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Late Holocene History of Waldsea Lake, Saskatchewan, Canada

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The post-Hypsithermal history of Waldsea Lake, a saline meromictic lake located in south-central Saskatchewan, has been deduced from a study of the changes in physical, mineralogical, and paleobiological parameters in sediment cores from the basin. Six lithostratigraphic units and three palynological zones are identified in the most recent sediment. These units and zones indicate that a shallow hypersaline lake with extensive mudflats existed about 4000 yr B.P. In response to the subsequent trend toward a cooler and wetter climate, deeper water conditions ensued, and by about 3000 yr ago a relatively deep stratified lake occupied the Waldsea Basin. A short climatic reversal about 2500 yr B.P. again caused low-water and mudflat conditions, but by 2000 yr ago the lake had regained its higher levels. The past 2000 yr of Waldsea's history have been relatively uneventful, except for a minor lowering of the lake about 700 yr B.P.

INTRODUCTION

Lakes occupying closed drainage basins often respond dramatically to environmental change. The sedimentary fill in these basins can yield a very sensitive record of past fluctuations in water chemistry, hydrology, organic productivity, lake levels, drainage basin characteristics, and climate.

Large areas of the northern Great Plains of Saskatchewan, Alberta, North Dakota, and Montana are characterized by internal drainage. These areas contain thousands of closed-basin lakes, ranging in size from small prairie "potholes" to several of the largest inland salt-water bodies in North America. Although most of these lakes are shallow and intermittent (i.e., playas), some are relatively deep. Several of the deep, perennial closed-basin lakes are meromictic. The objective of this paper is to discuss the most recent, 4000-yr history of one of these chemically stratified lakes—Waldsea Lake.

REGIONAL SETTING

Waldsea Lake is located in south-central Saskatchewan, approximately 100 km east of Saskatoon (Fig. 1). The area is underlain by 600 m of Mesozoic sandstones and shales and 750 m of Paleozoic carbonate rocks and evaporites. The surficial sediments of the area consist mainly of calcareous till and glaciolacustrine material (Meneley, 1964). The land surrounding Waldsea Lake is gently undulating and extensively cultivated. Natural vegetation of the region is typical aspen parkland, transitional between prairie grassland to the south and west and pine–spruce forests about 100 km to the north.

The area experiences a cold semiarid continental climate. The average daily temperature during January is −18°C; during July it is 19°C. Annual precipitation averages 36 cm; however, more than twice this amount can be lost by evaporation (CNC/IHD, 1978).

METHODS

Data for paleoenvironmental and chronological interpretation of Waldsea Lake have come from approximately 80 m of sediment core from 31 sites in the basin (Fig. 2). These cores range in length from 1 to 4 m, with the longer cores providing the basis for most of the interpretation in this paper. Coring was done during the winters of 1981–1984 with a modified Livingstone piston sampler. In addition, dredge samples of the upper 20–30 cm of sediment were collected during the ice-free seasons.

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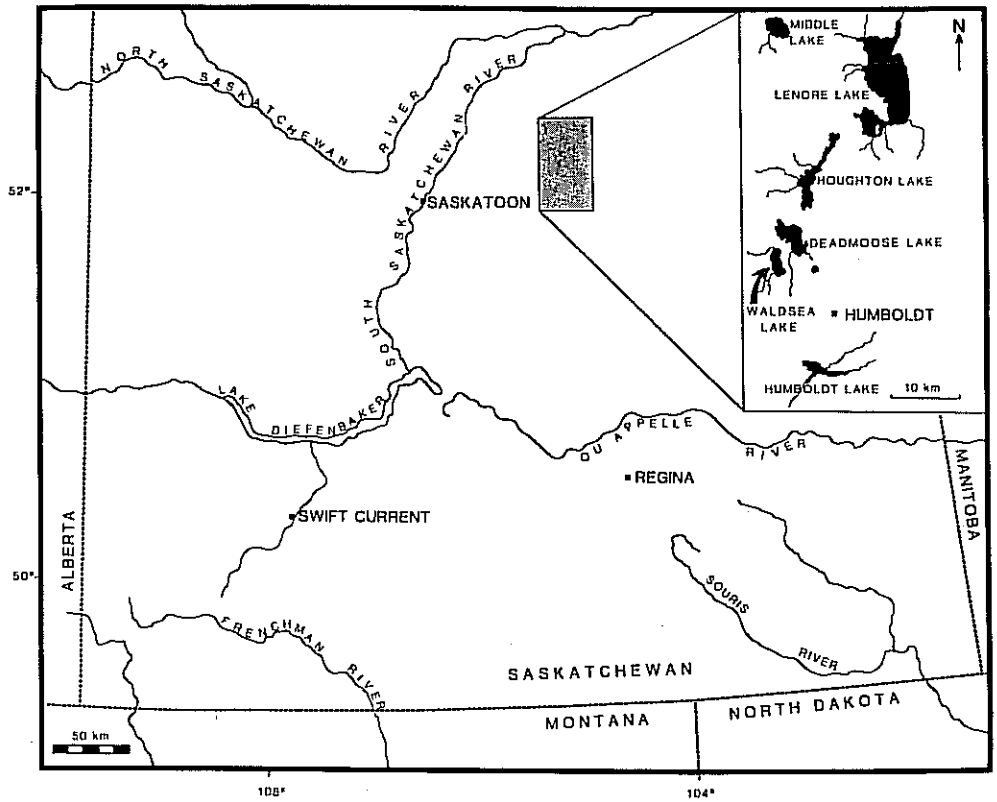


FIG. 1. Map showing the location of Waldsea Lake.

After extrusion and detailed description of the sediment cores for color, texture, bedding, macroscopic mineralogy, and organic content, subsamples were taken for various other physical, chemical, mineralogical, and paleobiological analyses, including water content, total organic matter content, total carbonate content, bulk and detailed mineralogy, trace metal content, and pore-water chemistry. Four samples of organic mud were dated by the radiocarbon method. One core was analyzed for pollen by S. Kroker (Quaternary Consultants, Winnipeg). All analyses were done by standard laboratory techniques as summarized in Last (1980), Schweyen and Last (1983), and Schweyen (1984).

MODERN WALDSEA LAKE

Waldsea Lake is one of several remnants of glacial Lake Melfort, which formed about 12,000 yr ago (Meneley, 1964; Christiansen, 1979). Morphologically the basin is simple, with steep sides, a relatively flat bottom, and a smooth shoreline (Fig. 2). The lake has a surface area of just under 5 km^2 and a natural drainage basin area of 32 km^2. Within the last decade construction of an extensive agricultural drainage system has increased the watershed area to about 47 km^2. Some of the main morphological and hydrologic parameters are given in Table 1.

