The lithostratigraphic record of late Pleistocene–Holocene environmental change at the Andrews site near Moose Jaw, Saskatchewan

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Abstract: Four lithostratigraphic units are recognized in a 5.8 m dugout excavation within hummocky terrain: diamicton (L1), laminated organic-rich gypsite (L2), calcareous clayey silt (L3), and massive clayey silt (L4). The basal diamicton is supraglacial till deposited within a shallow depression prior to 10 200 BP. Subsequent melt-out of buried, stagnant glacial ice created a shallow lacustrine basin ca. 10 000 BP. A subsequent 1200-year interval of severe aridity (to ca. 8800 BP) is reflected by a dominance of chemical sedimentation in a saline to hypersaline basin. A bed of sandy mud enriched in charcoal flakes and charred seeds at the top of this evaporitic unit records a period of drainage basin destabilization by prairie fires, which resulted in increased runoff and erosion. Sediments reflect a gradual transition, between ca. 8000 and 6000 BP, from the high-salinity and chemical-dominated sedimentary environment to a lake characterized by lower salinity and mainly fine-grained clastic sedimentation.

Résumé : Quatre unités lithostratigraphiques ont été reconnues dans une excavation de fosse-réservoir de 5,8 m en terrain bosselé : un diamicton (L1); une gypsite laminée riche en matières organiques (L2); un silt argileux calcaire (L3); et un silt argileux massif (L4). Le diamicton de base est un till supraglaciaire qui a été déposé dans une dépression peu profonde avant 10 200 BP. La fonte ultérieure de glace glaciaire enfouie stagnante a engendré un bassin lacustre peu profond à environ 10 000 BP. Un intervalle ultérieur très sec d'une durée de 1 200 ans (jusqu'à environ 8 800 BP) se traduit par la prédominance d'une sédimentation chimique dans un bassin salin à hypersalin. Une couche de boue sablonneuse enrichie en flocons de charbon de bois et en graines calcinées au sommet de cette unité évaporitique témoigne d'une période de déstabilisation du bassin versant par des feux de prairie, qui se sont traduits par un ruissellement et une érosion accrus. Les sédiments reflètent une transition graduelle entre environ 8 000 et 6 000 BP, à partir d'un milieu sédimentaire à salinité élevée et à prédominance chimique vers un lac caractérisé par une salinité plus faible et une sédimentation clastique essentiellement à grains fins.

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INTRODUCTION

Internally drained depressions within hummocky disintegration and ice-thrust moraines are common across much of the northern Great Plains. These depressions can provide both paleoecological data (Beaudoin, 1993, 1996; Beaudoin et al., 1996) and sedimentological and/or pedological data (Vreeken, 1994, 1996) that record environmental change during the late Pleistocene and Holocene. This paper examines environmental changes recorded by the physical and chemical sedimentology of one such site near Moose Jaw in southern Saskatchewan (Fig. 1), and complements the examination of plant macrofossils from this same site (Yansa, 1995, 1998; Yansa and Basinger, 1999).

PHYSICAL SETTING

The Andrews site is located on The Missouri Coteau upland in southern Saskatchewan (lat. 50°20'N, long. 105°52'W, elev. 720 m a.s.l.), 22 km southwest of Moose Jaw (Fig. 1). The sediments occupy an internally drained depression in hummocky disintegration moraine. The regional climate is strongly continental. Mean annual temperature is 3.8°C, with mean January and July temperatures of -14.2°C and 19.7°C, respectively, and mean annual precipitation is 357 mm (Longley, 1972; Environment Canada, 1993). Potential evapotranspiration often exceeds precipitation by more than 300 mm annually (Winter, 1989).

METHODS

A 5.8 m thick section was exposed at this site during the exca vation of a dugout in 1993.

