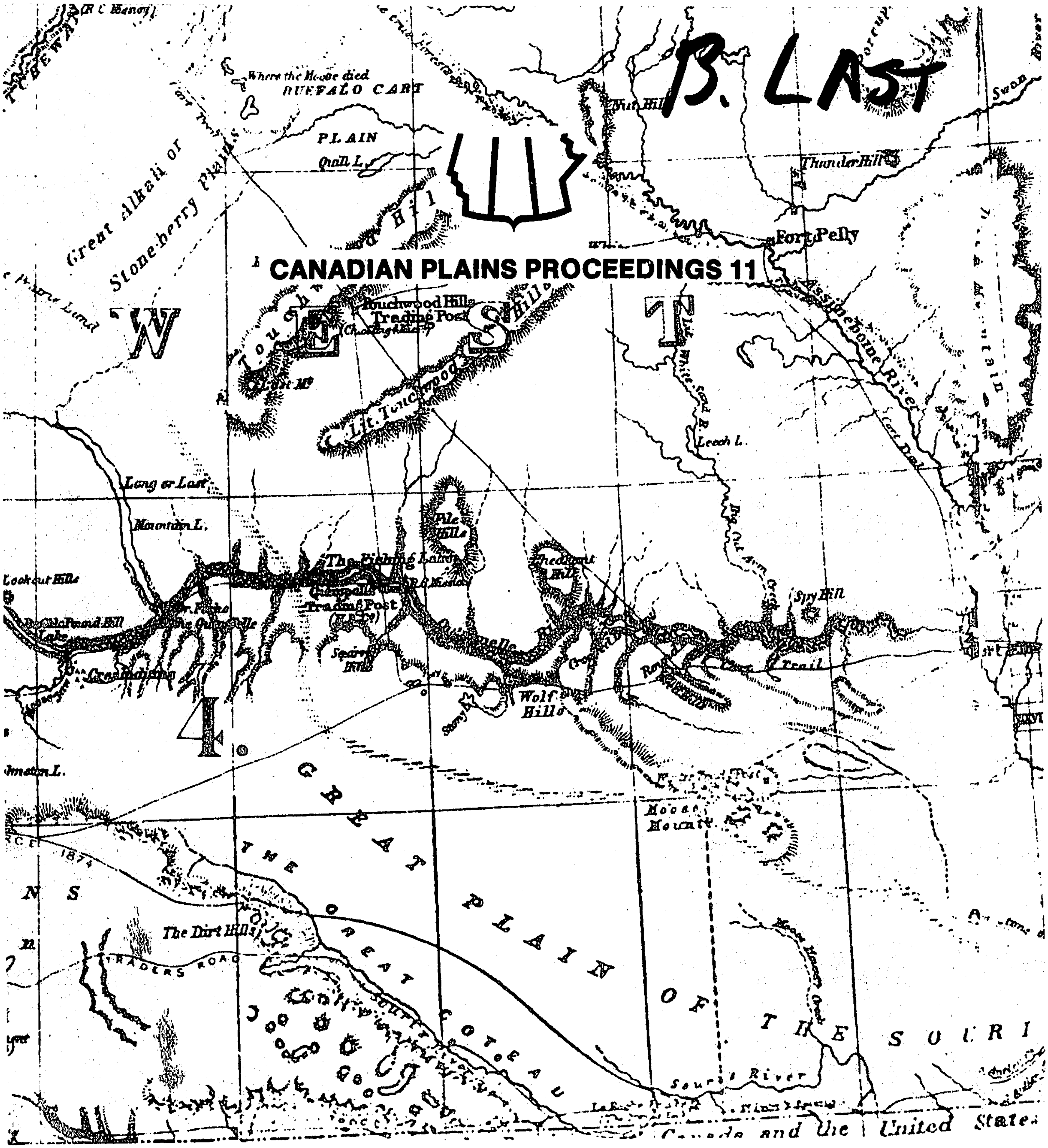

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SEDIMENTOLOGY AND PALEOHYDROLOGY OF WALDSEA LAKE, SASKATCHEWAN

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ABSTRACT

Waldsea Lake is a small meromictic saline lake in central Saskatchewan. The chemocline was first measured at 4 m depth in 1971, and has since dropped to 9 m. Despite its change in elevation, it is still capable of supporting a bacterial plate composed primarily of Chlorobium spp. Major ion chemistry shows that the lake is of the Mg-Na-SO_4-Cl type. The lake irregularly allows massive precipitation of carbonates in the form of aragonite and also occasionally gypsum. These events are rather shortlived, and are represented in the sediment as laminations of nearly pure aragonite of gypsum. Because the lake occupies a closed basin the lacustrine fill provides a detailed record of the late Holocene history of the lake. Sediment cores of the upper 4 m show a complex history of clastic, chemical, and organic sediment input. Superposed on this is an intricate assemblage of early diagenetic effects. The allogenic component consists of fine-grained quartz, dolomite, calcite, feldspars, and clays. Endogenic components include aragonite and gypsum. Early diagenetic dolomite, gypsum, and pyrite are also present. Organic content varies significantly but irregularly throughout the cores. Radiocarbon dating suggests that the upper 4 meters of sediment were deposited during the last 4000 years, and that sedimentation rates have varied significantly. Stratigraphically, these sediments indicate a small shallow, hypersaline lake with extensive mudflats existed in the basin about 4000 years B.P. With the exception of several small reversals, the lake has been continually deepening and becoming less saline throughout its history, likely due to the effects of a moderating climate.

