The Holocene history of Oro Lake, one of the western Canada's longest continuous lacustrine records

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Abstract

Over the past decade, there have been significant advances in our understanding of the Holocene history of the Great Plains region of western Canada. However, despite this increased interest, paleolimnological research is limited by a paucity of study sites with relatively long, uninterrupted stratigraphic sequences. To date, only three Canadian Great Plains lakes have provided complete, uninterrupted sequences spanning the past 10,000 years. Oro Lake is one of these. Oro Lake is small, perennial, and saline. It occupies a topographically closed basin on the Missouri Coteau in southern Saskatchewan, Canada. Its 10,000-year stratigraphic sequence consists mainly of well-bedded, calcareous, and gypsiferous clayey silts. A short-lived early Holocene freshwater siliciclastic-dominated lake occupied the newly formed basin immediately after deglaciation. At ~9300 BP, limnological conditions changed dramatically and abruptly. Since then, alkaline, high-salinity brines with high Mg/Ca ratios have prevailed. Stable meromictic conditions existed from about 9300 to ~7400 BP, with maximum salinities (>75 ppt) occurring at 8300 BP. About 7400 years ago, gradually increasing aridity during the mid-Holocene resulted in increased eolian sedimentation, reorganization of the groundwater influx, and occasional breakdown of meromixis. About 4000 BP, the lake returned to a mainly stratified water column with subaqueous soluble salts being precipitated from the monimolimnion, and aragonite and Mg-carbonates being generated from the mixolimnion. During the most recent 1000 years, periodic hypersaline conditions became more common, coincident with decreased concentrations of Ca^{2+} and complimentary increased proportions of Mg^{2+} and Na^+ ions. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The northern Great Plains of Canada extend from the Precambrian Shield near Winnipeg, Manitoba, westward for nearly 1600 km to the Foothills of the Rocky Mountains. The region is one of Canada's most productive agricultural areas. However, recurrent droughts, such as those of the 1930s and 1980s, underscore the sensitivity of the area to climatic and hydrologic change, and emphasize the significant threat of future climatic fluctuations to current agricultural practices. A clear understanding of past climatic and hydrologic conditions is a fundamental requirement to preparing for potentially adverse affects of future changes.

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Within this vast 700,000 km^2 subhumid-to-semi-arid region, there are millions of lakes. While the majority of these lakes are small, shallow, and ephemeral (i.e., playas), the region also contains several of western North America's largest lakes including Lake Winnipeg (24,400 km^2), Lake Manitoba (4700 km^2), Lake Winnipegosis (4600 km^2), and the Quill Lakes (400 km^2). In addition, the deposits of extinct Pleistocene and early Holocene proglacial lakes, such as Lake Agassiz and Lake Regina, form important and extensive geomorphic features in the region. Superposed on this wide spectrum of lacustrine basin types and morphologies is a great range in salinities and water compositions. Most of the ponded surface water in western Canada is saline or hypersaline; however, relatively freshwater lakes and reservoirs also exist. Every major water chemistry type is represented in the region.

The large number of lacustrine basins in the northern Great Plains offers an exceptional opportunity to study regional paleoenvironmental and paleoclimatic change (Vance, 1997; Lemmen and Vance, 1999a; Lemmen et al., 1993; 1997). Over the past decade, there have been significant advances in our understanding of the Holocene history of this region (Lemmen and Vance, 1999b), with the number of investigated lacustrine stratigraphic sequences more than tripling since 1988. To date, the paleolimnology of just over fifty extant basins and about a dozen late Pleistocene lacustrine sequences have been examined.

Despite this increased interest, paleolimnological research in the northern Great Plains of Canada still lags behind that of other areas such as the Foothills and Rocky Mountain areas to the west and the boreal forest region to the north and east (Sauchyn, 1997). Ritchie and Harrison (1993) identify only one site in the prairie region of western Canada having a limnological record extending back to 10,000 BP. To date, only very few of the extant lakes in the region have provided complete, uninterrupted sequences spanning the past 10 k years. Oro Lake is one of these. Our objective in this paper is to present the lithostratigraphy of this lacustrine sequence and to discuss the changes in physical and chemical limnology that have occurred during the Holocene as interpreted from the mineralogical and lithostratigraphic record. Investigations of the biological, magnetic susceptibility, and isotopic aspects of the record are ongoing and reported elsewhere (e.g., Padden, 1996; Vance and Last, 1996; Cywinska and Delorme, 1995; Stuart, 1999; Stuart et al., 1998).

2. Materials and methods

This report is based on the analysis of a total of approximately 16 m of core taken from three sites in the Oro Lake basin (Fig. 1) using a 3-in.-diameter vibracorer (Vance and Last, 1996). Supplementary core material of the upper 20 cm of the section at core site OR1 was provided by C.T.L. Stuart (Queen's University). Core OR1, taken in the deepest part of the lake (6-m water depth), recovered the thickest Holocene sequence (8.13 m); cores collected at OR2 (5-m water depth) and OR3 (2-m water depth) retrieved shorter sections (3.9 and 4.6 m, respectively). After visual logging and photographing (visible and xradiography), the cores were subsampled for a variety of physical, mineralogical and chemical parameters. A total of 650 subsamples from these cores were analyzed for bulk mineralogy, detailed carbonate and evaporite mineralogy, organic matter content, total carbonate mineral content, grain size, and moisture content. The subsampling interval was generally 2 cm except in the upper half meter of section in which it ranged from 1 to 0.25 cm.

Moisture content, organic matter content, and total carbonate mineral content were evaluated by weight loss on heating to temperatures of 65, 500, and 1000 °C, respectively (Dean, 1974). Particle size spectra for each subsample were determined using an automated laser-optical particle size analyzer (Galai CIS-1; Aharonson et al., 1986; Galai Production, 1989; Syvitski et al., 1991) after removal of organic matter by hydrogen peroxide treatment. Because of the high-sulfate min-

Fig. 1. Map of western Canada showing the location of Oro Lake (*). Also shown are the locations of other lakes mentioned in the text: the Andrews Site (A); Ceylon Lake (Cy); Chappice Lake (Ch); Clearwater Lake (Cw); Deadmoose Lake (Dm); Deep Lake (Dp); Devils Lake (D); Freefight Lake (Ff); Harris Lake (H); Ingebright Lake (In); Killarney Lake (Kl); Lake Manitoba (Mb); Moore Lake (M); Quill Lakes (Q); Redberry Lake (Rb); Waldsea Lake (Ws); and Lake Winnipegosis (Wg.) Inset map in the upper-left corner shows the bathymetry of Oro Lake and the location of the three coring sites.
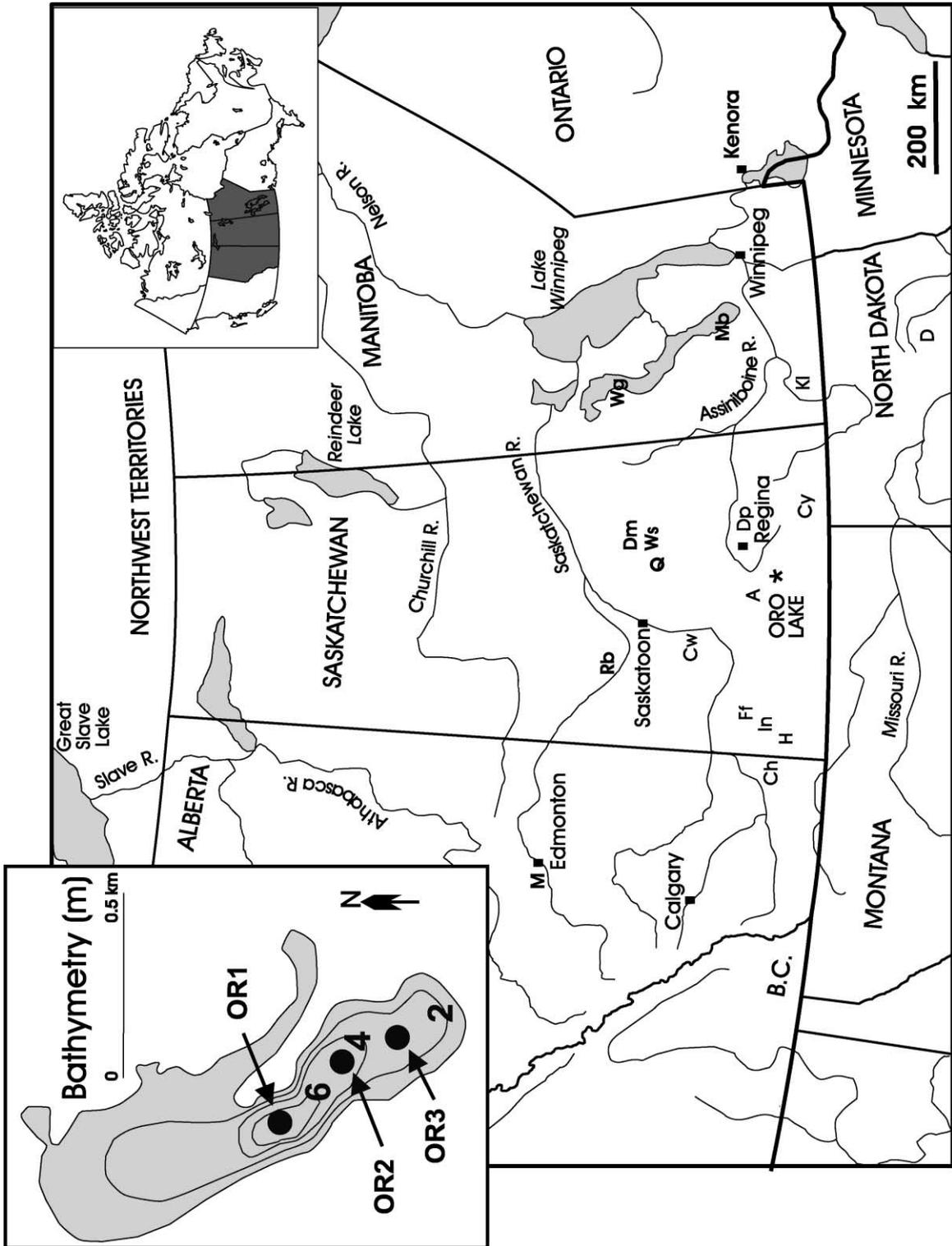
eral content of many of the samples, a 1% solution of Triton X100 was used as the dispersion agent, rather than disodium hexametaphosphate. Particle-size statistics (mean, median, standard deviation) were calculated by the moment method according to Allen (1981). Duplicate samples were prepared and analyzed every 25 samples and a standard run every 50 samples. These replicate analyses indicate precision of the particle size data is approximately ±2%.