Seventy-five sediment samples provided by C.H. Yans. were analyzed for moisture content, organic matter content total carbonate content, particle size, and mineralogy. A regu lar sampling interval of approximately 10 cm was used. except where bedding or other sedimentary features dictatec closer spacing. Moisture content, organic matter content, and total carbonate mineral content were determined by loss on ignition at 85°C, 500°C, and 1000°C, respectively (Dean. 1974). Particle-size spectra for each subsample were determined using an automatic laser-optical particle-size analyzer (GALAI CIS-1™; Aharonson et al. (1986), Syvitski et al. (1991)) after removal of organic matter by hydrogen peroxide treatment. A 1% solution of Triton™ 100X was used as the dispersing agent, rather than disodium hexametaphosphate, because of the high sulphate mineral content of many of the samples. Particle-size statistics (mean, median, and standard deviation) were calculated by the moment method according to Allen (1981). Duplicate samples were prepared and analyzed every 20 samples, and a standard was run every 50 samples. These replicate analyses indicate that precision of the particle-size data is approximately ±4%.

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
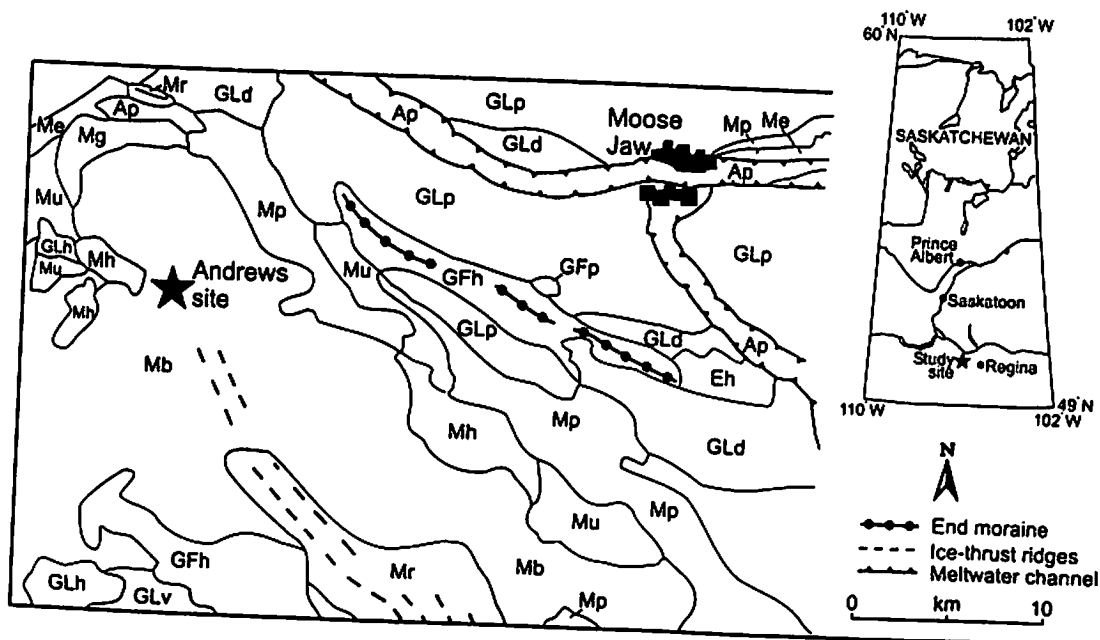

Figure 1. Location of the study site (indicated by a star) in hummocky moraine in southern Saskatchewan (modified from Saskatchewan Research Council, 1987). Surficial deposits of the study area: Ap, alluvial plain; GLp, GLv, GLd, GLh, glaciolacustrine (plain, veneer, drumlinoid, and hummocky respectively); GFp, GFh, glaciofluvial (plain and hummocky, respectively); Mh, hummocky moraine; Mr, ice-thrust ridge; Mb, hummocky disintegration moraine; Mp, Mu, Me, Mg, ground moraine (plain, undulating, eroded, and gullied, respectively); Eh = eolian (hummocky).
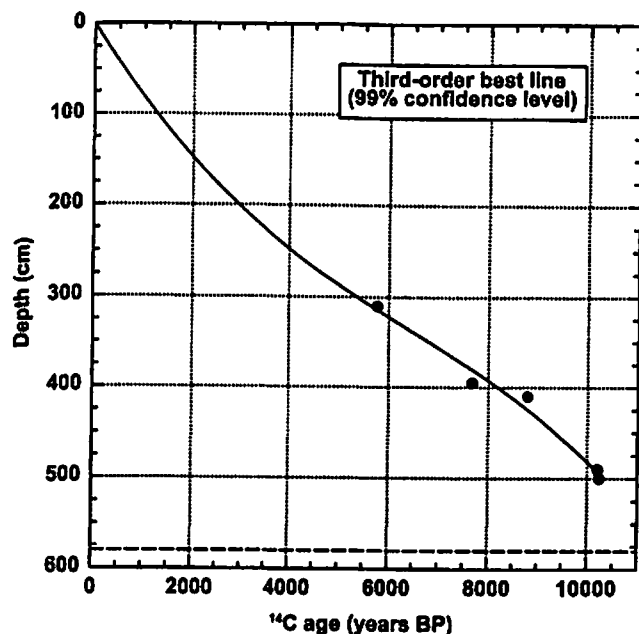
Figure 2. Depth versus radiocarbon age in the section from the Andrews dugout.

