09	2.89	7.95	24.08	41.98	0.00	59.1	20.88	7.99
142-144	16.34	11.16	8.35	23.92	40.23	0.00	71.1	31.85	6.69
144-146	24.64	4.43	8.32	25.45	37.18	0.00	68.4	30.70	4.39
146-148	23.74	3.50	8.19	23.21	41.36	0.00	70.3	31.72	5.14
148-150	21.92	7.73	10.30	24.06	36.01	0.00	70.9	33.99	3.64
150-152	42.35	0.00	13.82	43.84	0.00	0.00	66.6	27.63	2.19
152-154	35.08	7.92	7.40	31.05	18.54	0.00	55.7	20.12	5.03
154-156	9.61	39.74	6.90	26.93	16.82	0.00	44.1	13.39	6.52
156-158	23.14	7.79	13.28	30.66	25.14	0.00	70.1	33.57	6.23
158-160	28.49	3.53	8.68	36.43	22.87	0.00	59.6	21.48	6.43
160-162	14.84	23.23	11.94	17.73	32.26	0.00	45.8	12.59	7.27
162-163	15.88	32.07	4.50	19.69	27.86	0.00	49.0	13.96	5.82