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## Re-examination of the recent history of meromictic Waldsea Lake, Saskatchewan, Canada

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## Abstract

Waldsea Lake, a small ( $\sim$ 5 km<sup>2</sup>), meromictic lake in central Saskatchewan, is one of the most intensely studied saline lacustrine environments in western Canada. The high salinity and meromixis of this topographically and hydrologically closed basin result in exceptional preservation of fine lamination coupled with a diverse endogenic and authigenic mineral suite. This study applies new high resolution paleolimnological techniques to decipher the chemical and hydrologic fluctuations that have occurred in Waldsea over the past several thousand years and shows that significant geolimnological fluctuations have occurred within the past two millennia. © 2002 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Waldsea Lake occupies a small, topographically closed basin in south-central Saskatchewan, Canada. With nearly 30 papers, technical reports and theses published on the lake over the past three decades, it is one of Canada's best-studied perennial saline lakes. Much of the past and current scientific interest in Waldsea Lake stems from three factors. Firstly, it is a meromictic lake: the upper, relatively fresh, low density water mass does not regularly (seasonally) mix with the lower, hypersaline, high density water. Waldsea Lake is one of only four known meromictic lakes in the entire northern Great Plains region of western Canada (Last, 1989), an area comprising some 400,000 km<sup>2</sup> and millions of lakes. The elevated solute concentrations, coupled with low oxygen levels and the accumulation of high amounts of hydrogen sulfide in the monimolimnion, produce a toxic environment for most benthic organisms. Lack of bioturbation, as well as wind-generated wave energy, permits excellent preservation of sedimentary structures in the offshore areas of the lake.

Secondly, the saline to hypersaline nature of the water in Waldsea Lake offers a large scale natural laboratory where earth scientists can better understand the genesis and diagenesis of carbonate, sulfate, and sulfide minerals. For example, the presence of nondetrital dolomite in the sediments of Waldsea provides critical geochemical and environmental information about how this economically important mineral forms

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in low temperature, near-surface sedimentary settings (Last, 1990).

Finally, its location at the boundary between two major ecozones, the prairies to the south and the boreal forest to the north, suggests that the stratigraphic sequence preserved in Waldsea Lake should offer considerable potential for interpreting past changes in regional vegetation and climate. Similarly, due to its closed topographic and hydrologic nature, the lake sediments are particularly sensitive recorders of even minor hydrologic fluctuations and environmental changes. Thus, Waldsea Lake is able to provide a wealth of paleoenvironmental information for this ecologically pivotal area of western Canada.

Previous investigators, although recognizing a complex Holocene history of the lake, concluded that the past few thousand years in the basin to have been relatively uneventful. This is surprising considering the magnitude of the environmental changes that have taken place in the region over the past millennium. The objectives of this paper are twofold: (i) to provide an overview of past geolimnological and paleoenvironmental work on Waldsea Lake, and (ii) to examine and interpret the stratigraphic fluctuations that have occurred in detailed carbonate petrography during the past ca. 2000 years. These new mineralogical and petrographic results presented here are part of a larger on-going effort to better understand the recent history and paleolimnology of Waldsea Lake through the use of multiple proxies, including stable isotope and trace element geochemistry, organic Rock-Eval geochemistry, palynology, and ostracode biostratigraphy.



Fig. 1. Map of western Canada showing the location of Waldsea Lake within the major vegetation/ecozones of western Canada. Inset shows the location of the three prairie provinces in Canada.

## 2. Materials and methods

The sediment cores used in this study were acquired with a modified Livingstone piston corer (Wright, 1991) during winter using the ice cover as a stable coring platform. Cores were extruded while on the ice, allowed to freeze, and transported to University of Ma-nitoba where they were kept frozen until logging and analyses. Because the cores were not confined when frozen, there was only minor disruption of the lamination. Subsamples were collected at variable intervals (from 1 mm to 2 cm) throughout the cores as determined by the bedding features and amount of material required for analysis. Mineralogical analyses were done by standard X-ray diffraction techniques as described in Last (2001a), Hardy and Tucker (1988), Marquart (1986), Klug and Alexander (1974), Schultz (1964) and Goldsmith and Graf (1958). Crystal size data were collected using a laser-optical analyzer (Galai CIS-1). Details of these analytical techniques can be found in Last (2001b), Aharonson et al. (1986) and Allen (1981). Image