carbonate and evaporite mineralogy were determined using standard X-ray diffraction (XRD) techniques (Müller, 1967; 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). Nonstoichiometry of the dolomite and calcite was determined by measuring 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 20 samples. These replicate analyses indicate that the precision of the mineralogical data is approximately ± 8%. The abundances of the feldspar minerals were used to calculate an index of weathering. This index responds to the chemical stabilities of potassium feldspars (high stability) versus plagioclase feldspars (low stability) in a typical drainage-basin weathering profile. Although many factors influence the abundance of these detrital siliciclastic minerals, the ratio of K-feldspar to plagioclase in the offshore sediments of a small lake with a relatively homogeneous drainage basin should increase under more intense chemical weathering (i.e. warm temperatures, humid climate) and decrease under less severe conditions (i.e. cooler, drier climate).
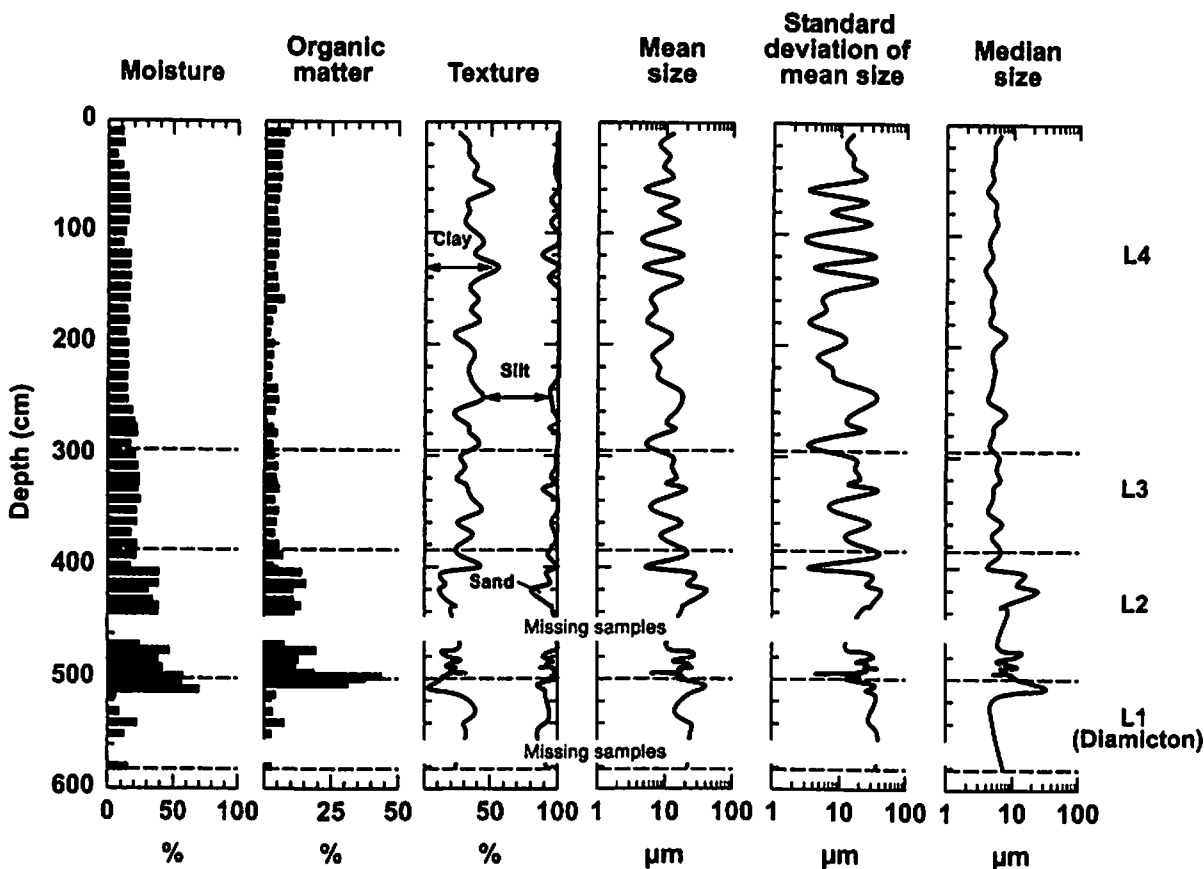