INTRODUCTION

Saline and hypersaline lakes are a common occurrence in the Great Plains of western Canada and the northern United States. Usually occupying closed drainage basins, these lakes range in size from small prairie potholes to several of the largest inland saline bodies in North America. By virtue of the closed nature of the basins, these lakes respond dramatically to environmental changes and thus their sediment records provide excellent documentation of such changes.

Waldsea Lake is a small, relatively shallow saline lake in central Saskatchewan. It has been known to be meromictic since 1971 (Hammer et al., 1978), and has been the subject of numerous biologically-oriented studies during the past decade. Despite its salinity (25 g/l mixolimnion, 68 g/l monimolimnion), Waldsea Lake is part of a regional park and recreation area. The objectives of this report are to: (a) discuss the modern sedimentology of Waldsea Lake; (b) describe the late Holocene stratigraphic record within the basin; and (c) interpret the fluctuations in various sediment parameters with regard to the paleohydrology and geochemistry of the lake.

SETTING

Waldsea Lake is located in the northern Great Plains of western Canada about 100 km east of Saskatoon, Saskatchewan (Fig. 1). The area experiences a cold continental climate with a mean January daily temperature of -20°C and a mean July temperature of 18°C. Annual precipitation at Humboldt, about 10 km south of the lake, averages 375 mm per year. Approximately twice this (750 mm) can be lost through evaporation from the lake's surface (CNC/IHD, 1978).

The area is characterized by hummocky to gently rolling topography with generally poorly integrated drainage and ubiquitous closed depressions. The surficial sediment of the region consists of 100-150 m of till with interbedded fluvial and lacustrine gravels, sands, silts, and clays. The bedrock of the area consists of about 1500 m of Phanerozoic sedimentary rocks overlying Precambrian granitic basement. The bedrock surface in the vicinity of Waldsea Lake shows considerable relief caused by glacial and post-glacial erosion (Meneley, 1967). A major bedrock channel, the Hatfield Valley, with relief of up to 100 m, runs north and east of Waldsea Lake.

The lake has a surface area of just under 5 km^2 with a natural drainage basin area of 32 km^2. An extensive farmland drainage system has increased the watershed area to about 47 km^2. Most of the drainage basin is used for agricultural purposes with cultivation extending to the edge of the lake on all sides.

Waldsea Lake has a mean depth of 5.8 m and a maximum depth of 14.5 m (Fig. 2). The shoreline is generally smooth (shoreline development of 1.3) and there are no islands or peninsulas in the basin. The morphometric characteristics of the lake are summarized in Table 1.

Though the hydrologic budget of Waldsea Lake is poorly known, it is estimated that the basin receives 2.5x106 m^3 of inflow