The lake is saline and meromictic, with a chemocline located at about 8 m depth. The mixolimnion averages 29 g/liter total dissolved solids and the monimolimnion about 53 g/liter. Because the chemocline also contains a bacterial plate composed of a green sulfur bacteria, *Chlorobium*, modern Waldsea Lake has received considerable systematic attention from biologists and

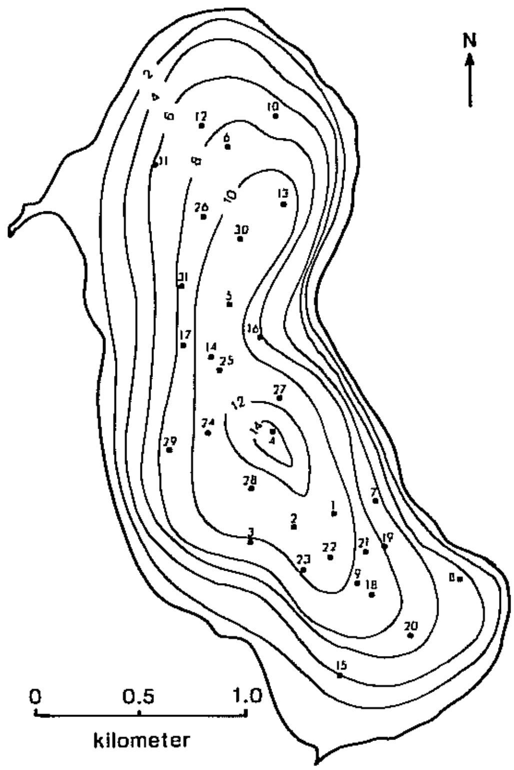


FIG. 2. Map of Waldsea Lake showing bathymetry and location of cores taken for this study. The bathymetric contour interval is 2 m.

limnologists (e.g., Hammer *et al.*, 1978; Lawrence *et al.*, 1978; Parker *et al.*, 1983; Swanson and Hammer, 1983). The ionic content of both water masses is dominated by sodium and sulfate, with secondary abundances of magnesium and chloride (Table 1). The entire water column is saturated or supersaturated with respect to various carbonate mineral phases at all times of the year, and, because of the high Mg/Ca ionic ratio of the brine, aragonite precipitation occurs (Schweyen and Last, 1983). The monimolimnion is also at or near saturation with respect to gypsum.

The modern sediments (upper 2 cm) of Waldsea Lake are mainly sands and silts in the nearshore areas, grading to finer-grained organic clays in the offshore areas. The sediments are composed of a complex mixture of detrital material (quartz, carbonates, feldspars, and clays), organic matter, endogenic precipitates (aragonite and gypsum), and very early diagenetic products (iron sulfides and carbonates). About half of Waldsea's modern offshore bottom sediment mass has been generated within the basin itself, either endogenically or authigenically.

STRATIGRAPHIC UNITS

General

Throughout most of the Waldsea Lake Basin the upper 4 m of sediment is well-laminated organic silty clay and clayey silt. Coarser-grained silts, sands, and gravels are found near the basin margins and in the lower half meter of the cored section in the northern part of the basin. Sediment colors are generally dark gray (2.5 Y 2.5/1) to dark greenish gray (5 Y 2.5/2) with abundant lighter laminae (10 YR 4/1) throughout. The moisture content decreases from 80% in the youngest sediment to about 40% at the base of the cores, whereas the pore-water salinity shows a general increase with depth to a maximum of about 100‰. Organic-matter content ranges from less than 5 to 60%, but does not exhibit any specific trend with depth. Thin zones of relatively pure organic fiber mats occur mainly within the lower 2 m of the section. Although the entire 4 m of sediment is well laminated, distinct packages of varve-like couplets predominate only in the upper half of the section.

Overall, the mineral suite of the older sediments in Waldsea Lake is similar to that of the modern sediments described above, except that magnesian calcite, protodolomite, magnesite, and mirabilite also occur. The various mineralogical parameters exhibit little systematic change with depth. Quartz, gypsum, and total carbonates increase slightly downward in the cores, while aragonite and clay minerals decrease with depth.

Lithostratigraphy

Based on sediment color, mineralogical

TABLE 1. MORPHOMETRIC, HYDROLOGIC AND CHEMICAL CHARACTERISTICS OF WALDSEA LAKE

Maximum length	3.7 km	
Maximum width	1.4 km	
Maximum depth	14.5 m	
Mean depth	8.1 m	
Area	4.7 km^2	
Volume	37.7×10^6 m^3	
Drainage area	47 km^2	
Length of shoreline	10.2 km	
Estimated annual inflow, direct precipitation, and diffuse runoff	1.6×10^6 m^3	
Streamflow	0.9×10^6 m^3	
Groundwater	1.0×10^5 m^3	
Estimated annual evaporation	3.5×10^6 m^3	
Brine Composition	Mixolimnion	Monimolimnion
K^+	4 mmole/liter	7 mmole/liter
Na^+	192 mmole/liter	304 mmole/liter
Ca^{2+}	8 mmole/liter	11 mmole/liter
Mg^{2+}	162 mmole/liter	231 mmole/liter
HCO_3^-	5 mmole/liter	7 mmole/liter
Cl^-	111 mmole/liter	250 mmole/liter
SO_4^{2-}	130 mmole/liter	313 mmole/liter

composition, texture, sedimentary structures, moisture content, and organic-matter content, six lithostratigraphic units can be recognized in the Waldsea Lake Basin. Not all of the units were encountered in all of the cores, and in some areas of the basin selected units were absent, as shown schematically in Figure 3. The main physical and mineralogical characteristics of each of these six units are summarized in Table 2.

Unit 1. The basal unit recovered from Waldsea Lake is a massive to coarsely laminated black organic silty clay and clayey silt. It is characterized by (a) an abundance of disseminated plant fibers and fiber mats up to 3 cm thick (Fig. 4A), and (b) crystals and lenses of mirabilite (Fig. 4B). The abundance of disseminated fibers, fiber mats, and mirabilite decreases upward in the unit. Most of the mirabilite is in the form of large, clear, isolated subhedral crystals, some of which have inclusions of mud or plant detritus. Occasionally the crystals show obvious dissolution and/or syntaxial overgrowths. Unit 1 is also relatively low in quartz, aragonite, and dolomite and high in calcite and gypsum. *Artemia* oogonia are very common and ostracods can occur concentrated in laminae. The unit has been identified only in the southern part of the basin; it grades laterally into and interfingers with Unit 2 to the north and Unit 3 upward in the section.