Fig. 2. Airphoto showing Waldsea and Deadmoose Lakes and bathymetry of the Waldsea basin. Also shown on the bathymetric map are the locations of the 35 core sites in the basin. Cores 6, 23, and 32 refer to the cores discussed in the text.

analysis and quantification of the aragonite crystal shapes were done using the shape analysis subroutine of the Galai CIS-1 PSA equipment (Galai Production, 1989). Chronostratigraphy of the recovered sequences was provided by <sup>14</sup>C dating as presented in Last (1991), Last and Schweyen (1985) and Schweyen (1984). Sediment trap methodology is presented in Last (1993, 1994), Håkanson et al. (1989) and Håkanson and Jansson (1983). Sample preparation and mounting techniques used for scanning electron microscopy follow the procedures outlined in Trewin (1988) and Goldstein et al. (1984).

# 3. Setting and modern geolimnology of Waldsea Lake

Details of the geolimnology, hydrology, and neolimnology of this basin can be found in Hammer (1978, 1986), Hammer et al. (1978), Lawrence et al. (1978), Parker et al. (1983), Schweyen (1984), Schweyen and Last (1983), Swanson and Hammer (1983), Last (1991), Last and Schweyen (1985) and Last and Slezak (1986, 1988). Because Waldsea Lake is so well studied, we will only briefly review the modern setting and sedimentary processes here.

Waldsea Lake is located in the Northern Great Plains of western Canada, about 100 km east of Saskatoon, Saskatchewan (Fig. 1), in an area of gently undulating topography. The basin is underlain by about 70 m of till, glaciofluvial, and lacustrine sediments (Meneley, 1964, 1967) which sit on Mesozoic sandstone and shale. With the exception of a regional park at the south end of the lake, the land surrounding the basin is intensively cultivated (Fig. 2). The lake is located within the aspen parkland vegetation zone, transitional between the shortgrass prairie to the south and west and the boreal forest zone to the north. The town of Humboldt, located 10 km south of the lake, receives about 36 cm of precipitation per year, however, nearly three times this amount can be lost by evaporation from the open water of the lake during the ice-free season (CNC/IHD, 1978). Mean temperatures for January and July are -18 °C and 19 °C, respectively.

Waldsea Lake has a surface area of about  $5 \text{ km}^2$  (Table 1) and the basin has a simple cone-shaped morphology (Fig. 2). The maximum depth of 14.8 m occurs in approximately the center of the basin. Mean

Table 1						
Morphometric	and hydr	ochemical	characteristics	of	Waldsea	Lake

Morphometry	
Surface area	4.65 km <sup>2</sup>
Drainage basin area	47.2 km <sup>2</sup>
Drainage area/lake area	10.2
Shoreline length	10.7 km
Shoreline development	1.3
Maximum depth	14.8 m
Mean depth	8.1 m
Relative depth	0.63%
Volume	0.04 km <sup>3</sup>
Volume development	1.7
Volume in mixolimnion	87%
Volume in monimolimnion	13%

Hydrochemistry (mg  $1^{-1}$ )

	Mixolimnion	Monimolimnion	
Ca <sup>2+</sup>	320	441	
Mg <sup>2+</sup>	3939	5616	
Na <sup>+</sup>	4414	6988	
K <sup>+</sup>	156	273	
HCO <sub>3</sub> <sup>-</sup>	231	427	
$SO_4^{2}$ -	12,488	30,067	
Cl <sup>-</sup>	4471	8863	
TDS (ppt)	25.4	67.2	
Ionic strength	0.61	1.03	
pH (pE)	8.7 (3.4)	7.8 (-5.3)	
H <sub>2</sub> S	0	590	

Terminology follows Wetzel (1975). The hydrochemical data represent the mean of approximately 100 samples taken over a 15-year period.

depth is just over 8 m. Several small and intermittent streams drain a catchment of approximately 50 km<sup>2</sup>. The lake's hydrologic budget is dominated by ground-water inflow and loss by evaporation. The basin is topographically closed with a spill point about 6 m above the present-day level. The hydrologic budget of the lake also indicates the lake is hydrologically closed. Water enters the lake mainly via groundwater inflow (plus streams, direct precipitation and sheet-flow) but only leaves by evaporation (Schweyen, 1984; Schweven and Last, 1983).