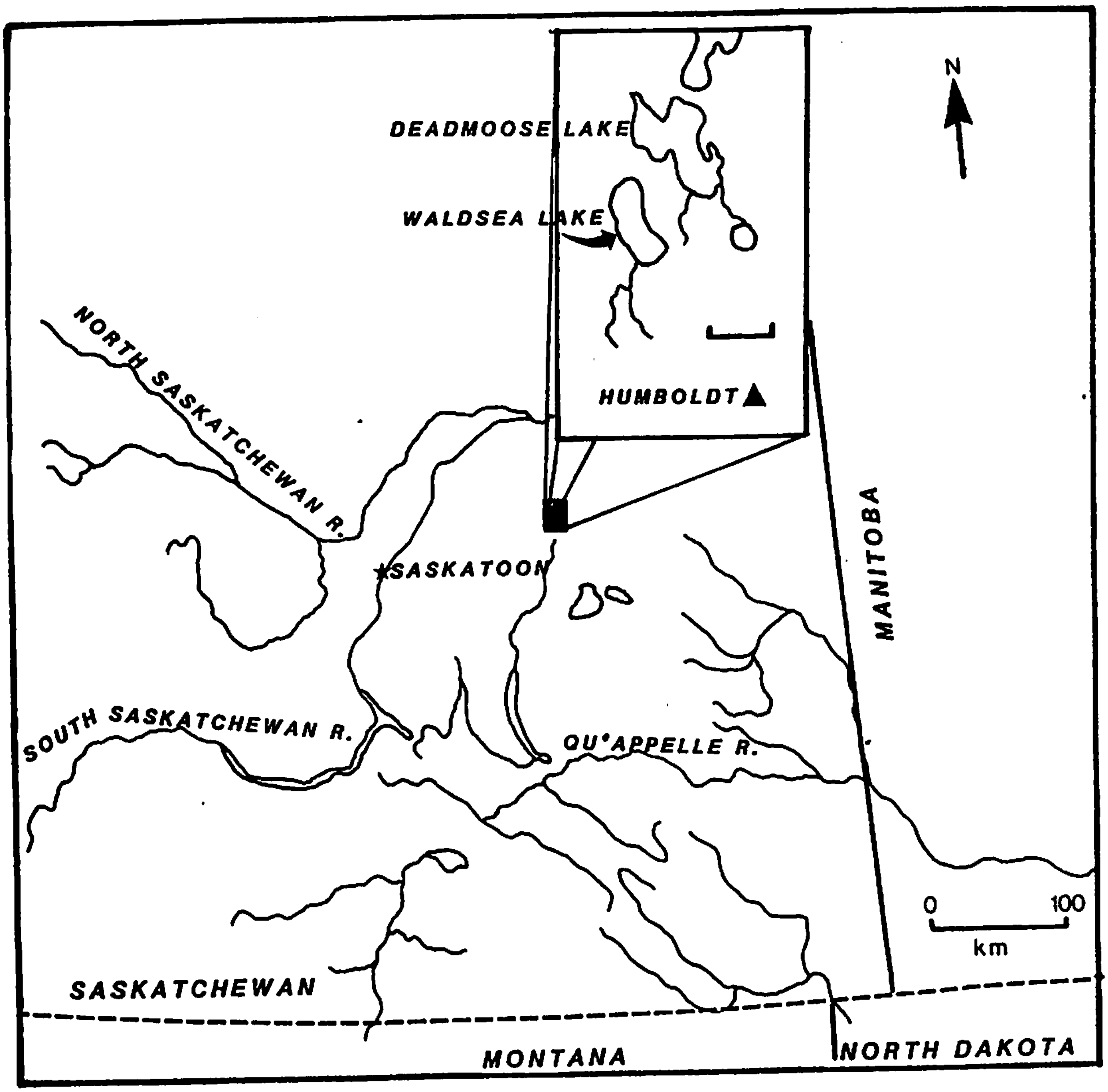

Fig. 1. Location map of Waldsea Lake area.
Scale bar on inset equals 2 km.