Unit 2. Unit 2 consists of finely laminated grayish-green gypsiferous sand, silt, and clay. The gypsum shows a variety of morphologies and textures, including euhedral lenticular plates, rosettes, and rounded grains (Figs. 4C and D). Organic fibers and fiber mats are present but are not so abundant as in Unit 1. Interbedding with carbonate-rich laminae is common. The carbonates of Unit 2 are also quite variable mineralogically and texturally. Calcite pellets and coated plant fragments, calcareous intraclasts, dolomite-cemented hardgrounds and laminae, and finely disseminated aragonite, protodolomite, magnesite, and hi-Mg calcite are all present in Unit 2 (Fig. 5). The unit exhibits a gradational upper contact with Unit 3. The precise stratigraphic relationship between Units 1 and

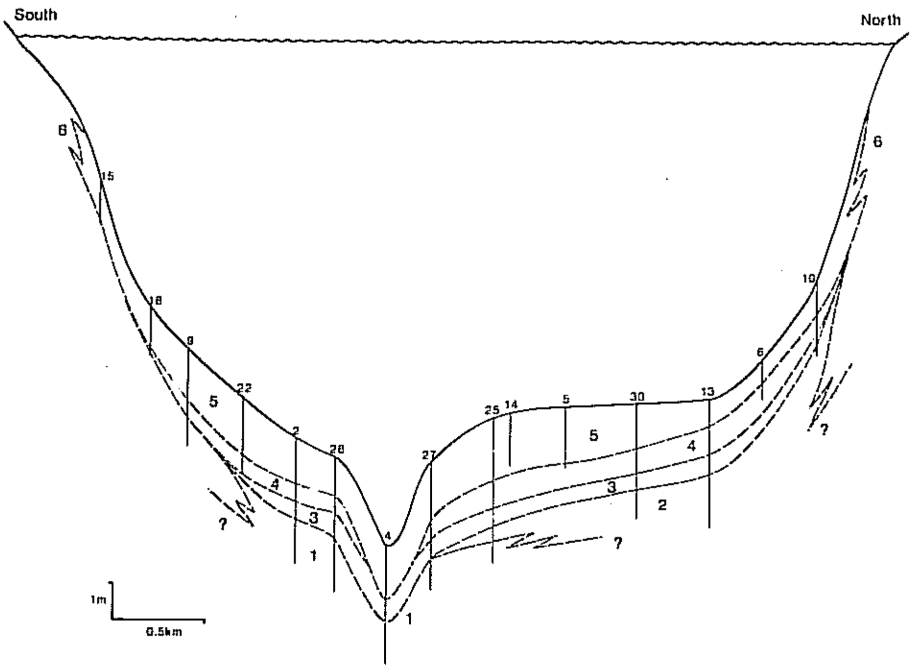


FIG. 3. Generalized north–south cross section showing basin-wide correlation of lithostratigraphic units in Waldsea Lake. Numbers at the sediment–water interface refer to core locations as shown in Figure 1.

2 is not known. In the northern part of the basin (north of location 30), coring was unable to penetrate Unit 2 completely. However, in the central part of the basin Unit 2 overlies Unit 1, whereas at the south end (south of location 24) Unit 2 is not present and Unit 1 grades upward into Unit 3.

Unit 3. Overlying Units 1 and 2 throughout most of the basin is a black to dark-brown well-laminated organic silty clay 50 cm thick. The lamination in this unit consists of an irregular sequence of millimeter-thick light/dark couplets (Figs. 6A and B), with the light laminae (7.5 YR 8/8) being composed entirely of finely crystalline aragonite and the dark portion being a mixture of carbonate minerals, clays, and organic matter. Some of the light laminae have a distinctive red (5 R 5/6) coloration, likely due to organic pigments (U. T. Hammer, 1982, personal communication). Detailed microscopic examination of individual couplets often reveals a finely laminated microstructure within the beds. As many as four microlaminations have been identified in a single light/dark couplet.

Unit 4. Unit 3 grades upward into a grayish-green gypsum-rich clayey silt very similar to Unit 2. Plant fiber mats, thin dolomite-cemented zones, and gypsum silt–sand laminae are present, whereas the fine-grained aragonite laminae, which are characteristic of the underlying Unit 3, are rare.

Unit 5. Unit 5 consists of up to 2 m of black organic silty clay similar to Unit 3. The unit is also finely laminated throughout with thin (0.5–1.0 mm) irregular white to yellowish-brown to pinkish aragonite–clay couplets. Occasional laminae composed of ostracods or quartz sand occur. Organic matter and moisture contents are high and increase upward in the section. The aragonite laminae are absent in the upper 4 cm of the unit.

Unit 6. In the nearshore portion of the basin Unit 5 grades laterally and interfingers with a relatively coarse clastic unit composed of quartz and carbonate-rich

TABLE 2. SUMMARY OF AVERAGE MINERALOGICAL AND PHYSICAL PARAMETER VALUES OF THE SIX LITHOSTRATIGRAPHIC UNITS RECOGNIZED IN THE LATE HOLOCENE SEDIMENT RECORD OF WALDSEA LAKE (BASED ON ANALYSES OF CORES, 4, 11, 13, 25, 26, 27, AND 31)

Unit	% Moisture	% Organic	Grain size		
			% Sand	% Silt	% Clay
6	43.2 (6)	7.9 (6)	82.1 (4)	16.8 (4)	1.1 (4)
5	75.9 (198)	22.8 (198)	1.0 (22)	29.2 (22)	69.8 (22)
4	63.2 (103)	24.1 (103)	1.5 (12)	46.0 (12)	52.5 (12)
3	66.1 (90)	28.6 (90)	1.1 (5)	28.8 (5)	70.1 (5)
2	59.0 (96)	28.1 (96)	6.2 (6)	37.9 (6)	55.9 (6)
1	61.9 (148)	25.4 (148)	1.9 (18)	29.8 (18)	68.3 (18)

Unit	Mineralogy							
	% Quartz	% Feldspars	% Clay minerals	% Gypsum	% Aragonite	% Calcite[a]	% Dolomite[b]	% Pyrite
6	72.1 (4)	12.0 (4)	ND[c] (4)	2.1 (4)	2.0 (4)	3.0 (4)	8.8 (4)	ND[c] (4)
5	6.3 (96)	10.1 (96)	28.4 (96)	21.1 (96)	7.6 (96)	3.1 (96)	8.0 (96)	15.4 (96)
4	8.2 (31)	12.6 (31)	19.2 (31)	25.7 (31)	5.8 (31)	3.3 (31)	12.8 (31)	10.3 (31)
3	4.9 (24)	9.8 (24)	29.9 (24)	17.2 (24)	10.1 (24)	5.1 (24)	9.0 (24)	14.0 (24)
2	11.8 (44)	8.4 (44)	29.2 (44)	26.1 (44)	6.0 (44)	2.8 (44)	11.7 (44)	4.8 (44)
1	3.8 (64)	4.9 (64)	29.5 (64)	31.9 (64)	2.5 (64)	17.3 (64)	7.0 (64)	4.6 (64)

Note. The figures in parentheses are the total number of analyses. The average sampling density for the mineralogical analyses is 1 sample/3 cm; for the moisture and organic matter contents: 1 sample/2 cm; and for the grain size data: 1 sample/5 cm. The sum of all the mineralogical parameters equals 100%; the sum of the grain size parameters equals 100%.

[a] Includes magnesian calcite.

[b] Includes protodolomite and magnesite.

[c] ND = not detected.

sand and silt. Organic matter and moisture contents are low, and macroscopic fossils rare. In several locations near the shoreline (cores 7 and 8) Unit 6 overlies a grayish-green compact gravelly, sandy, silty clay.