All samples analyzed for mineralogy were air-dried at room temperature, disaggregated in a mortar and pestle, and passed through a 62.5 μm sieve. Bulk mineralogy and detailed carbonate and evaporite mineralogy were determined using standard X-ray diffraction techniques (Klug and Alexander, 1974). Mineral identification was aided by the use of an automated search-match computer program (Marquart, 1986). Percentages of the various minerals were estimated from the bulk mineral diffractograms using the intensity of the strongest peak for each mineral as outlined by Schultz (1964) and Last (2001). Nonstoichiometry of the dolomite and calcite was determined by examining the displacement of the d_{104} peak on a detailed (slow) XRD scan (Goldsmith and Graf, 1958) and calculated according to Hardy and Tucker (1988). Duplicate samples were prepared and analyzed for bulk mineralogy every 10 samples. These replicate analyses indicate precision of the mineralogical data is approximately ±5%.

A chronology for the recovered stratigraphic sequences was established by accelerator mass spectrometry (AMS) radiocarbon ages, mainly on well-preserved seeds of upland and shoreline plants. A chronology for the upper 20 cm at site OR1 was established by ^{210}Pb as presented and discussed in Stuart (1999). Elemental analyses of brine and groundwater samples were carried out by atomic absorption, gravimetric, and turbidimetric methods. The molalities and activities of chemical species in the brines and the saturation state of the waters with respect to a variety of mineral components was calculated using WATEQF (Rollins, 1989).

3. Regional setting and geolimnology of modern Oro Lake

Oro Lake (49°47′N, 105°21′W, elev. 680 m a.s.l.) is located 80 km southwest of Regina, Saskatchewan,

and about 80 km north of the Canada–USA border (Fig. 1). The lake occupies a small, elongate basin just south of the Dirt Hills area on the Missouri Coteau. The Missouri Coteau is a major northeast-facing, drift-covered bedrock escarpment that extends some 1000 km from eastern South Dakota northwestward through North Dakota, Saskatchewan, and into eastern Alberta. The Dirt Hills are a series of parallel, deformed bedrock ridges mantled by about 100 m of glacial sediment. They were formed about 11,000 years ago by several surging ice lobes during deglaciation (Parizek, 1964; Aber, 1993). The Oro Lake basin likely formed shortly after this, probably as an ice-block melt-out kettle depression. The terrain around Oro Lake is hummocky, typical of the disintegration morainal topography of the Missouri Coteau.

Mean daily January temperature in the Oro Lake area today is about −16 °C; during July, it is 17 °C. Approximately 325 mm of precipitation falls per year, whereas more than three times this amount can be lost per year through evaporation (CNC/IHD (Canadian National Committee for the International Hydrologic Decade), 1978).

Oro Lake is small (0.5 km²) and relatively shallow (mean depth: 2.8 m; maximum depth: 6.1 m). The hydrology and modern limnology of the basin are poorly known. Several small, ungauged ephemeral streams drain the small (<10 km²) catchment. There is no surface outlet. Presumably, the modern hydrologic budget is dominated by groundwater inflow and loss by evaporation during the ice-free season. Like many other perennial prairie lakes, Oro Lake has experienced a marked reduction in lake-level over the past several decades. Once a popular recreation site, with a small regional park and day-use facilities located at the north end of the basin, declining lake levels and deteriorating water quality now restrict use of the lake.

Although there has been no neolimnolological or modern sedimentological research yet done, the Oro Lake water column was chemically stratified during sampling visits to the lake in 1994, 1995, 1999, 2001 (Table 1). The surface water averaged ~30 parts per thousand (ppt) salinity and the monimolimnion was about 45 ppt TDS. Unlike many of the other salt lakes in the vicinity (e.g., Shoe, Willow Bunch, Frederick, Old Wives), Oro Lake brine is dominated by Mg^{2+} rather than Na^+ (Fig. 2). Oro Lake has the highest meq% magnesium of any salt lake in the Great Plains

Table 1
Oro Lake hydrochemistry (ionic concentrations in mg l^{-1})

	9/1994		1/1995	5/1995	6/1997		3/1999		Groundwater		
	Surface	5 m	Surface	Surface	Surface	5 m	Surface	5 m	Shallow drift	Deep drift	Bedrock
Ca^{2+}	91.9	128	126	59			99.2	123	83	390	334
Mg^{2+}	4500	6640	5950	2120			5100	6540	279	313	230
Na^+	1940	2820	2680	1150			2190	2760	5.5	445	427
K^+	369	530	397	127			398	512	8	13	13
$HCO_3^- + CO_3^{2-}$	1033	1860	1398	585			1117	1800	369	959	1030
SO_4^{2-}	22,200	31,100	29,000	12,400			26,100	30,900	28.8	2080	1570
Cl^-	600	812	814	313			680	798	8.2	136	135
Total alkalinity	20.2	31.9	31				1010	1210	5.8	15.8	16.9
Si	3.12	14.1	6.73	2.25			4.01	13.9	0.01	0.08	0.07
F	6.4	7.4	7.0	10.3							
Li	2.56	3.74	3.44	1.5							
Ionic strength	0.51	0.75	0.68				0.60	0.70	0.01	0.08	0.07
TDS (ppt)	33.5	46.6	44.4	17.8	11	20	39.2	45.9	0.5	4.4	3.7
pH	8.7	8.1	8.4	8.6			9	8.8	7.9	7	7.3

Data from 6/1997 are from Stuart (1999). Total alkalinity is expressed as milliequivalents. Blanks indicate no data.

(cf., Last, 1992). The origin of this strong Mg^{2+} signature has not yet been resolved although it is clear the Oro brines represent a complex mixture of shallow ($Ca + Mg + HCO_3$), intermediate and deep ($Mg + SO_4$) groundwater contributions modified by evaporative concentration and mineral precipitation.

The entire water column of Oro Lake is strongly supersaturated with respect to many magnesium and magnesium + calcium carbonates; during winter, it is also saturated to supersaturated with respect to a variety of Mg- and Na-bearing sulfate salts. The surficial offshore bottom sediments (0–1 cm; see Table 3)
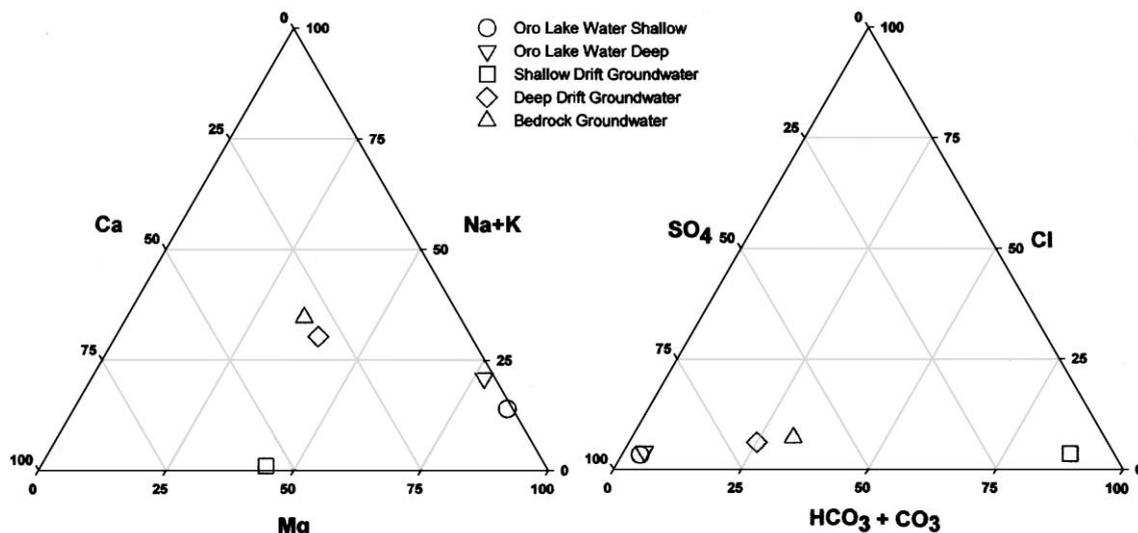

Fig. 2. Triangular plots showing the composition of Oro Lake water and groundwater (in meq%).

consist of a complex mixture of aragonite, Mg-calcite, disordered dolomite, hydrated magnesium sulfates (epsomite and hexahydrite), magnesium + sodium sulfates (konyaite and bloedite), calcium sulfate (gypsum), magnesium carbonate (magnesite), and detrital components (quartz, feldspars, clay minerals, calcite, and dolomite).

4. Chronology and correlation

Vance and Last (1996) and Stuart (1999) have presented the results of AMS radiocarbon dating of plant macrofossil remains from core OR1, located in the central part of the basin. These five dates plus six additional AMS dates from the other two cores in the basin are listed in Table 2. In order to compare the chronology and lake history derived in this study with other published paleolimnological efforts in the region, we use mainly uncalibrated ^{14}C ages; however, calibrated ages (calendar year BP) are also shown in Table 2.

Fig. 3 shows the depth–time plot for core OR1. The best-fit line (at 99% confidence level) emphasizes that the Holocene sequence recovered in this core is continuous with no obvious unconformities or significant interruptions in sedimentation from approximately 9700 years BP to present. Also shown in Fig. 3 is the correlation of lithostratigraphic units between the three cores. In addition to the ^{14}C-based chronology, Stuart (1999) has established a ^{210}Pb chronology of a short core taken at the OR1 site.