Waldsea Lake water is saline to hypersaline, with an average salinity of the mixolimnion of about 25 and 70 ppt TDS for the monimolimnion (Table 1). A phototropic bacterial plate, composed of the sulfur bacteria *Chlorobium*, exists immediately below the chemocline at about 8 m depth. Both the upper and



Fig. 3. Schematic summary of the modern chemical sedimentology of Waldsea Lake. The variations with depth in the water of the mineral saturation indices for aragonite, gypsum and mirabilite were calculated using WATEQ-F (Rollins, 1989) and the long-term (1982–1997) mean water compositions.

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lower water masses are strongly dominated by sodium, magnesium, and sulfate ions. The surface water is alkaline (pH 8.6–9.3) and, although the monimolimnion has a slightly lower pH, the entire water column is saturated or supersaturated with respect to various carbonate minerals at all times of the year (Fig. 3). Because of the high Mg/Ca molar ratio of the brines, aragonite is the stable calcium carbonate phase being precipitated in the lake today. The monimolimnion is also perennially saturated with respect to gypsum, as is the upper meter of the mixolimnion during winter. During winter, the surface water can also approach saturation with respect to various hydrated sodium and magnesium sulfates.

The modern bottom sediments exhibit a simple facies pattern (see Fig. 5 in Last and Slezak, 1986): a narrow (50-100 m wide) band of poorly sorted, coarse

siliciclastics at the shoreline and in the nearshore areas grades basinward into fine-grained, organic-rich, calcareous sediments. The modern offshore sediments are composed of subequal proportions of carbonate minerals and clay minerals (each approximately 30% of the inorganic component), with pyrite (20%), gypsum (10%), quartz (5%), and feldspar minerals (5%). The dominant carbonate mineral is aragonite, but small amounts of magnesian calcite, normal calcite, dolomite, and protodolomite also occur. In addition to these inorganic constituents, the modern offshore sediments comprise about 30% organic matter.

The details of the modern sedimentology and mineral genesis/diagenesis in Waldsea Lake are exceedingly complex because of the presence of two water masses, each having different salinities, chemical compositions, temperature and organic regimes,



Fig. 4. Composite mid- to late Holocene stratigraphic sequence from Waldsea Lake showing changes in lithostratigraphy, lamination, stable isotopic composition of endogenic carbonate minerals, brine salinity (interpreted from pore water geochemistry), regional vegetation (interpreted from pollen remains) and water levels. These data and interpretations have been compiled from Schweyen and Last (1983), Schweyen (1984), Last and Schweyen (1985), Last and Slezak (1986), Last (1991) and Last and Vance (1997).

and mineral saturation characteristics (Fig. 3). In general, the modern sedimentology is controlled by the interaction of the following factors: (i) evaporative concentration and organic productivity of the mixolimnion, which create highly supersaturated conditions and precipitation of endogenic carbonate minerals, (ii) seasonal freeze-out concentration of the upper part of the mixolimnion, which leads to inorganic precipitation of soluble sulfates, (iii) dissolution and re-precipitation of both carbonates and sulfates in the water of the monimolimnion, (iv) microbial sulfate reduction at the chemocline as well as within the monimolimnion, which gives rise to elevated H<sub>2</sub>S levels, penecontemporaneous dolomite formation, and sulfide mineral genesis, and (v) detrital influx by wind, sheetflow and streamflow.

## 4. A synopsis of the Holocene history of Waldsea Lake

The Waldsea Lake basin probably originated about 10,000 years ago as a remnant of glacial Lake Fulda (Schweyen, 1984), although our coring has yet to retrieve lacustrine sediment older than about 6000 years. The stratigraphy of the mid- to late Holocene sediment fill is known from over 80 m of core taken from 35 sites in the basin (Fig. 2). The subsurface facies are considerably more complex than the relatively simple modern sediment facies relationships. Although much of the offshore sedimentary sequence consists of well-laminated, fine-grained, organic-rich, calcareous muds similar to the modern deposits, there are significant variations in mineralogical composition, sedimentary structures, organic matter type and content, and isotopic and pore water geochemistry.