Chronology and Biostratigraphy

Four radiocarbon dates were acquired from the sediment core retrieved at location 27 (Table 3). Dates were obtained from either the dense interwoven plant-fiber mats or from disseminated fibers and organics within the inorganic mud matrix.

Characterization of the biostratigraphy of Waldsea Lake is based on palynological analysis of the core retrieved from location 25 near the center of the basin. Three pollen zones are identified (Fig. 7). The basal zone is a zone of increasing arboreal pollen, dominated by Gramineae at the base and *Pinus* at the top. Above this zone pine and spruce show a decrease while there is a cor-

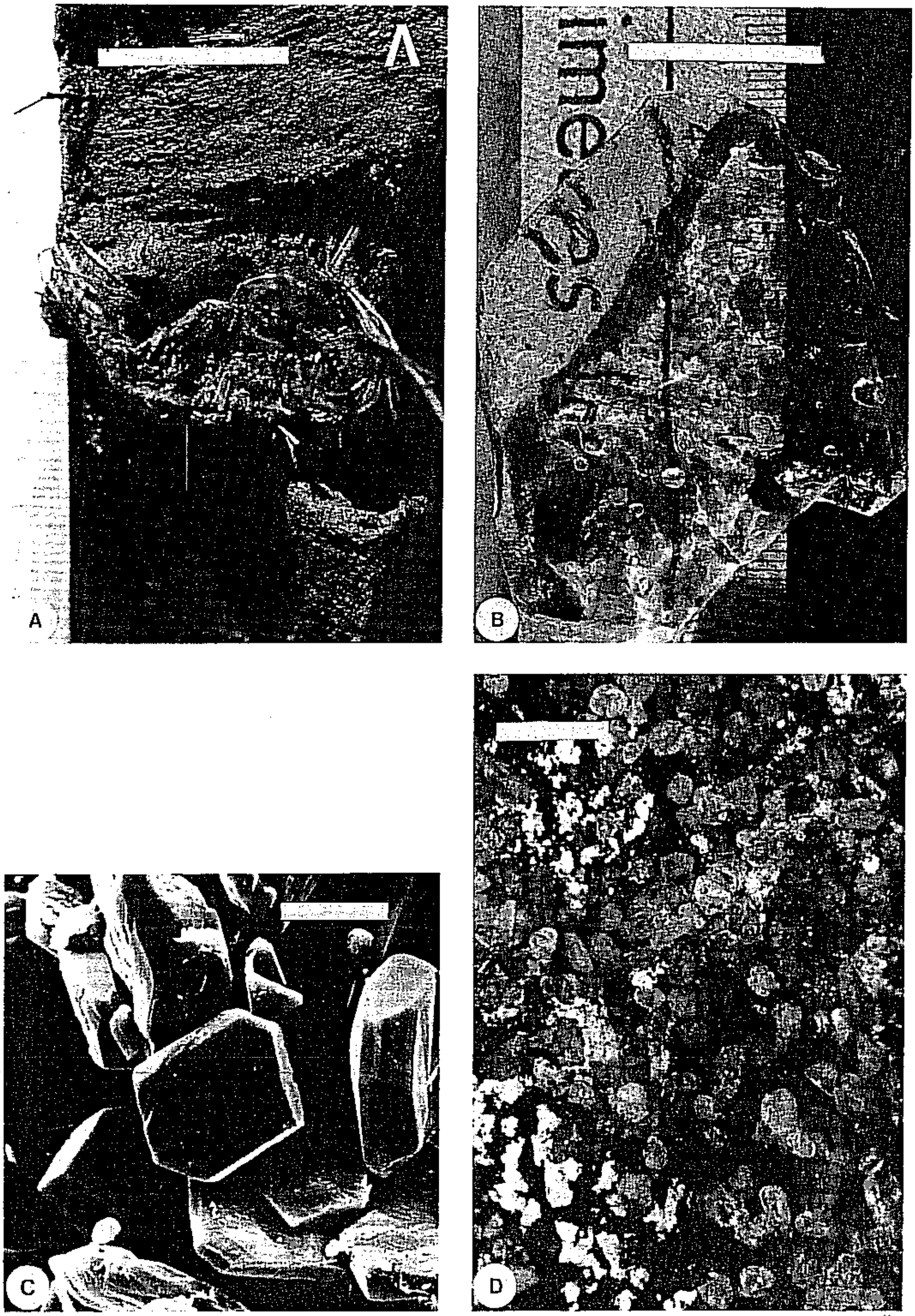
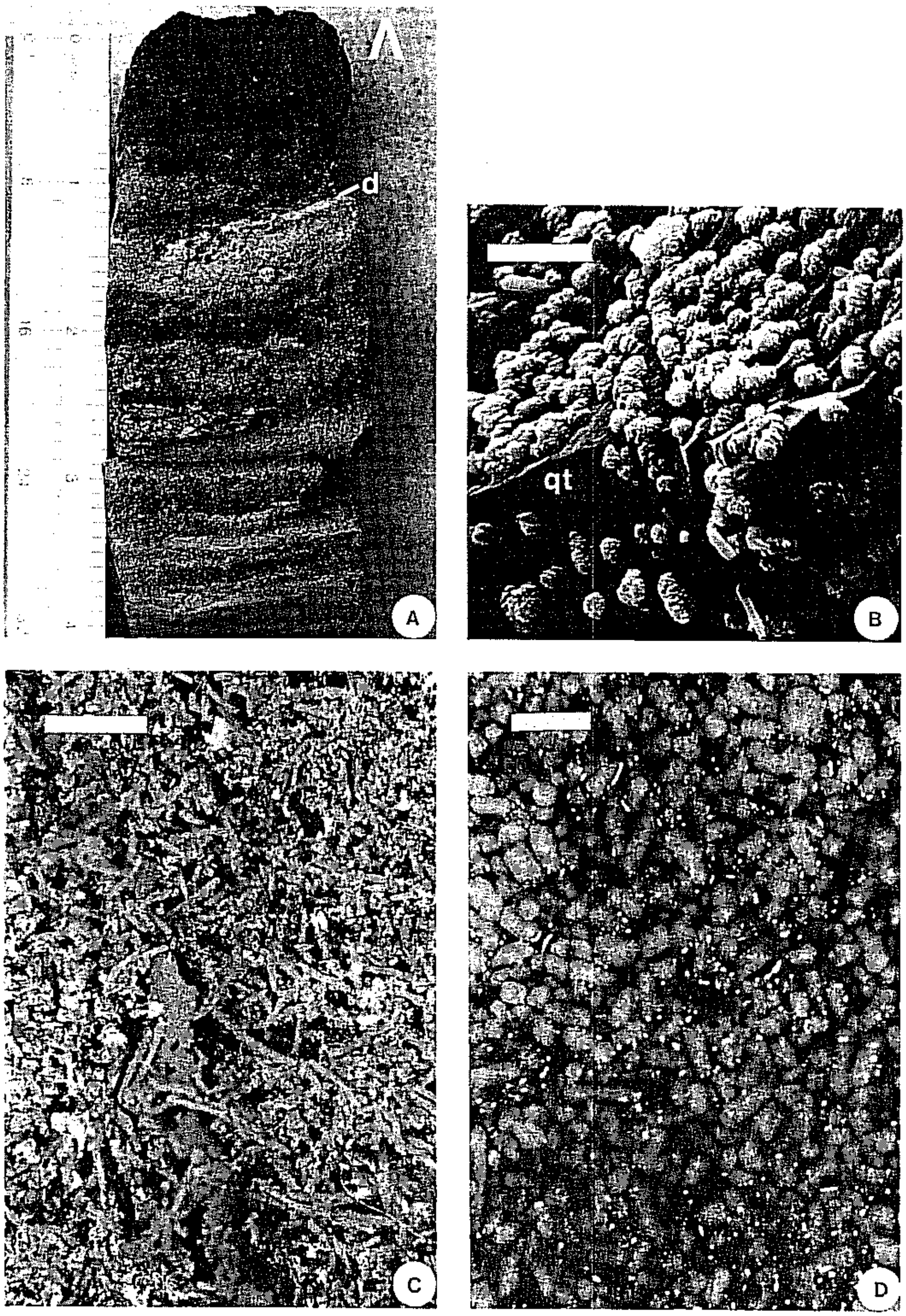