5. Lithostratigraphy

5.1. General

The Holocene stratigraphic sequences recovered from the three core sites in the basin generally consist of massive to well-bedded, slightly organic-rich, clayey silt. The upper meter of sediment is very soft with high moisture contents, whereas the lower ~20 cm recovered in each core are very firm and relatively dry. Moisture contents decrease gradually downward from greater than 80% at the surface to less than 50% in the lower half of the sections. Organic matter content is remarkably constant through most of the section (~15%); however, thin zones of organic-rich sediment overlie the basal dry zones in each core. Sediment colors are generally dark olive grey (Munsell: 5Y 3/2) to dark yellowish brown (10YR 3/6) and dark grey (2.5 Y 2.5/1). Texturally, the sediment is mainly clayey silt. Mean grain size ranges from less than 4 μm to greater than 40 μm, with an overall average of ~20 μm. With the exception of the upper half-meter of sediment and the lower 20 cm of the sections, parallel lamination is prominent. Most of the laminae consist of millimeter-scale light colored (10YR 8/4 to 5YR 6/2) beds. Composition of individual laminae is usually monomineralic or strongly dominated by one mineral. However, the composition can vary considerably over relatively short (cm-scale) stratigraphic distances. Often, these laminae occur in cm-scale packages or bundles of regularly spaced

Table 2
Oro Lake radiocarbon dates

Core and depth (cm)	Lab number[a]	Uncorrected ^{14}C age (year BP)	Calibrated age (cal. year BP)[b]
OR1: 109–111	CAMS 22356	970 ± 70	921
OR1: 310–313	CAMS 19173	4290 ± 60	4847
OR1: 562–563.5	CAMS 15588	6730 ± 60	7585
OR1: 755–757	CAMS 15587	9090 ± 70	10,224
OR1: 784.5–787.5	CAMS 15586	9420 ± 230	10,670
OR2: 177–179	CAMS 42979	5410 ± 50	6269
OR2: 255–258	CAMS 22366	7060 ± 50	7927
OR2: 338–341	CAMS 19174	8150 ± 60	9084
OR3: 145–150	CAMS 42978	2030 ± 120	1990
OR3: 335–338	CAMS 25801	6720 ± 60	7581
OR3: 440–442	CAMS 22367	8890 ± 60	10,146

[a] All from Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory.
[b] Calibrated ages (in calendar years BP) calculated using CALIB 4.2 (Stuiver et al., 1998).
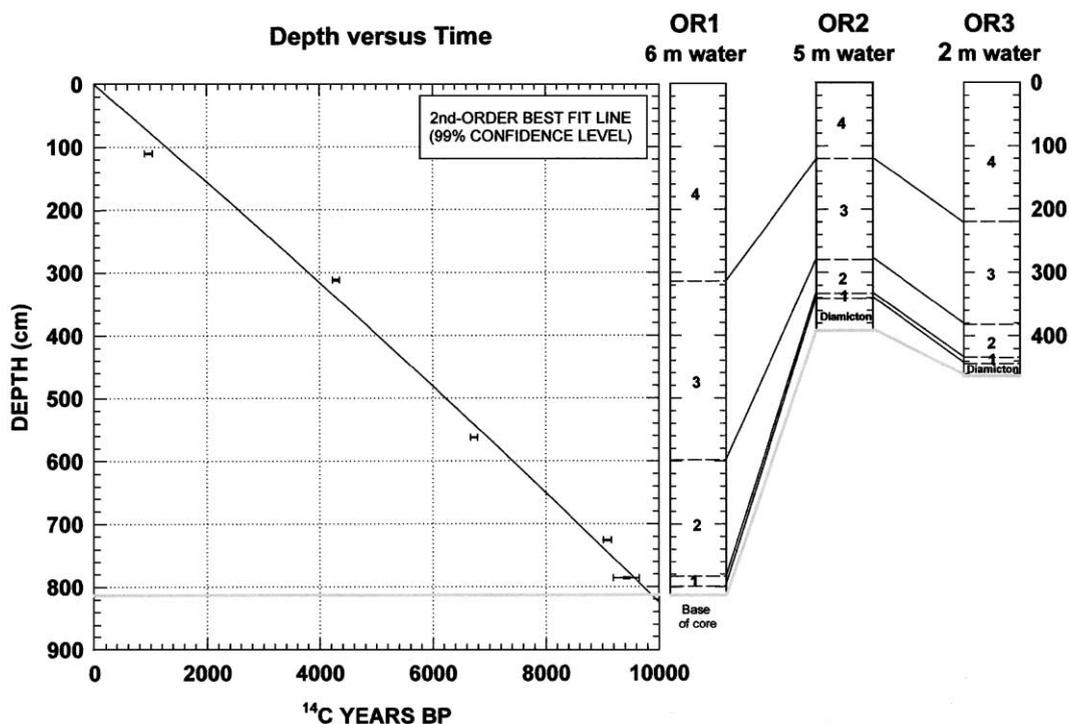
Fig. 3. Best fit line of depth vs. ^{14}C time in Oro Lake core OR1. Also shown are the stratigraphic positions and correlation of lithostratigraphic units in the three cores.

laminations alternating with massive or poorly bedded sequences. In addition, more indistinct, cm-scale light–dark banding is also common.

As shown in Table 3, the inorganic fraction of Oro Lake sediment, which comprises generally greater than 85% of the total sediment, consists of a mixture of soluble and sparingly soluble salts, carbonate minerals, and clay minerals, with minor amounts of quartz, plagioclase and potassic feldspars, ferromagnesian minerals, and pyrite. Although the paragenesis of this complex mineral suite is still being investigated, the high solubility of the sulfate salts and the lack of a source for most of the carbonate minerals within the drainage basin precludes their origin as clastic detrital material. It is likely that the clay minerals, quartz, feldspar minerals, calcite, and dolomite are detrital in origin (i.e., allogenic), being derived from erosion of the surrounding glacial deposits and transported to the lake by streams, sheetwash and wind. The sulfates, pyrite, aragonite, Mg-calcite, nonstoichiometric dolomite, magnesite, and

other soluble salts have most likely been derived from within the basin itself, either by direct precipitation from the water column (i.e., endogenic) or by postdepositional authigenic/diagenetic precipitation processes.

The carbonate minerals in Oro Lake sediment, comprising about 40% of the inorganic fraction, are dominated by aragonite, dolomite, and calcite (Table 3), with smaller amounts of magnesian calcite and disordered, nonstoichiometric dolomite (subsequently referred to as "protodolomite" in this paper), and sporadic occurrences of hydromagnesite [$4MgCO_3$ $Mg(OH)_2 \cdot 4H_2O$], magnesite ($MgCO_3$), and natron ($Na_2CO_3 \cdot 10H_2O$). Soluble evaporitic sulfate minerals dominate the lower and upper third of each sequence, and make up an average of about 30% of the sediment overall (Figs. 4–7). The soluble salt assemblage consists mainly of gypsum with irregular occurrences of thenardite (Na_2SO_4), bloedite [$Na_2Mg(SO_4)_2 \cdot$ $4H_2O$)], konyaite [$Na_2Mg(SO_4)_2 \cdot 5H_2O$], epsomite ($MgSO_4 \cdot 7H_2O$), and hexahydrite ($MgSO_4 \cdot 6H_2O$).

Table 3
Summary of average mineralogical characteristics of lithostratigraphic units

| | Lithostratigraphic unit | | | | | | |
	Diamicton	Unit 1	Unit 2	Unit 3	Unit 4	Surface sediment average	Overall average
% Total siliciclastic fraction	81.6	76.0	22.6	41.6	23.4	65.1	36.1
% Total clay minerals	25.9	50.5	16.8	26.3	20.0	59.8	24.8
% Quartz	25.0	10.1	3.1	8.1	2.1	0.8	5.7
% Total feldspar minerals	38.8	14.6	2.6	7.1	1.4	4.5	5.5
% Plagioclase	34.4	10.1	2.2	5.8	1.1	2.8	4.7
% K-feldspars	9.4	4.5	0.4	1.3	0.3	1.7	0.8
% Amphibole minerals	1.9	0.9	0.1	0.1	0.1	<0.1	0.1
% Total detrital carbonate fraction	18.4	11.6	16.5	23.9	10.8	6.1	20.8
% Calcite	3.2	6.9	1.4	5.2	3.7	<0.1	3.8
% Dolomite	15.2	2.3	5.8	13.7	8.8	6.1	10.0
% Total endogenic and authigenic fraction	np	12.4	60.9	34.5	65.8	28.8	43.1
% Magnesian calcite	np	1.3	0.4	0.1	0.4	1.8	0.4
Mol% $MgCO_3$ in Mg-calcite	nd	11.0	11.9	12.6	10.4	6.2	11.4
% Disordered dolomite	np	6.2	0.2	0.8	1.1	5.6	0.9
Mol% $CaCO_3$ in disordered dolomite	nd	66.1	70.0	65.5	68.1	64.0	68.0
% Aragonite	np	2.5	3.4	30.3	19.8	2.5	21.9
% Total Mg carbonate minerals	np	np	np	0.1	2.7	2.5	<0.1
% Total sulfate minerals	np	2.4	56.9	3.2	41.8	16.4	27.2
% Gypsum	np	2.4	56.5	3.0	27.9	7.7	26.4
% Total mg sulfate minerals	np	np	<0.1	np	4.3	2.9	<0.1
% Total Mg+Na sulfate minerals	np	np	np	np	3.4	2.0	<0.1
% Total Na sulfate minerals	np	np	0.1	0.2	6.2	3.8	0.2
% Total Na+Ca sulfate minerals	np	np	np	np	<0.1	<0.1	<0.1
% Total other sulfate minerals	np	np	<0.1	np	<0.1	<0.1	<0.1
% Total phosphate minerals	np	np	<0.1	np	<0.1	<0.1	<0.1
% Total chloride minerals	np	np	<0.1	np	<0.1	np	<0.1
% Pyrite	np	<0.1	np	<0.1	<0.1	np	<0.1
% Moisture	15.1	57.4	42.2	51.0	69.1	82.3	53.6
% Organic matter	2.1	30.9	20.3	12.4	21.8	20.6	16.2
% Sand	5.5	16.9	4.6	1.8	5.7	6.5	4.5
% Silt	74.9	76.7	81.5	70.3	88.6	90.2	80.8
% Clay	19.6	6.4	13.9	28.9	5.7	3.3	15.1
Mean (μm)	17	38.1	21.3	15.0	29.9	29.9	21
Median (μm)	8.2	30.6	14.7	8.8	24.8	35.7	16.1
Sedimentation rate[a] (cm 100 year^{-1})	nd	nd	8.2	8.3	7.9	nd	8.2

nd = Not determined; np = Not present.