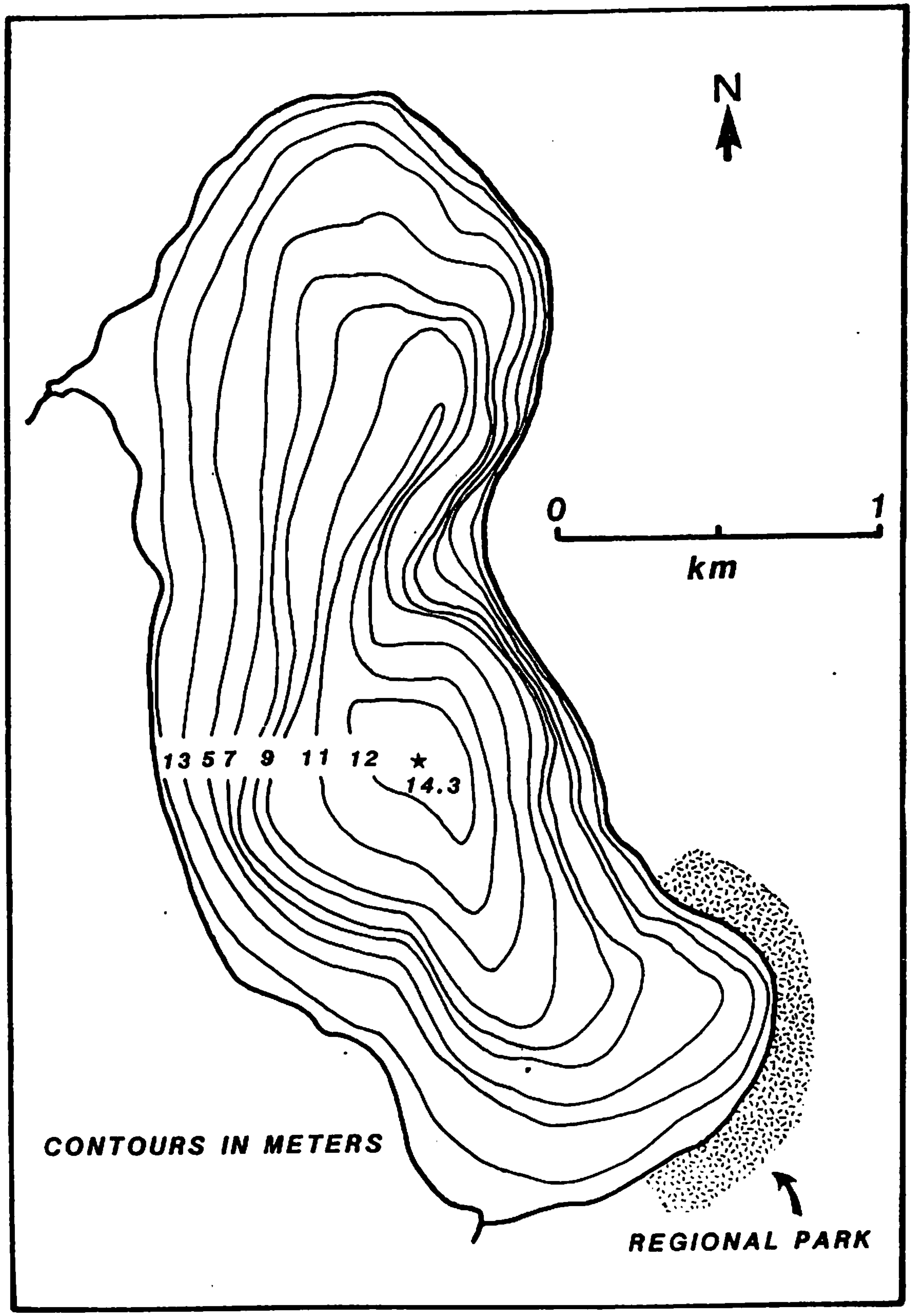

Fig. 2. Bathymetric map of Waldsea Lake (after Swanson, 1978).

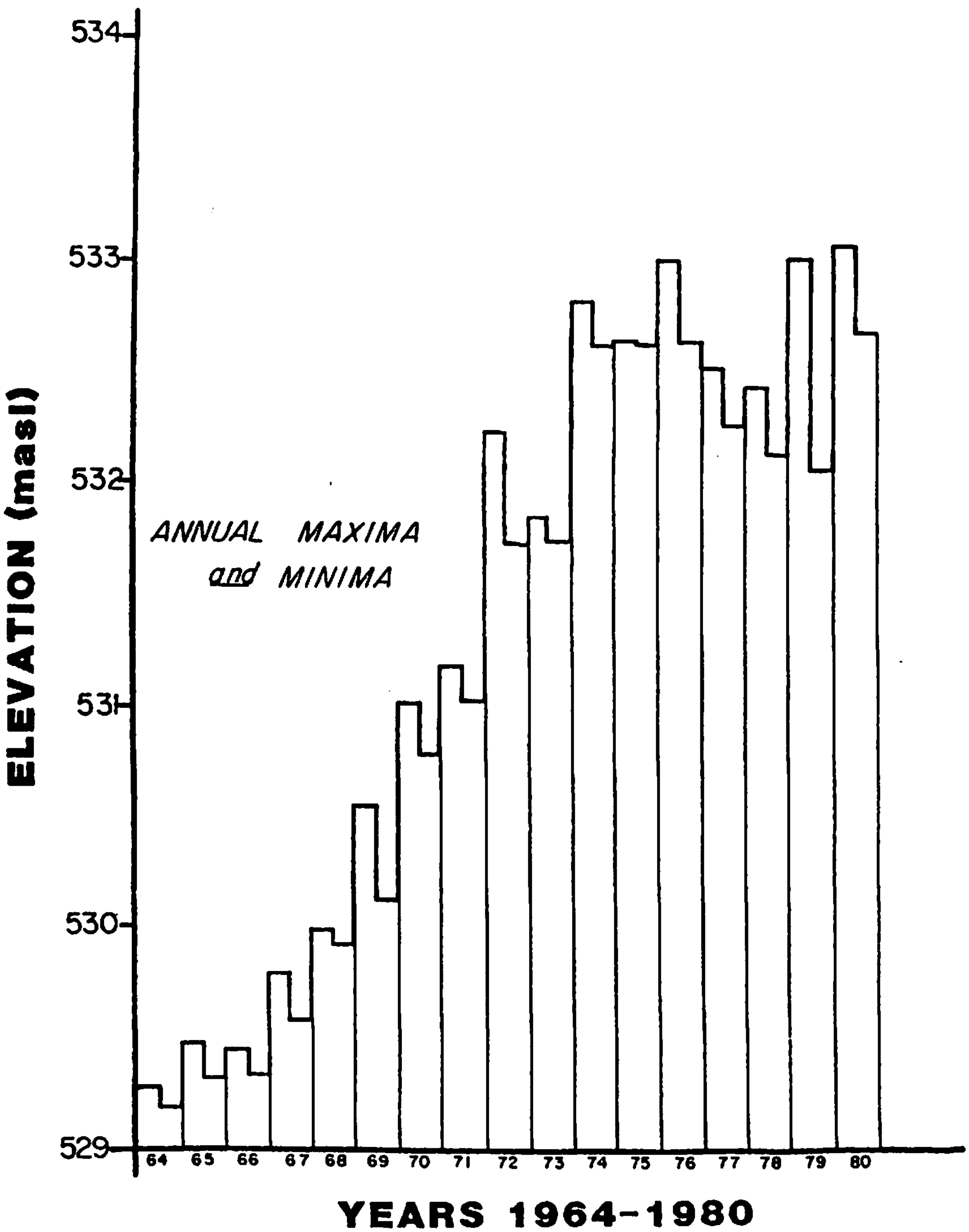

Fig. 3. Changes in surface elevation of Waldsea Lake since 1964.

annually via direct precipitation on the lake's surface and stream runoff. Approximately $3.5x10^6$ m^3 leaves the lake through evaporation. By difference, the groundwater contribution to the basin must be about $1x10^6$ m^3. The water level of Waldsea Lake has risen considerably during the past two decades (Fig. 3). This rise is likely due to an increase in the groundwater component of the hydrologic budget as there is only a very poor correlation (r=0.176) with precipitation changes.