FIG. 4. (A) Organic fiber mat from Unit 1. Scale bar = 2 cm. Arrow points toward the top of the core. (B) Clear subhedral mirabilite crystal from Unit 1. Scale bar = 2 cm. (C) Euhedral gypsum crystals from Unit 2 (bulk sediment sample). Scale bar = 25 μm. (D) Rounded gypsum grains from a gypsum silt–sand lamina in Unit 2 (bulk sediment sample). Scale bar = 0.5 mm.


d
A
qt
B
C
D

responding increase in herbaceous pollen types. The uppermost zone in Waldsea is relatively complacent except for a slight increase in several herbs at the top.

DISCUSSION

Interpretation of Lithostratigraphy

The six major lithostratigraphic units recognized in the Waldsea Lake Basin represent variations in depositional environment, water chemistry, and water depth. The oldest sediments recovered from Waldsea (Units 1 and 2) were deposited in a shallow, hypersaline playa lake. Because of the stratigraphic relationships of Units 1 and 2, it is likely that they were deposited contemporaneously as separate facies in the playa, with Unit 2 forming the marginal mudflat environment and Unit 1 representin the more basinward ephemeral salt lake (Fig. 8A).

The presence of mirabilite, a highly soluble evaporitic salt, in Unit 1 requires sodium + sulfate ion concentrations in excess of about 100–200‰ at temperatures of 10°–20°C. The distinctive morphology and nature of occurrence of many of the mirabilite crystals together with the high salinity of the pore water strongly indicate displacive intrasedimentary growth of the salt within a phreatic zone saturated with sodium sulfate. Nearly identical mirabilite crystals grow displacively in the ephemeral salt pans of modern playas in the region (Last, 1984), and similar intrasedimentary precipitation of halite is well known from many other hypersaline lake environments (e.g., Gornitz and Schreiber, 1981; Handford, 1982; Hardie et al., 1978). The lack of bedded evaporitic salts in the cored section further suggests that the playa basin was dominated by clastic inflow, probably from sheetwash, wind, and intermittent streamflow. Intrasedimentary salt growth is also capable of destroying internal bedding, thereby giving rise to the massive, nonlaminated nature of Unit 1.

Further evidence of strikingly different environmental conditions in Unit 1 relative to modern Waldsea Lake are (a) the presence of abundant *Artemia* (brine shrimp) egg capsules, (b) an abundance of vegetation mats and disseminated plant fragments, and (c) the absence of aragonite laminae. Although *Artemia* can occupy a wide range of salinities from about 30 to over 300‰, the optimal conditions for its survival and growth are generally considered to be between 50 and 200‰ salinity and 20°–30°C temperature (Geddes, 1981; Spencer, 1982). *Artemia* has not been reported from modern Waldsea Lake. The abundant plant fragments and organic fiber mats of Unit 1 were likely derived from emergent macrophytes and basin-margin vegetation. Very similar plant-fragment mats have been described from modern shallow intermittent lakes in the region (Last, 1984). The absence of distinct varve-like aragonite–clay laminae in Unit 1 suggests that the deep-water stratified conditions of today's basin did not exist.

Unit 2, which is characterized by abundant laminae of gypsum and carbonate minerals, was deposited, at least initially, on the margins of this shallow playa lake. This fringe zone was slightly higher than the main basinal area, where deposition of Unit 1 took place, so the sediments were not normally saturated with lake brine. Exposure, desiccation, and reworking of the sediment of Unit 2 is evidenced by the presence of (a) lithified crusts, (b) intraclasts

FIG. 5. Examples of carbonate fabrics from Units 2 and 4. (A) Core of part of Unit 2 showing a dolomite cemented lamina (d) overlying a zone rich in carbonate intraclasts. Scale is in inches; 1 in = 2.54 cm. Arrow points toward top of core. (B) Detail of dolomite-cemented crust from Unit 2. Microcrystals of dolomite (d) are coating a large detrital quartz grain (qt). Scale bar = 5 μm. (C) Calcite-coated plant fragments from Unit 2 (bulk sediment sample). Scale bar = 2 mm. (D) Pelleted carbonate material from Unit 4 (bulk sediment sample). Scale bar = 1.5 mm.