   [a] Calculated on the basis of a best fit line of depth vs. time for Core OR1 using the five ^{14}C dates and assuming no interruption in deposition.

Endogenic and/or authigenic phosphate minerals and very soluble halides occur in a small number of samples. Among the phosphates identified, brushite ($CaPO_4$), rockbridgeite [(Fe, Mn)$Fe_4(PO_4)_3(OH)_5$], and strengite ($FePO_4 \cdot 2H_2O$) occur most frequently. Halite was the only halide mineral identified.

The allogenic fraction of the sediment comprises mainly siliciclastic material (average 36%), with

Fig. 4. Stratigraphic variation in moisture, organic matter, and total carbonate mineral contents, texture (% sand, % silt, % clay), particle size (mean and median), mineralogy, detrital vs. endogenic + authigenic components, and clastic weathering index in core OR1. Radiocarbon dates are shown on right with lithostratigraphic units (Table 3). Dashed lines indicate lithostratigraphic unit boundaries. The detailed fluctuations in the upper meter of this core are shown in Fig. 5.
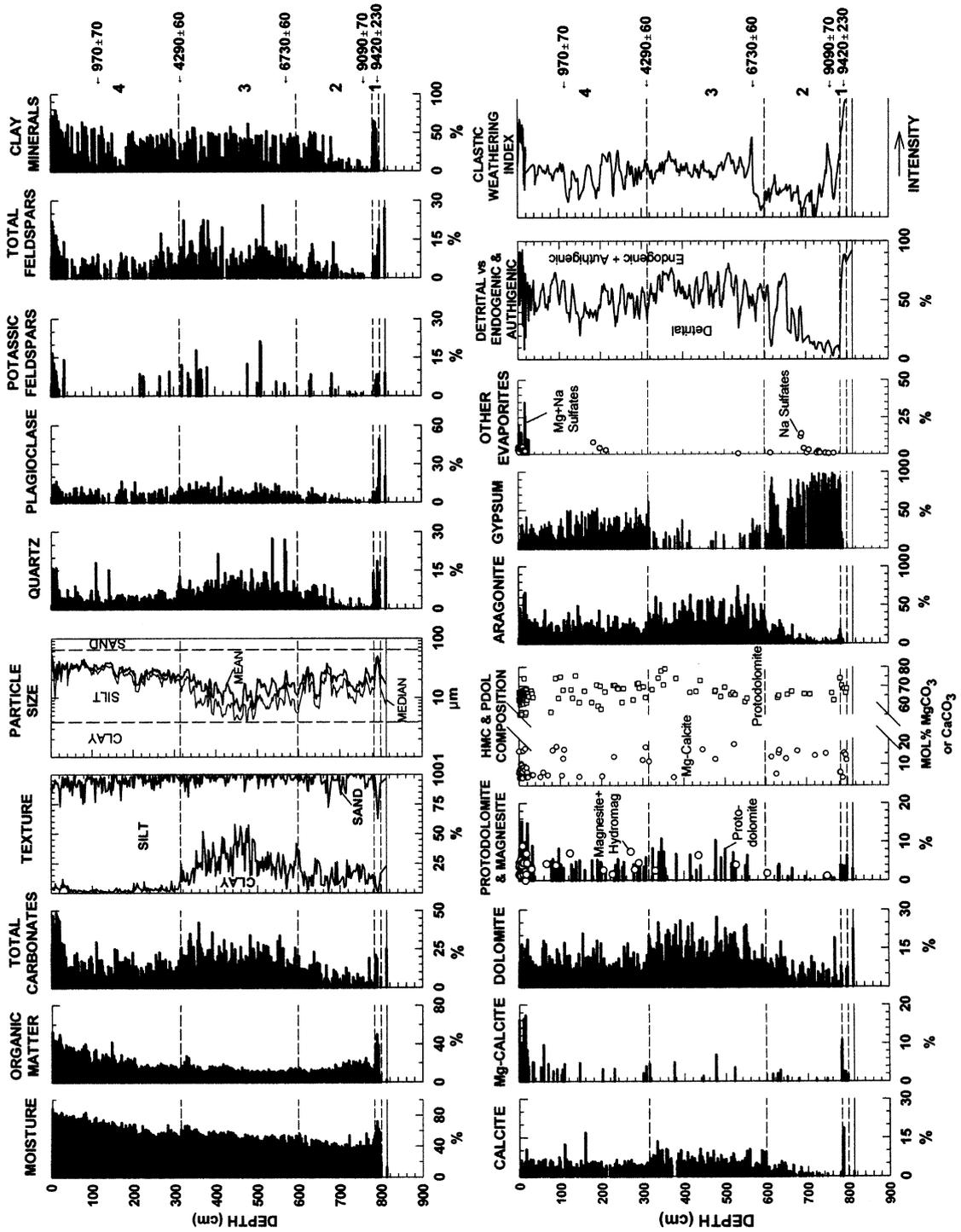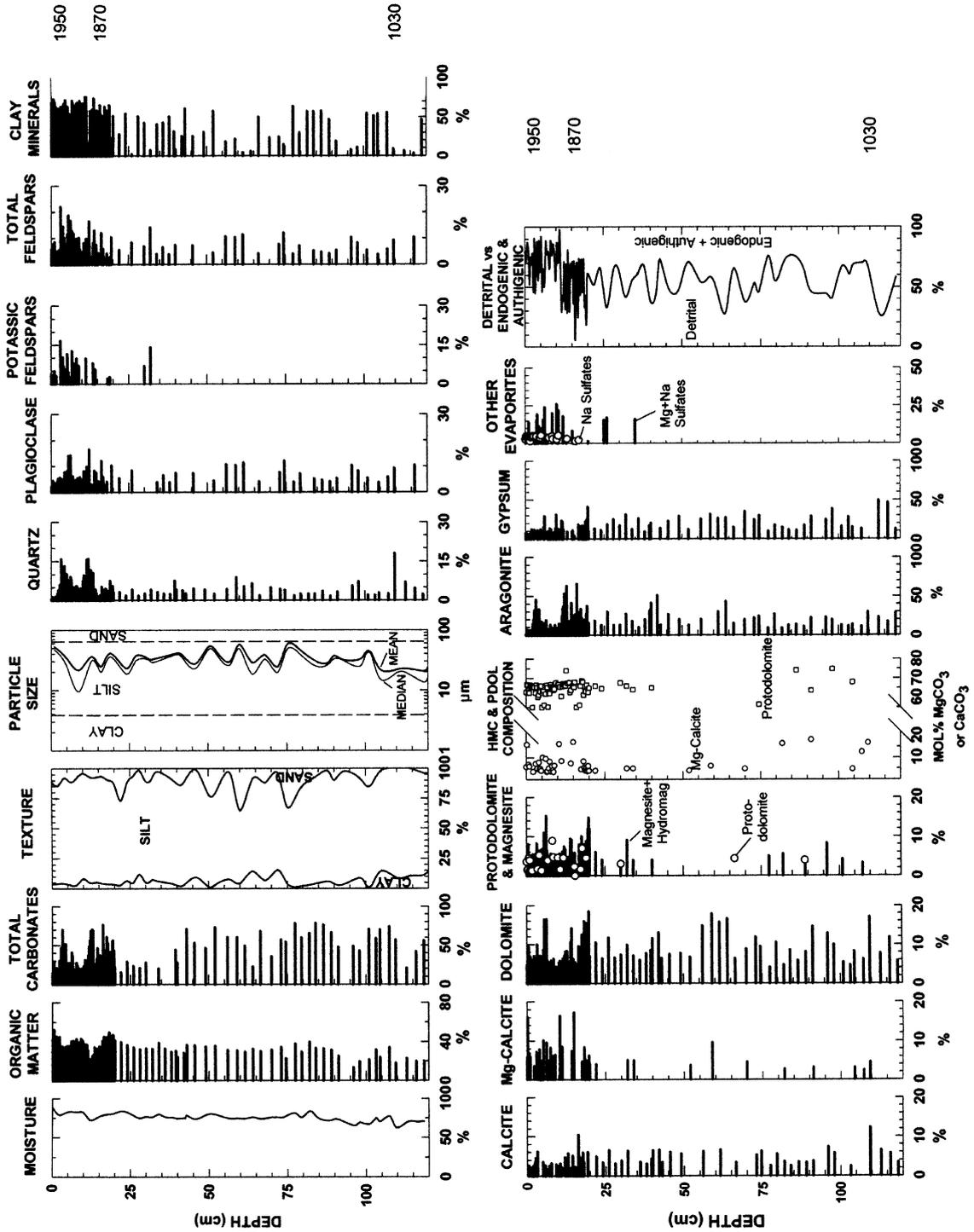
smaller proportions of carbonates ($\sim 20\%$). The siliciclastics are dominated by clay minerals; however, quartz, plagioclase, and potassic feldspars also occur in small amounts in nearly all samples. The detrital carbonates are dolomite and calcite. The ratio of these two minerals remains relatively constant throughout the sequence and compares well with the ratio of detrital carbonates in the tills and glacial deposits of the region (Teller and Last, 1981; Egan, 1982; Sun, 1996). The ratio of siliciclastics to detrital carbonates (clastic weathering index in Figs. 4–7) is also relatively constant throughout most of the sequence. This ratio, which reflects the relative chemical stability of siliciclastics versus carbonates (see Teller and Last, 1981; Last and Sauchyn, 1993), suggests little overall change in the intensity of chemical weathering processes within the Oro Lake watershed.

Based on the mineralogical composition, organic and moisture contents, and bedding features, the Holocene sequence recovered from Oro Lake can be subdivided into five lithostratigraphic units (Table 3, Figs. 4–7).

5.2. Diamicton (pre-9700 BP)

The lowermost unit (diamicton) is a firm, compact, structureless, siliciclastic-rich sandy, clayey silt with very low moisture and organic matter contents. Large (cm-scale) rounded carbonate pebbles are present in a matrix of finer-grained material. The mineral suite consists of subequal proportions of detrital feldspars, quartz, clay minerals, and carbonates. The carbonate fraction of the sediment consists entirely of stoichiometric, well-ordered dolomite and calcite of detrital origin. Endogenic and authigenic minerals, which dominate the overlying sediment, are absent in this lowermost unit.