Table 1. Selected morphometric parameters for Waldsea Lake

Surface area	4.64 km^2
Maximum depth	14.5 m
Mean depth	5.8 m
Shoreline length	10.7 km
Shoreline development	1.30
Volume	$37.69x10^6$ m^3
Volume development	1.70
Drainage basin area	47 km^2
Drainage area/lake area	10.0
Relative depth	0.63%
Maximum effective fetch	2.2 km
Percent volume in mixolimnion	88.06
Percent volume in monimolimnion	11.94
Stability of stratification	graphically 4260 g cm/cm^2
(Idso, 1973)	mathematically 3797 g cm/cm^2
Total dissolved salt	$6.93x10^8$ kg
Percent of total salt in mixolimnion	80.08
Percent of total salt in monimolimnion	19.91

Waldsea Lake is currently meromictic with the chemocline present at 9 m depth. A bacterial plate of about 30 cm thickness composed of green sulfur bacteria (mainly Chlorobium spp.) is located at the chemocline (Lawrence et al., 1978). The meromixis of Waldsea is primarily ectogenic in nature, with man-made drainage diversions and deliberate alteration of the peripheral vegetation having created conditions which are favourable to funneling freshwater runoff into the lake. This increased runoff has resulted in doubling Waldsea's volume in the last two decades. Though there is little actual water chemistry data from before 1971, an initial high salinity, and a rapid increase in volume with only a small increase in surface area, created a relatively stable meromixis. Since the early 1970s, though, the level of the chemocline has dropped 5 m, suggesting that the meromixis is not permanent and that with normal weather conditions and no further major drainage basin disruptions, Waldsea Lake will eventually revert to its previous dimictic state.

METHODS

Sediment cores and dredge samples were taken in order to study the present-day geochemical/sedimentological regime of Waldsea Lake, the developmental history of the basin, and any possible man-induced changes in the lake. The cores were retrieved using a modified Livingstone corer. Grab samples of the upper 10 cm of sediment were acquired using an Eckman-style dredge. Water samples were taken using a 2 L acrylic Kemmerer water bottle. Sediment pore water was squeezed from the cores using a Wildco pore water extractor.

The cores were analyzed for water content, organic content, and total carbonate content by weight loss on ignition (Dean, 1974). Bulk mineralogy and detailed carbonate mineralogy were semiquantitatively assessed by X-ray diffraction using the methods of Chung (1974a,b) and Goldsmith and Graf (1958). Texture, sedimentary structures, and colour (Munsell) were described from the fresh sediment cores. Trace element content of the cores was done by emission spectroscopy. All water samples were analyzed for major ions by standard laboratory techniques (Stainton et al., 1977).

WATER CHEMISTRY

Major ion data for Waldsea Lake are shown in Table 2. The chemistry of the mixolimnial water varies moderately from year to year as runoff increases or decreases. Monimolimnial water chemistry remains relatively constant. Even though Waldsea Lake water is perennially slightly supersaturated with respect to various carbonate phases, massive inorganic precipitation of carbonates due to evaporative concentration occurs endogenically on an irregular basis. The elevated Mg/Ca ratio (30-35) and high salinity of the water dictate that aragonite is the carbonate phase which will be precipitated (Muller et al., 1972). Analysis of the water chemistry data using the computer program WATSPEC (Wigley, 1977) indicates that the lake is also near supersaturation with respect to gypsum (log(IAP/Ksp) > 1).

Table 2. Average major ion chemistry of Waldsea Lake (Data from Lawrence, 1978).

Parameter	Mixolimnion	Monimolimnion
	ppm	ppm
Sodium	4100	7800
Magnesium	3350	6050
Calcium	106	177
Potassium	300	575
Chloride	4750	8650
Sulfate	16000	30000
Bicarbonate	122	122
Silica	0.3	30
pH	8.4	7.7
Eh	+10mv	-200mv
Specific conductance mmhos per centimeter	28.9	45.7

MODERN SEDIMENTOLOGY

The modern sediments of Waldsea Lake are mainly sapropelic silty clay and clayey silt in the offshore region of the basin, grading to slightly coarser sediments nearshore. The present-day shoreline deposits consist of a thin mantle of sand and gravel over till and Holocene soil. Due to the significant increase in the level of the lake over the past two decades, the beaches have not yet achieved an equilibrium profile, but rather consist of a wave-cut notch developed into glacial or early Holocene sediment.

Despite Waldsea's salinity and meromixis, physical sedimentation in the lake is very similar to what one might expect from any stratified freshwater lake of similar morphometry (see, for example, Sly, 1977). In Waldsea Lake winnowing of fine-grained material at the shoreline by wave action during transgression of the shoreline is likely a major source of sediment transported to the deeper basin, and may be responsible for accelerated sedimentation rates over the past 20 years. However, wind action is also capable of moving large volumes of allogenic sediment long distances on the Plains. Some of this wind-blown sediment inevitably falls into the bottom deposits. On the basis of our observations over the past two years, this aeolian material may be a very important component of Waldsea's modern sediment budget and efforts to quantify the relative contribution of each of the major allogenic sources are in progress.