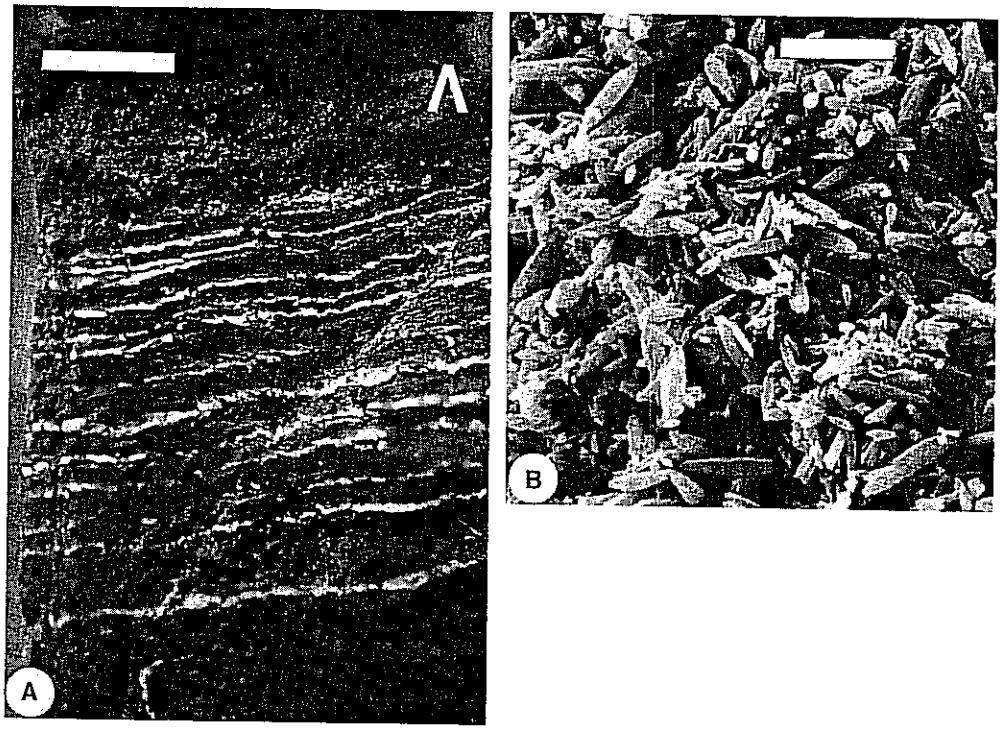


FIG. 6. (A) Core from Unit 3 showing fine aragonite (white)–clay (dark) lamination. Scale bar = 1 cm. Arrow points toward top of core. (B) Aragonite crystals from a lamina of Unit 5 (bulk sediment sample). Scale bar = 10 μm.

and laminae of carbonate sands and grits, and (c) rounded gypsum grains. Hardie *et al.* (1978) indicate that the formation of hard, dense crusts a few millimeters thick is characteristic of a dry mudflat environment in a playa setting. These crusts form by the evaporative pumping of subsurface brines up through the vadose zone to the surface of the mudflat. The presence of alkaline earth carbonates (dolomite, protodolomite, magnesite, hi-Mg calcite) probably indicates a relatively dilute (but still Mg-rich) subsurface brine, as opposed to the very concentrated Na-rich solution farther basinward. Although there may also have been soluble efflorescent crusts developed on the mudflats, as is so characteristic of the playas of the region today

TABLE 3. RADIOCARBON DATES FOR WALDSEA LAKE

Laboratory date (^{14}C yr B.P. ± 1σ)	Laboratory number	Depth and sample description
1230 ± 50	Beta-6891	Core 27, 86–90 cm, disseminated organics in clay matrix
2340 ± 70	Beta-6507	Core 27, 190–199 cm, plant fiber matrix
2920 ± 70	Beta-6508	Core 27, 283.5–290 cm, disseminated organics in clay matrix
3970 ± 90	Beta-6892	Core 27, 379–384 cm, plant fiber matrix

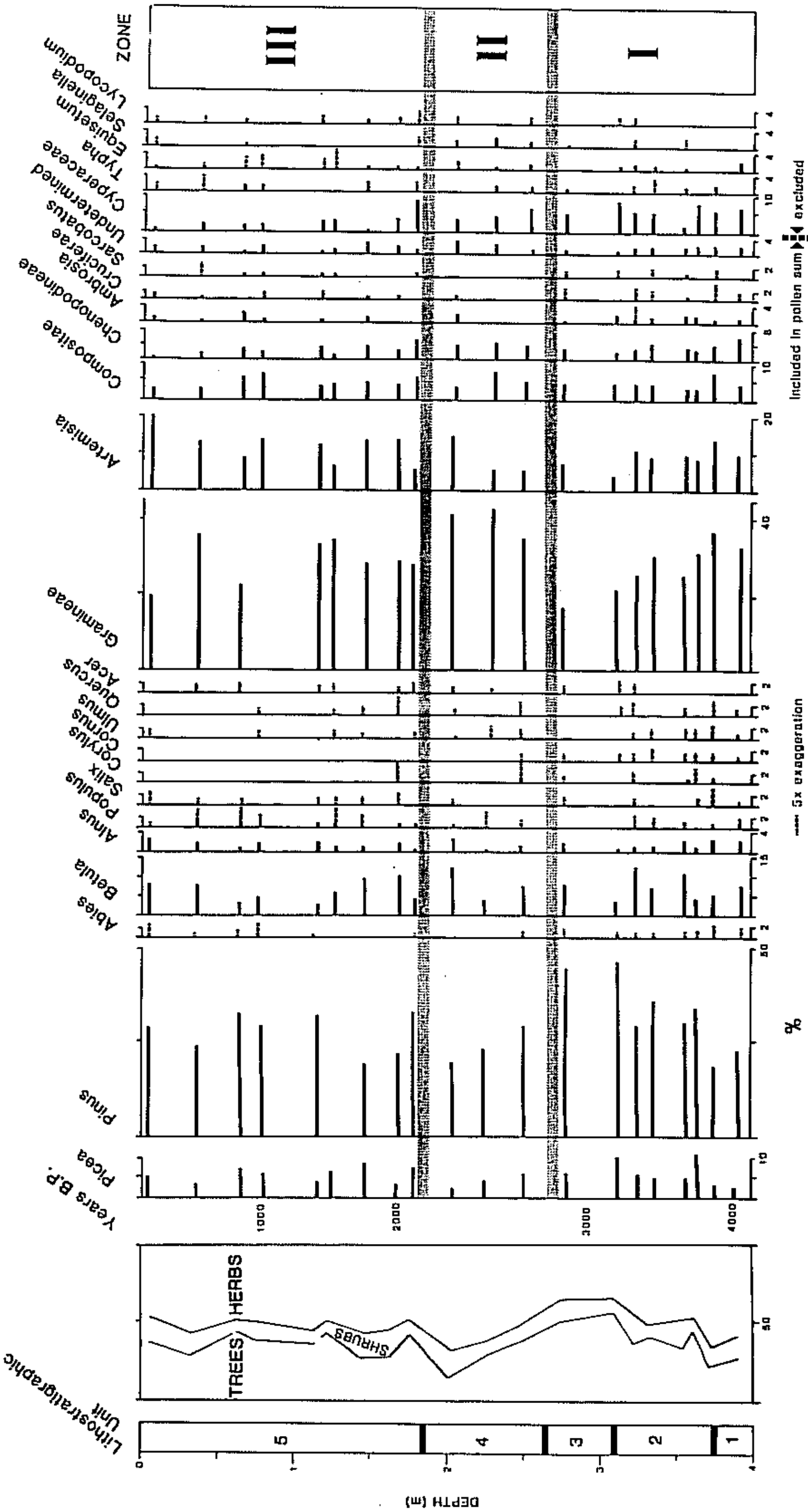


FIG. 7. Summary pollen frequency diagram showing variation in selected floristic types, pollen zones, and ^{14}C chronology from core 25. Pollen analysis was done by S. Kroker. Percentages were calculated on a pollen sum of at least 300 for each sample.