5.3. Unit 1 (9700–9300 BP)

Sharply overlying this basal diamicton is a thin (10–20 cm thick), massive to faintly bedded, calcareous, organic-rich clastic unit (Unit 1). Organic matter content is as high as 75% and the inorganic sediment is dominated by fine-grained siliciclastic material. The detrital carbonate mineral fraction is unusual in that it is dominated by calcite with smaller amounts of dolomite; the entire rest of the sequence in Oro Lake and in most other lakes of the region show a dominance of dolomite as the detrital carbonate component. This suggests that some of the calcite may be endogenic in origin rather than detrital material derived from the surrounding drainage basin tills and soils. However, the detailed petrography required to differentiate the detrital $CaCO_3$ from endogenic low Mg-calcite has not yet been completed. Although Unit 1 is dominated by organic matter and fine-grained detrital material, aragonite, Mg-calcite, protodolomite, and pyrite all exist in small amounts (Table 3). The core taken in the shallowest part of the basin (OR3; 2-m water depth) contains the greatest abundance of these endogenic carbonate precipitates ($\sim 40\%$; Fig. 6), suggesting a likely facies composition change from relatively pure organic matter + siliciclastics in the more offshore areas of the basin to more carbonate-rich sediment in shallower water environments.

5.4. Unit 2 (9300–7400 BP)

Immediately overlying the thin organic-rich clastics of Unit 1 is a relatively thick unit of laminated gypsite (Unit 2). Maximum thickness of Unit 2, approximately 2 m, occurs in core OR1 in the most offshore part of the lake, with progressively thinner sequences shoreward. The sediment of Unit 2 is moderately organic-rich ($\sim 20\%$) and shows increasing organic contents in the shoreward direction and decreasing contents upward in the unit. Composition ranges from nearly pure ($>95\%$) $CaSO_4 \cdot 2H_2O$ to a mixture of gypsum, detrital clay minerals, and detrital carbonates. Endogenic carbonate content is low except in the most shoreward core, in which gypsum-rich zones alternate with aragonite-dominated sediment (Fig. 6). Although most of the nondetrital

Fig. 5. Stratigraphic variation in moisture, organic matter, and total carbonate mineral contents, texture (% sand, % silt, % clay), particle size (mean and median), mineralogy, and detrital vs. endogenic + authigenic components for the upper 1.2 m of core OR1. Dates shown on right are calender years and are derived from the ^{210}Pb established by Stuart (1999) at this site and a single calibrated ^{14}C date at 110 cm (see Table 2). Sample density was 0.25 cm in the upper 20 cm and 2 cm from 20 to 120 cm. The moisture, texture, particle size, and detrital vs. endogenic + authigenic curves are plots of three-sample running means.
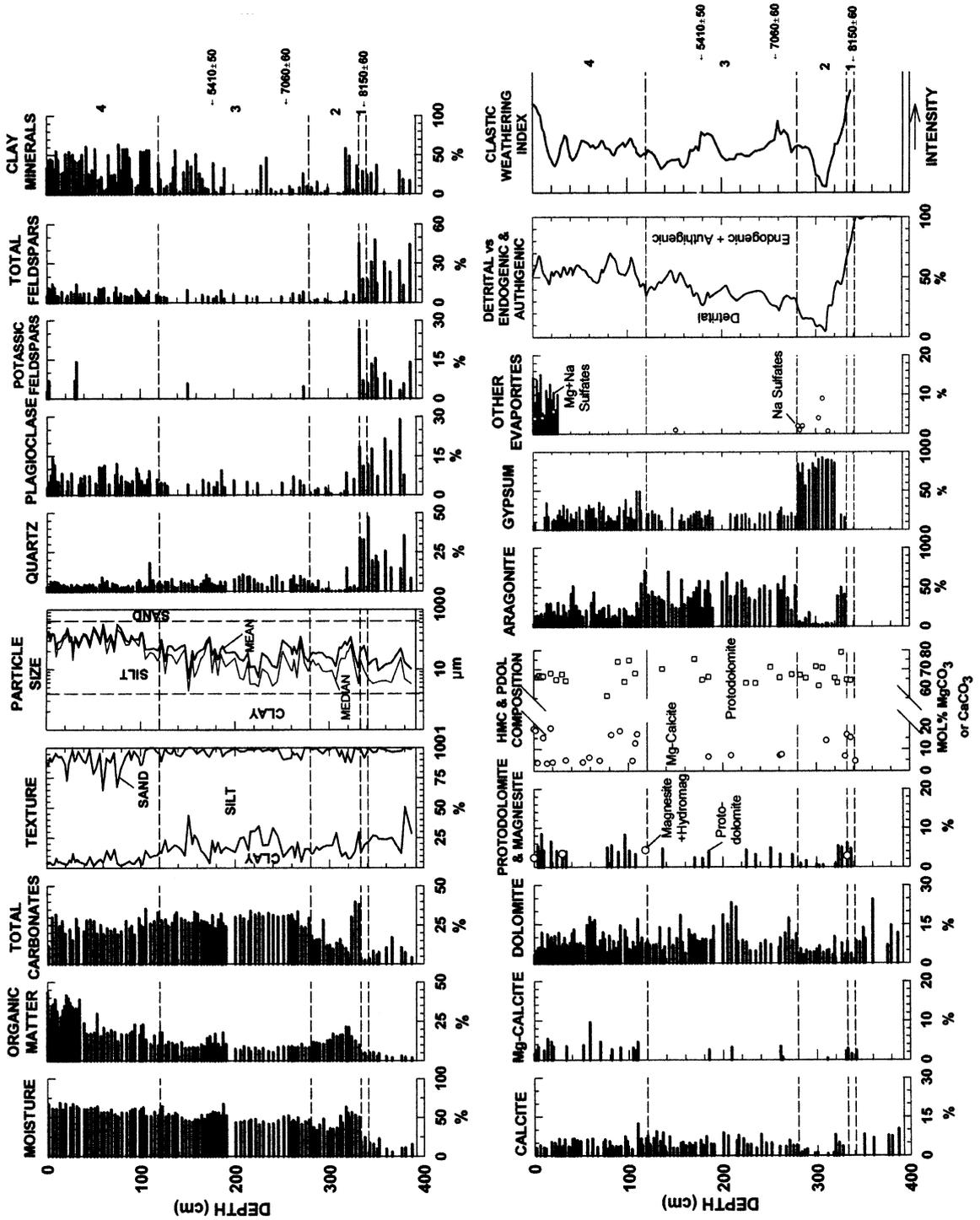
sediment is gypsum, the unit also contains small to trace amounts of sodium and magnesium sulfates, halite, and phosphates. In core OR1, the lower contact is sharp, but the upper contact is gradational over 20–30 cm into the overlying carbonate-rich sediment of Unit 3; in the other two cores, both the upper and lower contacts are sharp.

5.5. Unit 3 (7400–4000 BP)

Unit 3 is finely laminated to indistinctly bedded and color-banded, aragonitic clayey silt. It is distinguished from the underlying sediment mainly by the relatively low abundance of sulfate and other soluble evaporitic minerals and high proportion of endogenic carbonates, detrital carbonates, and siliciclastics. Thickness of the unit is greatest (~ 3 m) in the most offshore location (OR1), but thins to 1.6 m in the other two cores. With an average mean grain size of 15 μm, Unit 3 is also the most clay-rich unit of the entire sequence, averaging about 30% finer than 4-μm material. Aragonite is the dominant nondetrital mineral; however, protodolomite and magnesite also occur in small amounts throughout the unit. Many samples from Unit 3 in OR3, the most shoreward core, also contain Mg-calcite. Like Unit 2, this thick aragonitic unit is also well laminated, with a dominance of very thin to thin (<1 mm to 3 mm) monomineralic laminae. However, the unit also contains numerous centimeter-scale zones of massive to indistinctly bedded and banded material as well as convoluted and minor graded bedding.

5.6. Unit 4 (4000–present)

Unit 4, the uppermost lithostratigraphic unit in Oro Lake, is characterized by a decrease in endogenic carbonates and detrital components, and a significant increase in grain size and soluble evaporite mineral content relative to Unit 3. The lower contact of Unit 4 with Unit 3 is readily delineated by the change in texture (decrease in clay, increase in sand and increase in mean size) and gypsum content (Figs. 4–7). Organic matter shows a gradual increase upward in

the unit, as do moisture content and mean grain size. The evaporite mineral suite is dominated by gypsum, but also contains smaller proportions of bloedite and epsomite. Aragonite is the dominant endogenic carbonate and, unlike the gypsite of Unit 2, can comprise a significant proportion of the inorganic material (Table 3). Although both Units 3 and 4 contain Mg-carbonates, magnesite, hydromagnesite, and protodolomite occur more commonly in Unit 4. Similar to the older sections of the cores, there is a facies composition change in Unit 4 from the basin-center core to the more shoreward locations. In OR1 and OR2, the nondetrital components are dominated by $CaSO_4 \cdot 2H_2O$, whereas in OR3 the endogenic fraction is mainly aragonite with smaller proportions of gypsum. Similarly, Unit 4 in the core from the most nearshore position in the basin (OR3) contains no Mg-carbonates. Bedding in Unit 4 ranges from finely laminated to massive and is dominated by alternating packages of well-laminated sediment and poorly bedded material. The upper 60 cm of this youngest stratigraphic unit is nonbedded, with gradually increasing levels of hydrated sodium and magnesium sulfate salts and decreased gypsum upward in the section.