In addition to the allogenic component, which is composed of quartz, feldspars, dolomite, calcite, and clay materials, about half of Waldsea's offshore bottom sediment consists of materials generated from processes occurring within the water column (endogenic). This fraction is made up of organic debris, aragonite, and gypsum. As outlined above, the endogenic mineral phases are the result of inorganic precipitation caused by supersaturated conditions.

STRATIGRAPHY

The upper 4 m 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 5-45% but does not exhibit any specific trend with depth. Thin zones of relatively pure organic fibre mats occur within the lower 2 m of section. Sediment colours are generally dark grey (2.5Y2.5/1) to dark greenish grey (5Y2.5/2) with abundant lighter laminae (10YR4/1) throughout.

We divided Waldsea Lake sediments into five major stratigraphic units on the basis of texture, mineralogy, bedding characteristics, colour, and organic content. 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 (gypsite) 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).

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 preserved pigments. Within this sediment are mirabilite ($Na_2SO_4.10\ H_2O$) crystals which are commonly transparent and mud-free and show syntaxial overgrowths and gas-phase fluid inclusions. 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 indicated hypersaline conditions with the lake basin at the time of deposition, and probably a much lower lake level.

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 mm of each other in the section. The rounded gypsum silt is interpreted as primary gypsum undergoing dissolution, whereas the lensoid gypsum is a product of very early diagenesis. The carbonates within these units show even more eclectic textures and structures. These range from finely crystalline buff (10YR5/1) dolomite "hardgrounds" and cemented laminae to calcite-coated twigs and fine algal filaments. In addition these units commonly contain intraclasts of carbonate material that probably were partially consolidated and then ripped up and redeposited by storm-derived currents or waves. 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 and, as such, is either a primary precipitate or, more likely, a penecontemporaneous alteration product of pre-existing calcium carbonate. Although the genesis of this domomite in Waldsea Lake has not yet been fully resolved, both formative modes, that is, endogenic and authigenic, imply an elevated Mg^{2+}/Ca^{2+} ratio of the brine and possibly schizohaline conditions.

Unit 2 may be time-correlative with Unit 1, as Unit 1 occurs in the southern part of the lake, and Unit 2 has only been identified to the north. The key to understanding the conditions under which this could occur is by the paleomorphometry of the lake.