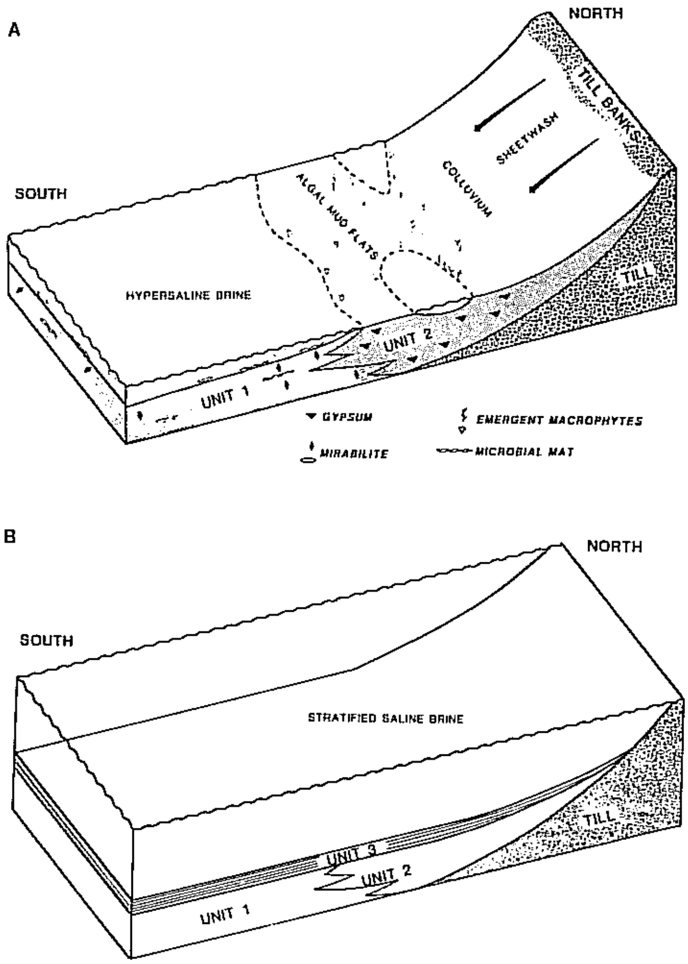


FIG. 8. Interpreted paleoenvironmental setting of Waldsea Lake during (A) deposition of Units 1 and 2, and (B) deposition of Unit. 3.

(Last, 1984), these crusts would be easily dissolved with succeeding high water levels and not incorporated into the stratigraphic record.

The carbonate-cemented crusts are brittle and can be readily broken into small platy fragments by sheetwash or wind. Calcareous intraclasts and carbonate sand/gravel laminae very similar to those of Unit 2 have been found on the modern mudflat of Freefight Lake in southwestern Saskatchewan.

The variety of gypsum forms and textures in Unit 2 indicates a polygenetic origin. The isolated euhedral crystals are early diagenetic products likely associated with dissolution of aragonite in the sediment or possibly dolomitization of other preexisting carbonates in the exposed mudflat. Laminae composed entirely of prismatic and lenticular crystals, however, are likely the result of direct precipitation from a temporary high water stand of the playa lake. Subsequent reworking of this gypsum by water or wind could easily abrade the crystals and further concentrate them in beds near the margin of the playa. This process of precipitation, reworking, and concentration has been identified in several of the modern ephemeral lakes of the region (Last, 1984).

In addition to being laterally correlative to Unit 1, Unit 2 also directly overlies it in some areas of the basin. This suggests that water levels in the basin were not stable and that periodically Waldsea was dominated by mudflat deposition.

Unit 3, which overlies Units 1 and 2, is characterized by an abundance of irregularly spaced aragonite laminae alternating with organic clays. Deposition of this unit took place in a relatively deep stratified lake (Fig. 8B). Each aragonite lamina represents basinwide precipitation of $CaCO_3$. Lack of laminae disruption by bioturbation suggests that anoxic conditions prevailed at the sediment–water interface, probably due to the development of meromixis. Even though individual aragonite laminae in general cannot be successfully traced for long distances, the entire package of laminated sediment can be easily correlated basinwide. The complete absence of any obvious biological forms and other noncarbonate grains within these pure aragonite layers suggests rapid inorganic precipitation. Minor dissolution features and etching seen on the aragonite crystals of some of the laminae indicate exposure to undersaturated solutions, possibly while settling through the lower pH brine of the lake's hypolimnion or monimolimnion.

The cause and triggering mechanism of aragonite precipitation in Waldsea Lake is not known. Supersaturation and precipitation of calcium carbonate can take place for a variety of reasons (Muller *et al.*, 1972), including photosynthetic uptake of CO_2 and consequent increase in pH, concentration changes brought about by evaporation or dilution, temperature changes, and mixing of brines of different compositions. The first two processes have been well documented in numerous lakes (e.g., Muller *et al.*, 1972; Brunskill, 1969; Kelts and Hsu, 1978; Last, 1982). In Waldsea the association of the aragonite laminae with carotenoid pigments seems to point toward an organic linkage. The irregular spacing and microstructure of the laminae, however, suggests that the precipitation event was not a regular or annual occurrence, as would be expected if biological CO_2 uptake or seasonal temperature fluctuations were the cause of precipitation. Furthermore, the presence of finely disseminated (nonlaminated) aragonite throughout the sediment indicates that the lake was continuously at or near saturation with respect to this carbonate mineral.

The aragonite of Unit 3 (and Unit 5) most likely can be related to periodic but irregular influxes and mixing of water of a different composition from the lake brine. Dilute inflow, probably associated with periods of increased streamflow, surface runoff, and precipitation, was likely rich in calcium and bicarbonate ions with a relatively low (<8) pH. As it entered and mixed with the highly alkaline and Mg-rich saline brines of Waldsea Lake, massive inorganic precipitation of aragonite would occur in the form of "whitings." Other physical, chemical, and biological factors such as primary organic productivity or simple evaporative concentration likely played a role in maintaining elevated levels of saturation between whiting events. Fluctuating Mg/Ca ratios within the sediment pore water gave rise to a complex series of early diagenetic carbonates including Mg–calcite (low Mg/Ca ratio), protodolomite, and magnesite (high Mg/Ca ratios).

Deep-water meromictic conditions in Waldsea were briefly interrupted, and Unit 4 saw a return once more to shallow-water mudflat deposition as evidenced by (a) abundant gypsum silt/sand laminae, (b) coarse texture, (c) calcareous hardgrounds and intraclasts, and (d) organic fiber mats. The lack of evaporitic salts such as mirabilite suggests that strongly hypersaline conditions may not have been prevalent.

Finally, the youngest lithostratigraphic units in Waldsea Lake record deposition again in a relatively deep-water offshore setting (Unit 5), with the coarse clastics of Unit 6 marking shoreline, nearshore, and minor deltaic sedimentation. The undisturbed fine lamination characteristic of

Unit 5 suggests development of a stratified water body. The irregular nature and microstructure of the aragonite laminae again do not support an annual periodicity of the rhythmites, but rather point toward less regular events as previously discussed.

Overall, lake levels and brine chemistry during deposition of Unit 5 were stable. There is some suggestion, however, of minor fluctuation in levels during the most recent record. Thin wedges of coarse clastics of Unit 6 extend well out into the basin from the northwest (locations 11 and 12) and the south (locations 8, 15, and 20).