6. Discussion

6.1. General comments

Although only a relatively small proportion of the lakes in the prairie region of western Canada have been cored, the Oro Lake record is unique. Oro Lake contains the longest uninterrupted laminated lacustrine sequence in the Canadian Great Plains. With the exception of the organic-clastics of Unit 1, the mineralogical record of Oro Lake suggests the water has been saline to hypersaline throughout most of the Holocene (Fig. 8). The ubiquitous occurrence of gypsum, a soluble evaporitic mineral, in Units 2–4 requires that brines of salinities at least ~ 15 ppt TDS occupied the basin continuously since early Holocene. In fact, concentrations were probably considerably higher than this minimum value for long periods in

Fig. 6. Stratigraphic variation in moisture, organic matter, and total carbonate mineral contents, texture (% sand, % silt, % clay), particle size (mean and median), mineralogy, detrital vs. endogenic + authigenic components, and clastic weathering index in core OR2. Radiocarbon dates are shown on right with lithostratigraphic units (Table 3). Dashed lines indicate lithostratigraphic unit boundaries.
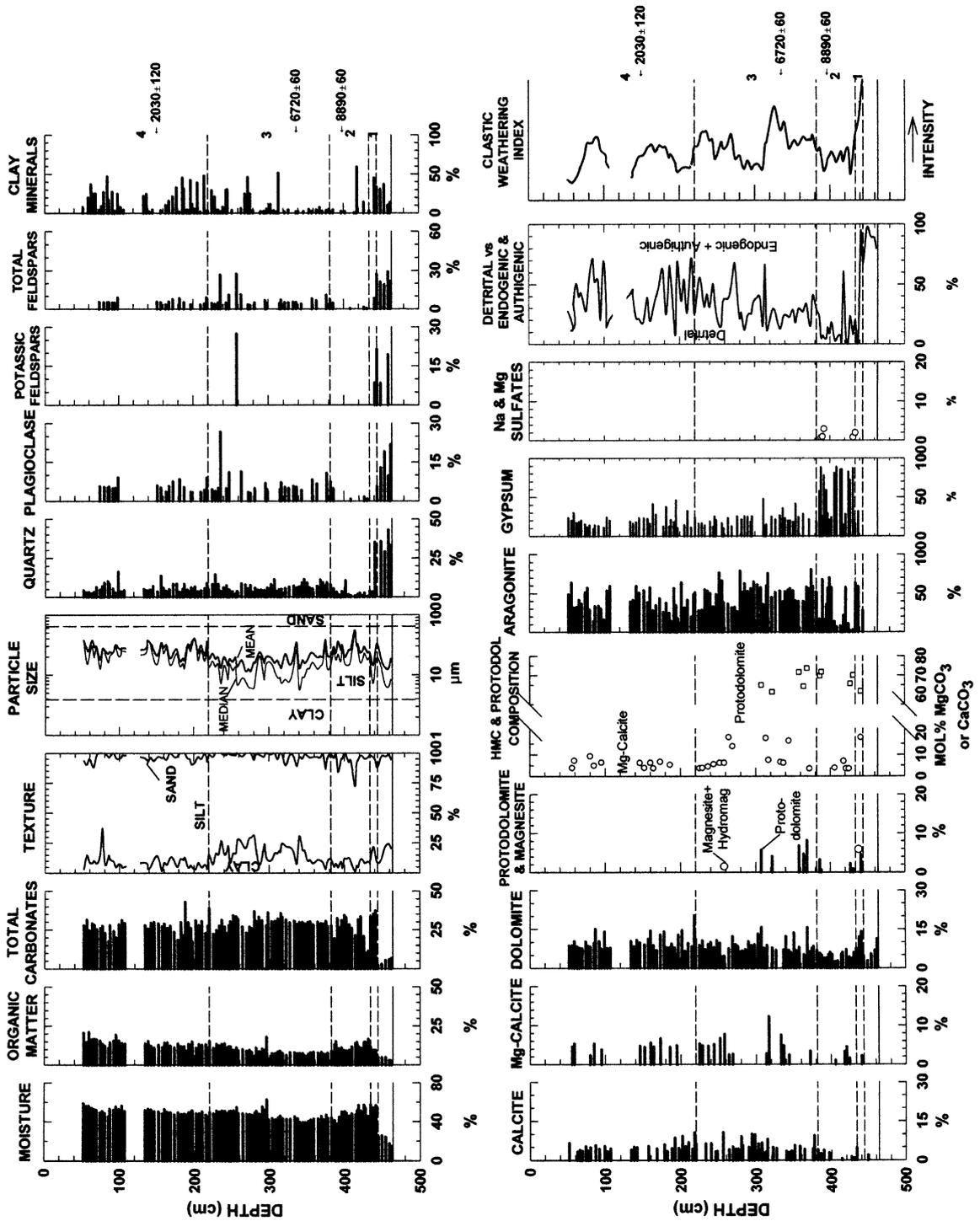
the lake's history. Today, every lake in the region in which gypsum is present in the modern sediments has salinity greater than about 30 ppt (Last, 1989; Last and Schweyen, 1983). Furthermore, the occurrence of other soluble evaporites in Units 2 and 4, such as thenardite, bloedite, and epsomite, points toward at least temporary episodes of much higher salinity (>75 ppt) conditions at the sediment–water interface.

The thick accumulation of laminated and bedded sediments, and the absence of exposure horizons, unconformities, and pedogenic zones, features which are common in other Holocene lacustrine sequences in the Prairies (Teller and Last, 1982; Last and Vance, 1997), indicate the Oro basin never experienced extended periods of dry or very low water conditions during the Holocene. The generation and preservation of laminae and the fine-grained nature of the sediment imply relatively deep water conditions persisted throughout the past ~10 k year. However, more precise estimates of past water depths cannot be deduced on the basis of the physical or mineralogical records alone. In western Canada, fine-grained, laminated offshore sediments occur in salt lakes with mean depths as shallow as 3 m and as deep as 24 m. While it is difficult to reconstruct water depths on the basis of only three cores in a stratigraphic section, it is evident from the elevation differences shown in Fig. 2 that depths in the central part of the basin were at least greater than 7–8 m during deposition of Units 2 and 3 and greater than 4–5 m during Unit 4.

The lack of disruption of bedding in Oro Lake by bioturbation suggests that anoxic conditions prevailed at the sediment–water interface. These relatively deep water and anoxic conditions, particularly if taken in context with the continuous record of saline to hypersaline brines, imply that Oro Lake may have been meromictic during much of the Holocene. However, it must be emphasized that presently there is no evidence to indicate long-term accumulation of annual laminae or varve couplets, nor is there any other apparent regular rhythmicity in the Oro record.

The complexity of sedimentary facies resulting from the diverse array of geochemical, biological, and physical processes operating in high salinity and meromictic lakes has been well illustrated in numerous other studies in the Great Plains (e.g., Schweyen and Last, 1983; Last, 1993, 1994, 1999; Last and Slezak, 1986; Van Stempvoort et al.1993; Valero-Garcés and Kelts, 1995; Valero-Garcés et al., 1997). Although comparable detailed modern sedimentary facies analyses in Oro Lake have not yet been completed, it is most likely both the carbonate and sulfate laminae represent short-term, aperiodic basinwide inorganic precipitation events. As shown in other perennial saline lakes in the region (e.g., Waldsea Lake, Deadmoose Lake, Freefight Lake, Redberry Lake, Medicine Lake), aragonite and other carbonate mineral laminae can be generated by various intrinsic and extrinsic triggering mechanisms including changes in streamflow, surface runoff and groundwater input, or pH and concentration changes brought about by evaporation or dilution, brine mixing, and organic productivity. In addition to carbonates, in these and other deep water lacustrine environments, gypsum and other soluble minerals can precipitate as (i) seasonal salts from the upper part of the water column (due to both summer evaporative and winter "freeze-out" concentration mechanisms), (ii) travertine and spring discharge encrustations, and (iii) true subaqueous evaporites from the saturated monimolimnion or from the chemocline.

In contrast to this overall stable and relatively complacent record of deep water and high salinity during most of the Holocene, the endogenic mineralogy implies the precipitating brine underwent dramatic changes in composition during the past 10,000 years. Again with the exception of the lowermost lacustrine unit (Unit 1) and the basal diamicton, the most striking fluctuations within the stratigraphic record are in aragonite and gypsum: Units 2 and 4 are dominated by $CaSO_4 \cdot 2H_2O$, with relatively little endogenic $CaCO_3$, whereas Unit 3 shows a dominance of aragonite and only minor amounts of gypsum. This inverse correlation between the abundances of gypsum and aragonite ($r = -0.71$; significant at $\alpha = 0.001$; Figs. 4–7) points toward alternation be-

Fig. 7. Stratigraphic variation in moisture, organic matter, and total carbonate mineral contents, texture (% sand, % silt, % clay), particle size (mean and median), mineralogy, detrital vs. endogenic + authigenic components, and clastic weathering index in core OR3. Radiocarbon dates are shown on right with lithostratigraphic units (Table 3). Dashed lines indicate lithostratigraphic unit boundaries. The upper 50 cm of core was lost; gaps indicate missing core samples.
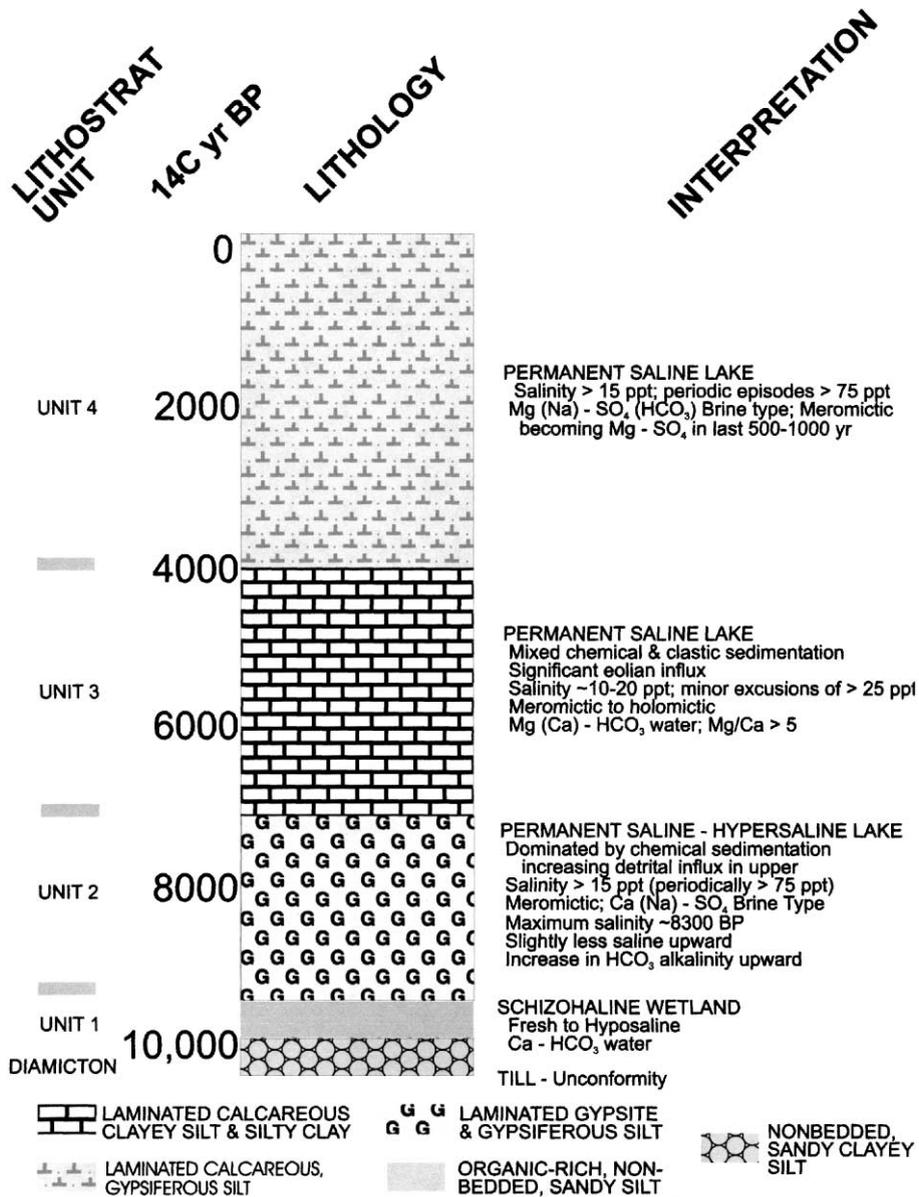
Fig. 8. Composite stratigraphic section from Oro Lake showing the lithostratigraphic units, chronostratigraphy, and interpreted limnological conditions.