Table 2

Radiocarbon dates of the mid to late Holocene sequence from Waldsea Lake (originally reported by Schweyen, 1984; Last and Schweyen, 1985; Last, 1991)

$^{14}$ C year BP $\pm 1\sigma$	Core number and depth	Material dated	Laboratory number
$     \begin{array}{r}       1180 \pm 80 \\       1230 \pm 50 \\       2340 \pm 70 \\       2920 \pm 70     \end{array} $	24:79 cm 27:88 cm 27:194 cm 27:286 cm	disseminated organics disseminated organics plant fiber mat disseminated organics	Beta 6888 Beta 6819 Beta 6507 Beta 6508
$3970\pm90$	27:381 cm	plant fiber mat	Beta 6892



Fig. 5. Photographs of representative sections of cores from Waldsea Lake showing aragonite (white or light gray) lamination. Scale bar is 1 cm. Photograph A is from core 32; photograph B is from core 6.

Each of these parameters provide clues to past depositional environments and long-term geochemical evolution of the basin brines. These stratigraphic data and interpretations, summarized in Fig. 4, have been presented and discussed in Schweyen (1984), Schweyen and Last (1983), Last and Schweyen (1985), Last and Slezak (1986), Last and Vance (1997) and Teller and Last (1990). Table 2 summarizes the radiocarbon dates that were used to establish the late-Holocene chronology.

The oldest (mid-Holocene) offshore deposits are laminated to massive, chemically precipitated sediments (gypsum, mirabilite, magnesite, hydromagnesite and protodolomite) mixed with relatively coarse grained siliciclastics. This mid-Holocene sequence is also punctuated by numerous exposure horizons, desiccation zones and cemented beds. The presence of these bedding features, recognized by their distinctive pedogenic-like structure and relatively low moisture content, within this lowermost sequence hinders both recovery of older Holocene sediment and establishment of absolute chronology. These laminated to massive salts and siliciclastics represent deposition in a shallow, saline, clastic-dominated playa environment where water levels fluctuated from several meters depth to dry conditions. The presence of laterally equivalent peloidal carbonates, tufa and microbial laminated sequences indicates this shallow, sulfatedominated hypersaline brine pool was surrounded by carbonate springs and algal covered mudflats.

Beginning about 4500 years ago, deeper water conditions prevailed in the basin and the complex array of chemically precipitated and microbial laminated playa/mudflat sediments at the base of the recovered section grade sharply upward into organicrich, aragonitic muds. These finely laminated sediments were deposited in a relatively deep, meromictic lake as the hydrologic budget of the basin became increasingly more positive (Fig. 4). The monimolimnion of the lake at this time was considerably more saline than that of the modern lake, however, the upper water mass may have been similar to today's salinity and composition. The fine, irregularly spaced aragonite laminae probably were generated by fallout sedimentation from repeated, basin-wide whiting events, in which massive inorganic calcium carbonate precipitation occurred in the mixolimnion. These aperiodic, short-term (several days to several weeks) events were most likely stimulated by irregular influxes of dilute calcium-bicarbonate-rich surface water which, upon mixing with the highly alkaline and Mg-rich saline and hypersaline brines, caused elevated levels of supersaturation, rapid nucleation, and precipitation. These deep-water, meromictic conditions have evidently persisted in Waldsea Lake for most of the past 4500 years except for a short excursion back to mudflat/ playa conditions between 2800 and 2000 years BP.



## **ARAGONITE LAMINAE - CRYSTAL SHAPE**

Fig. 6. Variations in aragonite crystal shapes in selected laminae from Core 23. Examples shown on the left illustrate laminae composed mainly of ellipsoidal (rice-grained) crystals; examples on the right show laminae in which the aragonite is mainly of acicular morphology.