Figure 3. Stratigraphic variation in moisture content, organic matter content, texture (% sand, % silt, % clay), and particle size (mean, standard deviation, and median). Letters and numbers in capitals on the right side of the figure (e.g. L1) and horizontal dashed lines refer to lithostratigraphic units.

Both conventional and accelerator mass spectrometry (AMS) radiocarbon ages were acquired for this study by Yansa (1995, 1998) (*see* Yansa and Basinger, 1999). The dearth of suitable organic materials in the upper 300 cm of the measured section precluded dating of these sediments (Yansa, 1998). All dates are reported here as radiocarbon years before present. The chronostratigraphy employed in this paper was established by fitting a third-order polynomial to the ^{14}C dates and assuming continuous, uninterrupted sedimentation to present and no postdepositional compaction (Fig. 2).

RESULTS

General description

The exposed section consists of 80 cm of diamicton overlain by 500 cm of nonglacial sediments. Overall, there is little systematic change in sediment texture (average composition: 4% sand, 67% silt, 29% clay), other than a slight fining-upward trend in mean grain size (Fig. 3; Table 1). The lowermost : of sediment are somewhat coarser grained and more poo sorted (higher standard deviation) than the rest of the secti while the upper 2 m of the section exhibit regular alternat between relatively fine-grained and coarse-grained se ments (Fig. 3). Moisture and organic matter contents are b relatively low (<30% and <10%, respectively), exc between 4 and 5 m depth.

The sediments are composed predominantly of detri clay minerals (46%) and detrital siliciclastic minerals (30% with smaller proportions of detrital carbonate minerals (8 and endogenic and authigenic carbonates and evaporit (16%) (Table 1). Detrital sediments dominate except for th interval between about 4 and 5 m depth (Fig. 4), which cor tains a higher proportion of endogenic and authigenic compo nents. The endogenic and authigenic fractions of th sediment consist mainly of gypsum ($CaSO_4 \cdot 2H_2O$), wit minor amounts of disordered, nonstoichiometric dolomit ($Ca_{0.x}Mg_{0.y}(CO_3)_2$) and magnesian calcite (Table 1, Fig. 5) Other carbonate and sulphate salts occur sporadically withir

Table 1. Summary of average mineralogical and grain-size characteristics of lithostratigraphic units.