tween a sulfate-dominated brine and one more enriched in HCO_3^-. However, because Oro Lake was likely meromictic throughout much of the Holocene, this need not necessarily imply dramatic changes in water sources or significant variations in hydrology. For example, during deposition of the gypsite of Unit

2, the endogenic components were likely derived mainly from a calcium-sulfate-saturated monimolimnion or from the chemocline, with relatively little contribution of material from the mixolimnion. In contrast, during deposition of the carbonate-rich Unit 3, the upper water mass became the dominant

source of most of the endogenic sediment with little or no subaqueous salt precipitation. The lateral gradation from almost entirely aragonite in Unit 3 in the most offshore core (OR1) to mixed aragonite–gypsum in the more nearshore cores suggests that the seasonally flooded mudflat areas of the basin were likely sites of intense evaporative concentration and salt precipitation.

Thus, throughout most of the Holocene, Oro Lake held a relatively stable, deep and probably chemically stratified water body, with a monimolimnion at or just slightly above saturation with respect to evaporitic sulfate salts and a mixolimnion at or near carbonate mineral saturation. Although the gypsum–aragonite–gypsum sequence of Units 2–4 suggests deposition from significantly different brine compositions, this is most readily accounted for simply by alternating the loci of endogenic mineral precipitation within the water column between the mixolimnion and the monimolimnion. Alternatively, occasional breakdown of meromixis, giving rise to the infrequent massive and poorly laminated sections of the sequence that occur mainly in Unit 3, would also account for a dilution of the saturated bottom waters, reduction in $CaSO_4 \cdot 2H_2O$ generation, and a relative increase in $CaCO_3$ contribution to the sediment of Unit 3. However, the prevalence of fine, undisturbed laminae indicates that nonstratified water conditions did not persist for long periods of time.

The lateral trends toward more evaporitic salt content in the nearshore direction within each unit likely reflect the presence of seasonally flooded saline evaporitic mudflats surrounding the basin. The predominance of aragonite and the secondary occurrences of Mg-bearing carbonates, such as magnesite, protodolomite, and magnesian calcite throughout the section, not only reflect the high pH and alkaline conditions, but also emphasize the overall elevated Mg/Ca ratio of the waters. The Mg/Ca molar ratios in the lake were never less than about 2 (corresponding to Mg-calcite deposition) and at times were approaching 100 or more (protodolomite and magnesite precipitation).

Deposition of the thin organic-rich Unit 1 and the basal diamicton are exceptions to this general statement of elevated salinity and meromixis throughout the Holocene. The basal diamicton was deposited either directly by glacier ice or, more likely, represents debris slumped from the unstable basin slopes during the lengthy period of postglacial disintegration of buried ice. The thin organic-rich lacustrine sediments immediately overlying this basal diamicton (Unit 1) were deposited in a fresh to hyposaline, but highly productive lake or slough with water depths in the central part of the basin more than about 5 m. Cywinska and Delorme (1995) note that this basal lacustrine sediment in OR1 is particularly rich in ostracodes. Thus, the unusually high calcite/dolomite ratio may reflect the very high ostracode shell content. The lateral change in composition of Unit 1, from organic–detrital sediment in the basin-center core to sediment with a higher endogenic mineral content toward the more nearshore areas, suggests that the shallow water and shoreline areas of the lake may have been evaporitic carbonate mudflats.

6.2. Lake history: early Holocene

The late Pleistocene and earliest Holocene was a period of rapid environmental change in the northern Great Plains. Although the active margin of the glacier retreated from the Missouri Coteau in southern Saskatchewan about 11,000–12,000 years ago, disintegration of stagnant ice buried beneath the thick glacial sediment of the Coteau continued for several millennia. This gradual melting initiated a wide variety of topography reversals and caused rapid evolution of drainage systems and other landscape features (Clayton and Freers, 1967; Christiansen, 1973; Bluemle, 1991). In addition to creating the thousands of small lake basins ("prairie potholes") that characterize the hummocky collapsed topography of the Coteau, the melting ice provided a large and constant source of water to the local hydrologic systems during the early phases of these lakes.

Studies of early postglacial vegetation elsewhere in the region suggest a relatively cool, but wet, climate prevailed during the late Pleistocene, which allowed a boreal forest type of vegetation to become established over much of the area (e.g., Klassen, 1989; Grimm, 1995; Grimm and Clark, 1998; Yansa, 1995, 1996; Yansa and Basinger, 1999). At the Andrews site, a small sediment-filled "kettle" situated on the Coteau about 40 km northeast of Oro Lake, lacustrine sedimentation began about 10,200 years ago in a relatively deep, freshwater pond surrounded by a white

spruce forest (Yansa, 1998). Although the oldest lacustrine deposits in the Oro basin postdate those of the Andrews site by about 500 years, conditions were similar: Unit 1 in Oro Lake was deposited in a relatively deep (greater than 5 m), freshwater to slightly brackish lake.

Sedimentation in the offshore area of this newly developed basin was dominated by detrital inorganic material and both detrital and endogenic organic matter. The influx of most of the inorganic sediment was from freshly exposed glacial deposits of the small watershed and basin slopes although the unusually high calcite/dolomite ratio of Unit 1 indicates bio-induced $CaCO_3$ precipitation was also important. Even though the lake was deep, fresh, and dominated by clastics and organic sediment, the nearshore and peripheral mudflat areas of the basin were likely sites of evaporative concentration and carbonate mineral precipitation as evidenced by the occurrence of small amounts of aragonite, magnesite, protodolomite, and gypsum in Unit 1 in core OR3.

However, this early Holocene freshwater lake was short-lived and by about 9300 BP limnological conditions in the Oro basin changed dramatically. Alkaline, high-salinity brines with high-to-very high Mg/Ca ratios dominated the lake throughout most of the remainder of the Holocene. Although the water was saline, lake levels remained high and relatively stable; at no time during the past 9300 years did the water drop sufficiently to subaerially expose the bottom sediments. Indeed, for much of the Holocene a stable, deep-water meromictic lake existed in the Oro basin.

During the 2000-year period between about 9300 and 7400 BP, offshore sedimentation in the basin was dominated by precipitation of subaqueous soluble salts from a saturated monimolimnion. Water salinities were likely about 30–40 ppt, with occasional excursions to greater than 70 ppt. An abrupt change to elevated salinities and alkalinities after the basal freshwater phase is also recorded in the ostracode stratigraphy of OR1 (Cywinska and Delorme, 1995). Closer to shore, endogenic and authigenic carbonates derived from the nearshore and mudflat carbonate "factory" intermixed and diluted the basinal salts, creating a sedimentary facies pattern similar to that which occurs in a number of other deep-water perennial saline lakes in the region today (e.g., Last,

1993, 1994; Sack and Last, 1994; Valero-Garcés and Kelts, 1995).

The occasional excursions to hypersaline conditions were relatively frequent about 8300 years BP, suggesting Oro Lake brine reached maximum salinity at this time. Likewise, Padden (1996) shows that maximum inferred δO^{18} enrichment (i.e., maximum evaporative influence) in the lake waters also occurred at this time. The ~8300 BP salinity maximum in Oro Lake corresponds well with subaerial exposure and desiccation of the offshore bottom muds at Clearwater Lake, a small perennial lake on the Missouri Coteau about 200 km northwest of Oro (Last et al., 1998), and maximum drought conditions interpreted at the nearby Andrews site (Aitken et al., 1999; Yansa and Basinger, 1999).

The transition of Oro Lake from a freshwater, clastic–organic matter-dominated sedimentary environment to a saline/hypersaline salt-precipitating basin was abrupt. Similar early Holocene transitions from fresh to saline and/or hydrologically open to closed, evaporitic conditions have been documented at numerous other sites in the region including the Andrews site, Ingebright Lake, and Clearwater Lake (all in Saskatchewan), Lake Manitoba and Killarney Lake (both in Manitoba), Moore Lake (Alberta), and Pickerel Lake, Moon Lake, Medicine Lake, Devils Lake, and Coldwater Lake in United States (see discussions and compilations of recent work in Vance and Last, 1994; Valero-Garcés and Kelts, 1995; Laird et al., 1996; Valero-Garcés et al., 1997; Last et al., 1998; Aitken et al.,1999; Shang and Last, 1999; Dean and Schwalb, 2000). Not all of these fresh-to-saline transitions were as abrupt as that recorded at Oro, nor are they precisely synchronous over the region. This is probably due, in part, to limited chronological control (Vance, 1997), and, in part, to various local hydrological or topographic factors that may buffer a lake's response to an external signal including such factors as position within the landscape, magnitude and source of groundwater discharge and lag time of this groundwater-driven signal, and the development of complex intrinsic sedimentary feedback mechanisms (see also discussions in Valero-Garcés and Kelts, 1995; Webster et al., 1996; Birks and Remenda, 1999; Remenda and Birks, 1999; Wilson and Smol, 1999). Nonetheless, it is clear from the consistent regional response that this early Holocene change in the Cana-

dian Plains was the result of a widespread decrease in available moisture under a warmer and/or drier climate, which was most likely associated with increased summer insolation.