Interpretation of Palynology

The pollen record of the oldest sediment recovered from Waldsea Lake (Zone I) indicates that the Hypsithermal episode of maximum warmth and aridity had already given way to cooler and moister conditions, and suggests a regional vegetative cover of grass-dominated aspen parkland. The upward increase in pine, spruce, and other boreal elements at the expense of grass pollen in Zone I confirms the continued development of a relatively cool, moist climate in the area.

At about 2800 yr B.P. the pollen of Zone II suggests a return to more open prairie conditions. Grass and most other herb pollen increase at the expense of pine and birch, indicating an expansion of prairie into the previously wooded areas.

This brief warm period ended about 2000 yr B.P. with the establishment of the essentially modern assemblage dominated by pine, birch, grass, and sage pollen (Zone III). The small increase in *Artemisia* and Cruciferae at the very top of the core may indicate agricultural development and ranching in the area.

History

The early history of Waldsea Lake is not yet known because our coring has not penetrated the entire postglacial sediment record. The basin probably originated as a simple depression on the hummocky ground moraine of the area; however, other possible origins such as hydrodynamic "blowout" by groundwater discharge or collapse due to dissolution of underlying Paleozoic salt have been suggested for other lakes of the region (Christiansen, 1971; Christiansen *et al.*, 1982), and should not be ruled out a priori. The entire area was probably occupied by a series of large ice-marginal lakes between 12,000 and 11,500 yr B.P. (Meneley, 1964). These proglacial lakes were short lived, as evidenced by the very thin veneer of glaciolacustrine sediments in the region. High water levels are recorded by indistinct and poorly developed strandlines in the Waldsea area about 10 m above the present lake surface. Waldsea Lake, along with nearby Deadmoose, Middle, Houghton, and Lenore lakes, likely came into existence as distinct entities shortly after 11,500 yr B.P. as the glacier ice retreated and the proglacial lakes drained to the south and east.

The effects of the mid-Holocene drought on Waldsea Lake are unknown. However, the sediment of Units 1 and 2 shows that by about 4000 yr B.P. water levels in the Waldsea Basin were much lower than that of the modern lake (Fig. 9). The basin at this time was very similar to many of the playa lakes found in the northern Great Plains today. A shallow, probably ephemeral, hypersaline brine pool was surrounded by extensive, periodically vegetated mudflats. Intrasedimentary precipitation and growth of soluble salts occurred in the concentrated, Na-rich pool, while evaporative drawup of less-concentrated but carbonate-rich shallow groundwater in the mudflat areas generated calcareous hardgrounds and crusts. The basin was dominated by fine-grained clastic influx from diffuse sheetwash off the surrounding till banks, stream inflow, and wind transport. The exposed surface crusts on the mudflats were susceptible to reworking by storm runoff, resulting in their breakup and redeposition as detrital particles of gravel, sand, or mud size. There is also some evi-

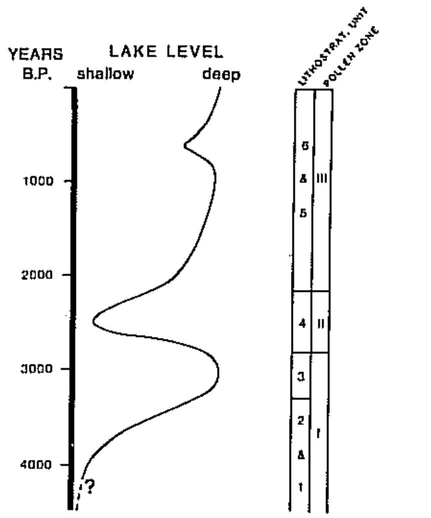


FIG. 9. Interpreted lake-level fluctuations in Waldsea Lake. "Shallow" indicates playa conditions with depths <1 m; "deep" indicates depths probably >5 m.

dence of algal precipitation of carbonates in Unit 2, probably in the form of fenestral, loosely cemented tufas. Extensive gypsum precipitation occurred on the mudflats or on the playa lake floor. Abrasion of the sand-sized euhedral gypsum crystals and reworking by water and wind resulted in clastic gypsum laminae up to 10 mm thick at the margins of the playa.

Lake levels and water chemistry between 4000 and 3000 yr B.P. were unstable. At times the entire basin became a saline mudflat dominated by organic clastics and sulfate–carbonate precipitation. However, as the climate continued to cool and became wetter after the Hypsithermal (pollen Zone I), high-water conditions became more common. By about 3000 yr B.P. a relatively deep-water (probably >5 m) stratified lake occupied the Waldsea Basin.

The sediments deposited in this lake (Unit 3) were dominated by endogenic carbonate and allogenic clays, quartz, and finely disseminated organic matter. The brine was still saline at this time, and relatively stable meromictic stratification likely developed. Elevated Mg/Ca ratios (>12) were combined with the organic uptake of carbon dioxide and evaporative concentration in the closed basin, resulting in a continuous rain of aragonite to the lake bottom. Aperiodic influxes of relatively dilute calcium and bicarbonate-rich runoff caused whitings and massive inorganic carbonate sedimentation.

A short reversal in the climatic cooling trend took place between about 2800 and 2200 yr B.P. (pollen Zone II), and marked an abrupt return to shallow-lake/mudflat conditions. Gypsum precipitation and sedimentation, and the formation of dolomite-cemented laminae and organic fiber mats (Unit 4) again occurred throughout the basin.

This low-water phase was short lived, and by about 2000 yr B.P. the lake had returned to a stratified, deep-water environment in response to the moderating climate and a more positive hydrologic budget. There is little evidence in Unit 5 and pollen Zone III of major fluctuations in the lake over the last 2000 yr. Aragonite precipitation from brines with elevated Mg/Ca ratios has been continuous, punctuated by whiting events probably associated with substantial inflow of carbonate-rich runoff. The organic-matter content has increased slightly during this time, suggesting gradually increasing levels of productivity or a relative decrease in clastic influx. At about 700 yr B.P. incursion of coarse-grained shoreline/nearshore sediments farther out into the basin occurred, implying a slightly lower water level.

The interpreted lake levels and paleoclimates during the past 4000-yr history of Waldsea Lake bear remarkable similarity to the environmental conditions suggested for Devils Lake, North Dakota, approximately 350 km to the southeast (Callender, 1968, Fig. 45). Both stratigraphic sequences suggest gradually deepening but oscillating lake levels after the Hypsithermal in response to the cooler and wetter climate, with Devils Lake reaching a maximum level around 3500 yr ago. A subsequent brief low-water stage associated with warmer conditions is recorded in both basins, followed by a resurgence of high levels about 2000 yr ago. Most recently, Devils Lake was affected by multiple level fluctuations during the 700-yr period after 1200 yr B.P., culminating in a very low-water stage about 500 yr ago. This may correlate with the less dramatic drop in Waldsea Lake at 700 yr B.P.

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