## 5. Aragonite laminae petrography

Detailed petrography of the aragonite in the deepwater laminated sequence of Waldsea Lake offers new insight into the paleolimnology of the basin. Although much of the stratigraphic sequence from Waldsea Lake is finely laminated, our comments and observations here apply to the sediments deposited during the past ~2000 years (approximately the upper 2 m of sediment).

The aragonite laminae range in thickness from about 0.2 mm to just under 2 mm. Overall, the laminae are widely spaced (two to three laminae per centimeter) but much closer spacing does occur (Fig. 5). Upper and lower contacts are invariably sharp and horizontal. The laminae are usually white (Munsell: 5YR 8/1) to pale yellow (2.5Y 8/4) with occasional red (2.5YR 5/8) to pink (5YR 7/4) colors. The pink and red colors rapidly fade upon exposure of the core, and are presumably associated with deposition of organic material from the red to purple colored bacterial plate at the chemocline or staining by pigments. There is no apparent periodicity in the frequency or thickness variation of the laminations within the upper 2 m of section, although the detailed image analysis and statistical evaluation necessary to properly identify a non-random occurrence (cf. Zolitschka, 1996; Pike and Kemp, 1996) have not been completed.

Individual laminae are composed entirely of extremely well-sorted, euhedral, micron-sized CaCO<sub>3</sub> crystals. The almost complete absence of biological and other non-carbonate grains suggests that the layers represent rapid inorganic precipitation and accumulation without dilution by non-carbonate endogenic minerals, siliciclastics, or organic debris. The laminae show considerable variation in both size and morphology of aragonite crystals. Individual CaCO<sub>3</sub> crystals range in shape from acicular to ellipsoidal, but are usually uniform in any single layer (Fig. 6). Most of the laminae have fine, needle-like crystals that are typical of the aragonite formed in many other perennial saline lakes in the northern Great Plains region (e.g., Valero-Garcés and Kelts, 1995; Sack, 1993; Van Stempvoort et al., 1993; Slezak, 1989). The aragonite in some of the laminae, however, has a distinctive wheat grain or rice grain morphology. This ellipsoidal aragonite has been noted in other deep water saline lakes in Canada and Australia, as well as from the

Black Sea, and is indicative of newly formed CaCO<sub>3</sub> crystals settling through a relatively deep, stagnant, somewhat undersaturated water column (Sack and Last, 1994; Gell et al., 1994; Last and De Deckker, 1990; Stoffers and Müller, 1978; Hsü, 1978).



Fig. 7. Stratigraphic variation in the percent of acicular crystals in individual aragonite laminae from core 6. As discussed in the text, laminae with relatively low proportions of acicular crystals suggest relatively shallow chemocline depths and slightly undersaturated monimolimnion conditions, whereas laminae with high proportions of acicular crystals indicate relatively greater chemocline depths and near-saturated conditions in the bottom water.

Conditions in Waldsea Lake today are such that ellipsoidal aragonite does not form and the modern bottom sediments contain only acicular CaCO<sub>3</sub>. This is because both the mixolimnion, where the aragonite is forming, and the monimolimnion are very close to saturation with respect to aragonite. However, geochemical modeling (Schweyen, 1984) indicates that shallowing of the chemocline by about 4 m would produce undersaturated conditions in the lower water mass and, in turn, create conditions favorable for the generation of rice-grain aragonite crystals. Thus, laminae with ellipsoidal aragonite crystals indicate the presence of a stratified water column in which the chemocline was considerably shallower than that of the modern lake, or, alternatively, the monimolimnion was less saturated (more undersaturated) with respect to  $CaCO_3$ .

The proportion of euhedral acicular aragonite crystals relative to other shapes in laminae from one of the cores near the basin center increased dramatically at about 500 years BP (Fig. 7). This suggests that the depth to the chemocline increased significantly in the lake about that time, possibly due to the influx of more freshwater via precipitation and stream runoff, increased wind mixing of the mixolimnion, or an increase in the degree of saturation with respect to CaCO<sub>3</sub> of the monimolimnion.

The crystals in individual laminae are extremely well sorted (average  $\sigma < 1.0 \ \mu\text{m}$ ) and have a mean size ranging from less than 2  $\mu$ m to more than 26  $\mu$ m (see



Fig. 8. Examples of variations in mean aragonite crystal size in laminae from core 6. Size spectra are shown as histograms of the relative abundance of the crystals in each size category. Note the logarithmic scale of the size axes.