6.3. Lake history: mid-Holocene

Although Oro Lake has remained a saline alkaline system since 9300 BP, beginning about 7400 years ago deposition gradually shifted from mainly soluble sulfate salts to sparingly soluble carbonates mixed with fine clastics and only minor evaporites. It is tempting to view this mid-Holocene period of dominantly aragonite-laminated mud deposition in the Oro basin as reflecting a slight freshening of the brines, possibly associated with a more moderate climate, following the maximum salinity conditions at ∼ 8300 BP. An increased effective precipitation component in the hydrologic budget of the basin could result in an undersaturated monimolimnion (with respect to gypsum) and increased aragonite production from the mixolimnion. Increased runoff might also account for the increase in proportion of fine-grained detrital components of Unit 3 and could lead to occasional destratification of the meromictic water column to create the poorly bedded and indistinctly banded zones that occur in Unit 3.

The interpreted climatic conditions in the northern Great Plains during this time are still enigmatic. The onset of a somewhat more positive hydrologic budget in Oro Lake about 7400 years ago corresponds well with several other lacustrine records from the Canadian Plains region: (i) the formation of a fresh to brackish semipermanent pond at the Andrews site (Yansa, 1998; Aitken et al., 1999); (ii) a return to a hydrologically open, nonevaporitic freshwater system in Clearwater Lake (Last et al., 1998); (iii) the occurrence of relatively humid conditions at Ingebright Lake, a hypersaline playa in southwestern Saskatchewan (Shang and Last, 1999); (iv) the development of a "permanant" (i.e., non-playa) lake in the Manitoba basin in the eastern Prairies (Last et al., 1994; Curry, 1997; Risberg et al., 1999); and (v) a shift from groundwater-dominated inflow to mainly surface influx in Harris Lake, southwestern Saskatchewan (Last and Sauchyn, 1993). Likewise, in Devils Lake, North Dakota, maximum salinity also occurred early in the Holocene (∼ 8 k years) and was followed

by a 4500-year period of fluctuating, but generally lower salinities (Haskell et al., 1996). Finally, the increase in clastic influx in Oro Lake at this time is coincident with a widespread northern hemisphere cooling event, which has been linked to a short-lived perturbation in the North Atlantic thermohaline circulation caused by the final catastrophic draining of Lake Agassiz and Lake Ojibway (Barber et al., 1999). However, within the constraints of our chronostratigraphy, the influence of this "8.2 k cal. year cooling event" in Oro Lake must remain tentative.

In contrast to a more positive hydrologic budget, an alternative explanation for the larger amounts of detrital clastic influx in Oro Lake between 7300 and 4000 BP is that this material could have been airborne rather than transported by streams or sheetwash. Although indications of increased eolian (loess) activity are anomalously absent from the Canadian Plains region (Lemmen and Vance, 1999b), increases in eolian sediment during this time have been noted in Pickerel Lake, South Dakota (Dean and Schwalb, 2000), and Deep Lake and Elk Lake in Minnesota (Dean, 1997; Hu et al., 1999). In these lakes, the mid-Holocene increased eolian influx is interpreted to be a response to decreased available moisture (and, hence, decreased vegetation cover) combined with strengthening of westerly zonal winds. There is also abundant paleolimnological evidence from the northern Great Plains to support this mid-Holocene increased aridity as discussed in numerous overviews (e.g., Laird et al., 1996; Vance et al., 1996; Lemmen and Vance, 1999a,b).

In addition to the examples cited above in the United States, Chappice Lake, a small hypersaline playa in southeastern Alberta, experienced significant fluctuations in water levels, from dry to shallow to deep, during 7.5–6.0 kyears (Vance et al., 1992, 1993). Ceylon Lake, about 80 km southwest of Oro, changed from a deep, hydrologically open, freshwater lake to a saline playa about 7000 years ago (Last, 1990). Deep Lake, a small ephemeral basin near Regina, records maximum salinity and increases in xerophytic and saline-tolerant pollen taxa about 7.2–6.4 kyears BP (Sauchyn and Porter, 1996; Vetter et al., 2000).

Although an eolian source for the fine-grained clastics of Unit 3 in Oro Lake is plausible, nonetheless, it is somewhat more difficult to reconcile the *decreased* evaporite content of the unit if a relatively

more arid climatic setting were in place. Similarly, higher aridity during the mid-Holocene is not readily compatible with the general trend toward lower δO^{18} brines (less evaporative enrichment) and lower δC^{13} values for cellulose in the lake after the early Holocene (Padden, 1996).

One final possible scenario to explain the carbonate-rich/gypsum-depleted muds of the mid-Holocene in Oro Lake is that increased aridity lead to lower water levels and eventual complete breakdown of the chemically stratified system. Mixing of the relatively dilute upper water mass with the saturated monimolimnion would result in a net salinity decrease in the newly holomitic water column and a shift from gypsum-dominated offshore sediments to aragonite-rich muds. In this case, presumably seasonal development of a thermally stratified water column was sufficient to prevent bioturbation and disruption of the aragonite laminae. Although somewhat shallower, the lake was still deep enough, or the basin sheltered enough, to prohibit wind-generated wave mixing of the bottom sediments. A more arid mid-Holocene climate over a period of several millennia might also decrease the regional groundwater table sufficiently such that the basin no longer received influx from the sulfate-rich deep drift and bedrock aquifers, thereby increasing the relative proportion of carbonate-rich near surface and shallow groundwater (see also Teller, 1998).

6.4. Lake history: late Holocene

About 4000 years ago, sedimentation in Oro Lake again shifted toward higher sulfate salt precipitation and lower carbonate and siliciclastic deposition. Although the increase in evaporite content in Unit 4 seems incongruous with the general record of overall cooler and wetter conditions in the Great Plains after the mid-Holocene (cf. overviews in Ritchie and Harrison, 1993; Laird et al., 1996; Lemmen and Vance, 1999b), this probably occurred in response to renewed development of a chemically stratified water column in which gypsum was being derived from the saturated monimolimnion and aragonite was precipitating from the mixolimnion. In addition, less arid conditions gave rise to a relatively greater contribution of sulfate-rich groundwater. Similarly, the striking decrease in clay-sized material in the offshore sedi-

ments deposited after 4000 BP probably reflects a decrease in eolian influx to the basin. The lateral gradation from gypsum-rich sediments in core OR1 to mixed gypsum–aragonite in OR2 and dominantly aragonite in the OR3 indicates the peripheral mudflats and nearshore areas of the basin were likely sites of carbonate mineral precipitation, rather than areas of evaporitic sulfate formation as was the case during the mid-Holocene. Padden (1996) also interprets a continuing trend toward decreased aridity during the late Holocene from the stable oxygen and carbon records in OR1.

Although the physical and mineralogical records suggest a relatively complacent late Holocene history in the Oro basin, our chronology of the past 4000 years of deposition is only poorly constrained, and poor core recovery of the upper meter of section precludes a more detailed, high-resolution exposition of the most recent history of the lake. Relatively constant proportions of soluble salt, endogenic carbonate minerals, and detrital components indicate the continued persistence of a relatively deep, stable, saline and chemically stratified water column. According to Cywinska and Delorme (1995), the ostracode record preserved in OR1 similarly indicates few environmental changes over the past 4–5 kyears. Although the Medieval Warm Period ($\sim$ 1000 BP) does not appear to be documented in the physical/mineralogical record of Oro; beginning about 600 years ago, the indistinct bedding suggests meromixis periodically broke down, perhaps due to increased aridity associated with the Little Ice Age. The development of a holomictic water column is coincident with an increased enrichment in δO^{18} lake water (Padden, 1996) and an increase in soluble salts. Finally, beginning about AD 1700, episodes of hypersalinity became more frequent and coincided with a gradual trend toward a more Mg^{2+}-rich brine. In addition to this increase in Mg-salt precipitation, in the early part of the 20th century, the basin experienced a significant increase in detrital influx, probably associated with European land clearing and agriculture.

7. Conclusions

There are few long paleoenvironmental records in the vast northern Great Plains of western Canada.

Thus, with its 10,000-year-long record of uninterrupted deepwater sedimentation, Oro Lake is one of the most important paleolimnological sites in the region. However, meromictic conditions, combined with saline to hypersaline brines and a groundwater-dominated hydrologic budget, complicate the climatic and hydrologic interpretations of the mineralogical and physical records. Early Holocene events in the Oro basin are clear and unambiguous: an early freshwater lake occupied the basin immediately after deglaciation. This quickly and abruptly gave way to a deep, saline–hypersaline meromictic lake by 9300 BP. Maximum salinity occurred about 8300 years ago, coinciding with other regional evidence of early Holocene maximum aridity. The mid-Holocene environmental conditions at Oro Lake are enigmatic. Although it is reasonable to attribute the decrease in soluble salts and increased carbonate and detrital sedimentation during the mid-Holocene to a more positive hydrologic budget, it is equally plausible that increased aridity in the region resulted in an a significant increase in eolian influx, an overall more dilute body of water because of the breakdown of meromixis, and a more carbonate-enriched/sulfate-depleted chemical system through reorganization of the groundwater input to the basin. The sedimentary sequence deposited during the past 4000 years lacks strong evidence for significant fluctuations in the general environmental and limnological conditions (i.e., deep water, saline, meromixis, stable lake levels) although the past several hundred years have seen an increase in Mg^{2+} in the brine and greater frequency of a nonstratified water column.

Acknowledgements

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