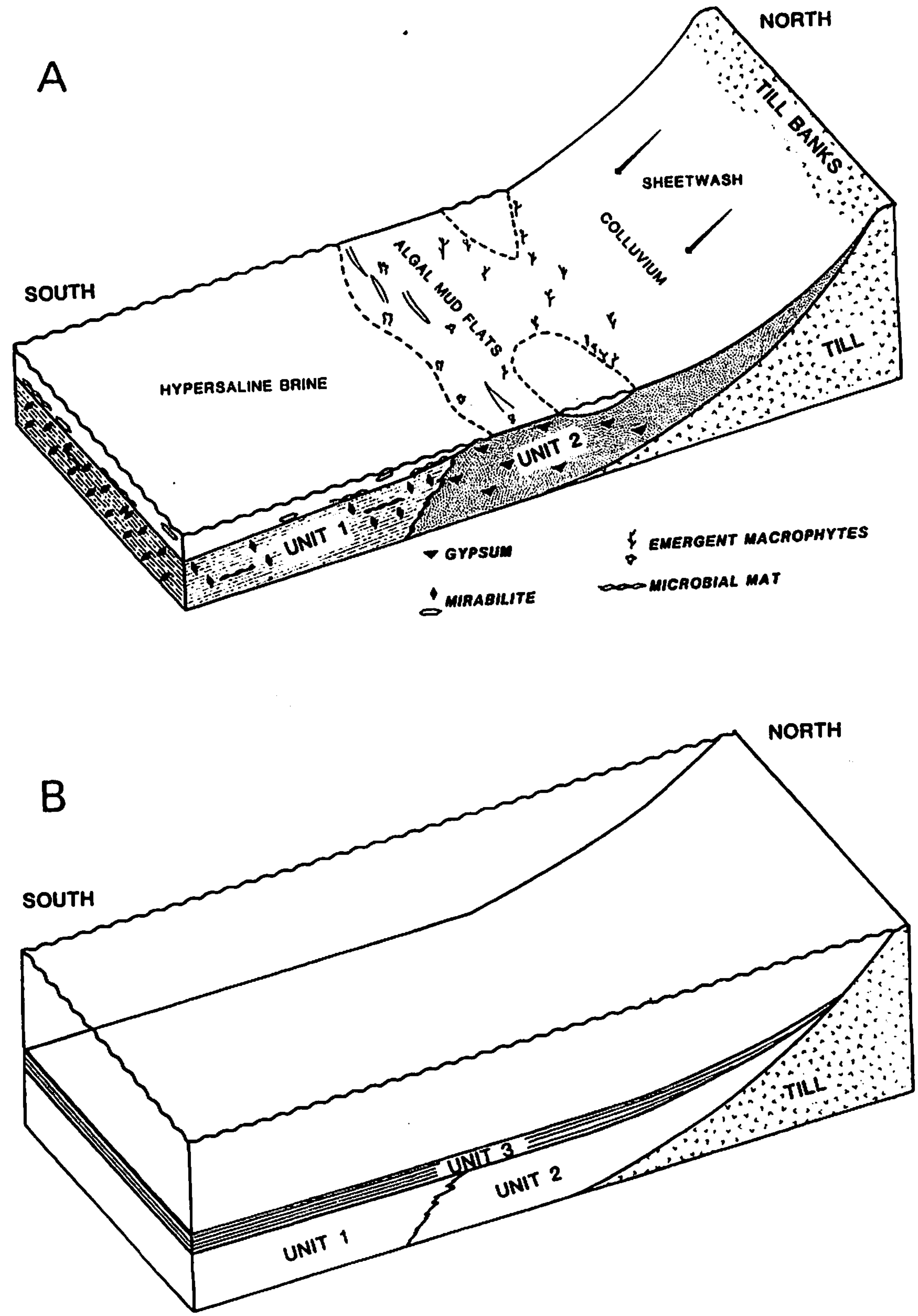

Fig. 4. Schematic block diagram representing the interpreted environmental setting of Waldsea Lake during deposition of Units 1, 2, and 3. A is about 4000 years B.P.; B is about 3000 years B.P.

Fig. 4 shows the interpreted palemorphometry in relation to the cross section of the sediments recovered from Units 1, 2, and 3.

Units 3 and 5 consist exclusively of dark brown to black silty aragonite-rich sapropel to silty sapropelic mud with irregularly spaced very fine-grained aragonite laminae. The colour of these laminae range from white (7.5YR8/8) to buff (10YR5/1) but some show a distinct red (5R5/6) colouration. This latter colour is attributed to organic pigments, such as carotenoids and chlorophylls, sedimented with or either immediately before or after the aragonite precipitaton. Because the aragonite occurs mainly in distinct and relatively pure laminae, it is likely that each lamina was deposited during a "whiting" event. These events may have been produced by high levels of supersaturation brought about by evaporation or accelerated biological uptake of carbon dioxide during photosynthesis. In view of the limited biota due to the salinity of the lake system, the former mechanism seems more plausible.

Aragonite also exists in a disseminated form in Units 3 and 5, indicating that the water column has remained at least slightly supersaturated during relatively long periods of time. Radiocarbon dating of the sediment at the base of Unit 5 yielded an age of 2340±70 years (Beta-6507). The uniformity and thickness of this unit and its similarity to Unit 3 indicates that chemical and hydrologic conditions did not change significantly during long periods of time.

Based on the nature of the lacustrine fill in the Waldsea Lake basin and on the fluctuations in the parameters evaluated, a late Holocene developmental history of the lake can be deduced (Fig. 5). Approximately 4000 years ago a small hypersaline lake existed in the southern portion of the Waldsea Lake basin. Hypersaline mudflats produced laminated carbonate and gypsum sediments (Unit 2) to the north, probably at the same time as the organic and salt-rich mud of Unit 1 was being deposited to the south. Increased runoff and decreased evaporation due to gradual climatic change allowed the expansion and deepening of the lake and deposition of Unit 3. A minor climatic reversal returned evaporative conditions to the basin with possible contraction of the lake and deposition of the gypsum/carbonate rich sediment of Unit 4. This evaporite phase was short-lived, however, and the lake continued to deepen after about 2300 years B.P. Unit 5, with its irregularly spaced aragonite laminae in a mud matrix, suggests relatively constant "deep" water clastic sedimentation conditions, punctuated by frequent massive carbonate precipitation from the water column.

Despite striking evidence of man's activities and manipulations of Waldsea Lake and its catchment area during the past half-century, there seems to be little evidence of significant anthropogenic impact within the sedimentary record. Our preliminary chemical analyses of the heavy metal content of the sediment (including Cd, Cr, Co, Cu, Fe, Pb, Hg, Ni, Ti, V, and Zn) has failed to identify any type of enrichment above background levels in the