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examples in Fig. 8). Although many geochemical and environmental factors combine to determine the size of precipitated inorganic crystals, one of the most important is the length of time the crystal resides in the supersaturated solution. Thus, the stratigraphic variation in aragonite crystal size in the laminae is, in large part, a reflection of the depth of the supersaturated water column. In the modern lake, this is essentially the depth of the mixolimnion (or the depth to the chemocline). Using aragonite crystals collected in sediment traps from modern Waldsea Lake and other aragonite-precipitating basins (Fig. 9), it is possible to calibrate the stratigraphic variation in crystal size in terms of the vertical extent of the supersaturated water column (i.e., approximate depth to the paleochemocline). Other factors, such as the degree of supersaturation and the amount of crystal size modification that may take place during settling through an undersaturated monimolimnion may affect these estimates, but crystal size should offer a reliable means of estimating past chemocline depths.

The fluctuations in interpreted chemocline depth of Waldsea Lake over the past 2000 years, based on the mean crystal size of aragonite crystals in two cores in the basin, are shown in Fig. 10. Core 6, the same core on which the detailed aragonite shape analysis was done, is located near the deepest part of the basin (Fig. 2). Core 23 is located about a kilometer north of core 6 in ~10 m water depth. Numerous fluctuations are superposed on an overall trend toward increasing crystal size (i.e., greater chemocline depth) upward in the cores. Although these fluctuations do not match precisely, there is good general correspondence between the two cores. Both cores show a significant increase in interpreted chemocline depth during the most recent 500-year period and generally shallower chemocline depths between about 500 and 1700 years BP. These overall changes correspond well with the changes in water column conditions interpreted from the aragonite crystal shape analyses. In addition, the crystal size data from core 6 suggests a more complex record of fluctuations between 500 and 1700 year BP,



**CRYSTAL SIZE VERSUS MIXOLIMNION DEPTH** 

Fig. 9. Relationship between endogenic aragonite crystal size and the depth ("thickness") of the supersaturated water column in modern sediments from five aragonite precipitating saline and hypersaline lakes.



Fig. 10. Stratigraphic variation in interpreted chemocline depth based on detailed aragonite crystal size spectra collected from laminae of two cores from Waldsea Lake. The dark continuous line is a three-sample running average.

which does not appear to be reflected in core 23. The significance of this more complex pattern is not readily apparent, but may be related to the greater overall depth of this site in the basin.

## 6. Conclusion

Waldsea Lake is one of western Canada's best studied perennial saline lakes. Its location at the boundary between prairie and forest ecosystems suggests that the stratigraphic record in this basin holds considerable promise as an important archive of paleoenvironmental information. Previous investigations have highlighted a complex mid-Holocene history of the basin and a somewhat more complacent recent history. Our investigations of the detailed carbonate mineralogy and petrography and, however, have shown that significant geolimnological fluctuations have also occurred within the past two millennia.

Although brine chemistry and water column reconstructions provide valuable insight into the past chemical and physical conditions in the lake, it must be emphasized that the Waldsea Lake depositional system is considerably more complex than simple nonmeromictic salt lakes or shallow plava basins (cf. Shang and Last, 1999; Last et al., 1998; Vance et al., 1997). Thus, the history of chemical change and water column variation in this closed basin is difficult to interpret with respect to extrinsic environmental factors such as climate. These chemical changes are likely indicative of the complex interplay between changing watershed conditions (e.g., drainage basin size, vegetation cover), surface water hydrological fluctuations (e.g., lake size, depth, river inflow, diversion), and variations in groundwater contributions and composition, all of which may or may not be directly related to climate. Deciphering the interrelationships between lake hydrology, regional climate, and the chemistry of a brine is an arduous task even in a simple lacustrine system. Few lakes in the northern Great Plains offer an unambiguous record of climate change; Waldsea Lake is no exception. Nonetheless, examination and documentation of the interplay between the many intrinsic processes operating within the basin and the various extrinsic or external factors that may help control the geochemical aspects of the lake is essential for a proper assessment of the lacustrine record.

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