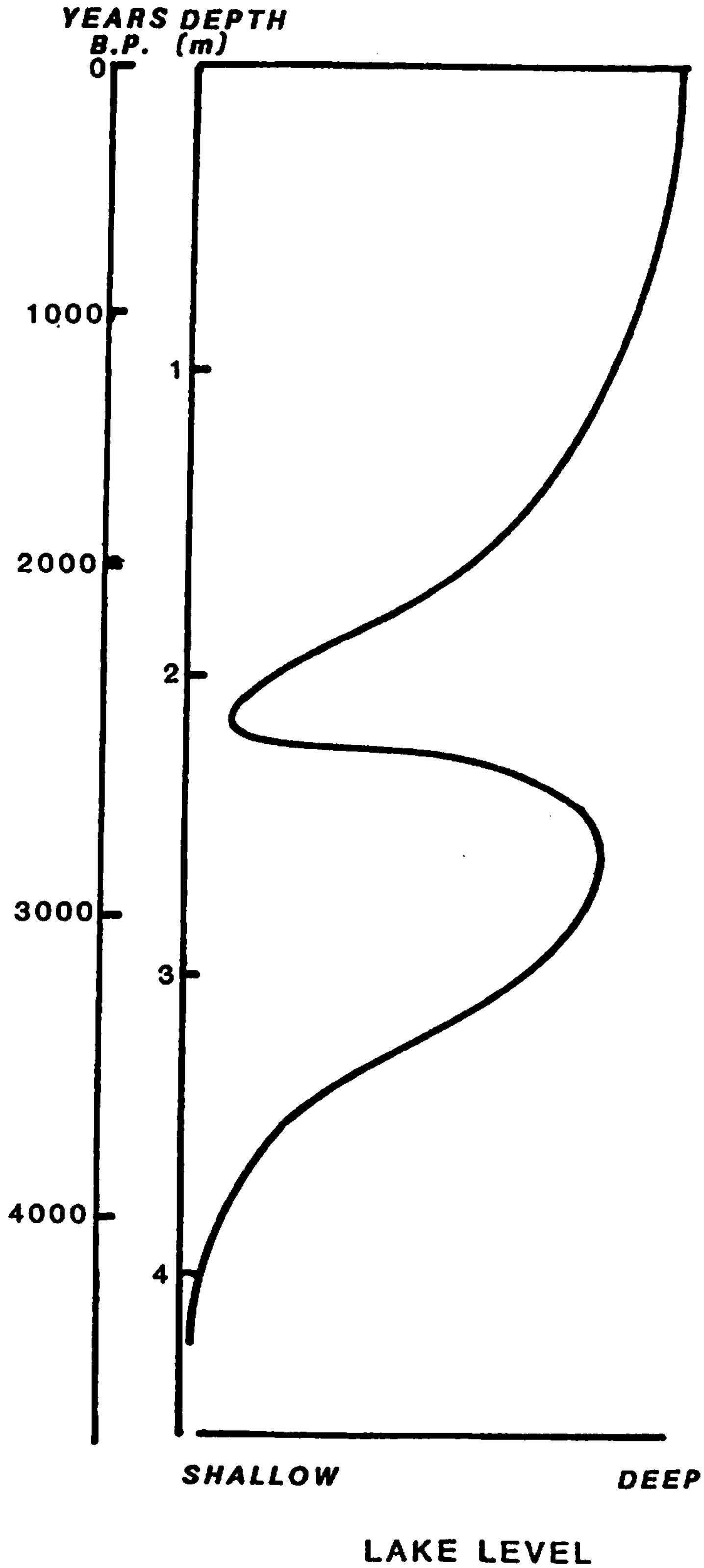

Fig. 5. Generalized lake level history of Waldsea Lake during the last 4500 years.

most recent deposits. Although our dating and chronology of the upper sections of lacustrine fill is not yet complete, there is no obvious change in sediment character or distribution in the top several decimeters, suggesting relatively little actual disruption (in terms of quantity and type of sediment) associated with agricultural development. While it is likely that man's actions have contributed directly to the generation and maintenance of meromixis in the lake over the past two decades, this meromixis is relatively unstable. Continued mixing within the mixolimnion will soon lower the chemocline to the lake bottom and Waldsea Lake will revert to its previous dimictic state.

CONCLUSIONS

Geolimnological studies on Waldsea Lake are at present in an exciting stage. Because the lake has been saline to hypersaline thoughout most of its last 4000 years, bioturbation is almost completely lacking. Thus, the sediment fill records an extremely detailed history of changes in chemical, vegetational, and hydrologic, as well as diagenetic conditions within and around the basin. Although variations in these environmental conditions are all intimately interdependent, the driving mechanism for maintenance or change in the type and rate of sedimentation is climate. An understanding of the way in which Waldsea Lake, as a sedimentological as well as biological system, responds to given hydrologic and chemical conditions, will make it possible to derive useful information on the temporal pattern of past climatic changes.

Our initial work on the late Holocene record in the lake has indicated that the relative proportions of endogenic and allogenic materials are not constant, and probably fluctuate in response to increased or decreased runoff. From the section of sediments retrieved and studied to date, physical and mineralogical parameters indicate that the lake was at a much lower phase approximately 4500-4000 years ago, and that with only one important reversal at about 3000 years B.P., lake level has been rising nearly continuously for the last 2300 years. This is likely coupled with an overall decrease in salinity, even though small amounts of solid salts of mirabilite are being dissolved out of the sediment and entering the lake by diffusion.

Our most pressing task in the immediate future is to gain a better understanding of the precise mechanisms controlling early diagenesis of the inorganic components in the sediments, particularly those involving the various carbonate and sulfate mineral phases. Once we have a clearer picture of the nature of these diagenetic reactions, a sedimentological-geochemical model for Waldsea Lake can be constructed, and then used to help predict the way in which closed lakes such as this respond to changes in level, chemistry, and other man-induced modifications.

ACKNOWLEDGMENTS

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