	Lithostratigraphic unit				
	L1	L2	L3	L4	Core average
% total clay minerals	28.7	38.9	52	56	45.9
% quartz	15.6	11	17	21	16.2
% total feldspar minerals	14.1	9.9	11	14	12.8
% plagioclase feldspars	6.9	6.5	6.9	8.6	7.4
% K-feldspars	7.1	3.5	4	5.8	4.8
% amphibole minerals	0.3	<0.1	0.2	0.1	0.1
% total carbonate minerals	21.2	15.8	12	4.4	13.1
% total detrital carbonate minerals	21	11.7	9.7	0.6	7.5
% total endogenic + authigenic carbonate minerals	<0.1	4.2	1.9	3.8	5.7
% total calcite	5.2	5.3	2.7	1.8	3.5
% low-Mg calcite	5.2	3	1.4	0.4	1.9
% magnesian calcite	<0.1	2.3	1.3	1.3	1.6
Mol % $MgCO_3$ in magnesian calcite	n.d.	4.3	8.2	10	7.2
% total dolomite	16	10	9	2.6	9.6
% well-ordered dolomite	14.8	8.7	8.3	0.2	5.8
% disordered dolomite	<0.1	1.2	0.7	2.4	1.6
Mol % $CaCO_3$ in protodolomite	n.d.	64	69	67	63.4
% magnesite	n.p.	n.p.	n.p.	<0.1	<0.1
% aragonite	n.p.	0.5	n.p.	n.p.	<0.1
% gypsum	6.2	27.9	2.6	<0.1	10.7
% (Mg + Na)-sulphate salts	n.p.	1.3	1.7	1.4	0.6
% Na-sulphate salts	n.p.	0.1	0.2	0.1	<0.1
% detrital fraction	98.2	71.6	89	89	81.5
% endogenic + authigenic fraction	1.8	28.4	11	11	18.5
% moisture	23.1	34.5	23	16	24.4
% organic matter	4.6	19.8	4.6	4.3	9.3
Mean particle size (µm)	22.8	18.6	13	10	14.8
Standard deviation of mean particle size	32.1	22.6	18	14	19.3
Median particle size (µm)	10.3	9.4	5.5	5.1	7.3
% sand	9.8	5.4	3	2.1	4.2
% silt	66.7	73.8	66	62	67.1
% clay	23.7	20.8	31	36	28.8
Sedimentation rate[1] (cm·(100 a)$^{-1}$)	n.d.	4.3	3.4	5.1	4.6

n.d. = not determined; n.p. = not present.
[1] Calculated on the basis of a best-fit line of depth versus time (Fig. 1) using the six ^{14}C dates of Yansa (1997) and assuming no interruption in deposition.

the section; these include bloedite ($Na_2Mg(SO_4)_2 \cdot 4H_2O$), thenardite ($Na_2SO_4$), or the hydrated species mirabilite ($Na_2SO_4 \cdot 10H_2O$), aragonite ($CaCO_3$), and magnesite ($MgCO_3$) (Fig. 5).

Over the entire section, variations in the proportions of the various siliciclastic components (quartz, K-feldspar, plagioclase, amphiboles) are all significantly correlated with one another (linear correlation coefficients are significant at the 95% confidence level) and with the various grain-size parameters, and inversely correlated with the abundance of organic matter, gypsum, and the detrital carbonates. Similarly, detrital calcite and dolomite are covariant and are negatively correlated with the endogenic carbonate minerals. The abundance of gypsum has a significant positive correlation with mean and median grain size and a negative correlation with clay content, suggesting that this soluble evaporite mineral is dominant in the coarser fraction of the sediment.

Lithostratigraphy

The four lithostratigraphic units recognized in the section (Table 1, Fig. 3–5) are described below (in order from the base of the section).

L1 — Diamicton

Extending from the base of the section to 500 cm depth, this unit consists of slightly gravelly, sandy mud with low moisture and organic matter contents. In addition to the relatively coarse mean grain size and high sand content, this poorly sorted detrital unit is marked by high detrital carbonate content and the absence of endogenic and authigenic components.

A coarse organic debris layer (510–500 cm depth), indicated by a sharp increase in sediment organic matter content at the top of L1 (Fig. 3), consists largely of macrofossils of *Picea glauca* (white spruce), *Rubus idaeus* (raspberry), *Shepherdia canadensis* (soapberry), and charcoal flakes, charred wood, and seeds in a sandy mud matrix (Yansa, 1995). Roots associated with white spruce trunks penetrate these organic-rich sediments. Both the roots and trunks have been radiocarbon dated at 10 200 BP (Yansa, 1995, 1998; Yansa and Basinger, 1999).

L2 — Organic-rich gypsite

A 1 m thick (400–500 cm depth), thinly laminated (laminae 2–5 mm thick), organic-rich evaporite unit overlies the diamicton. The clayey silt is characterized by high gypsum,
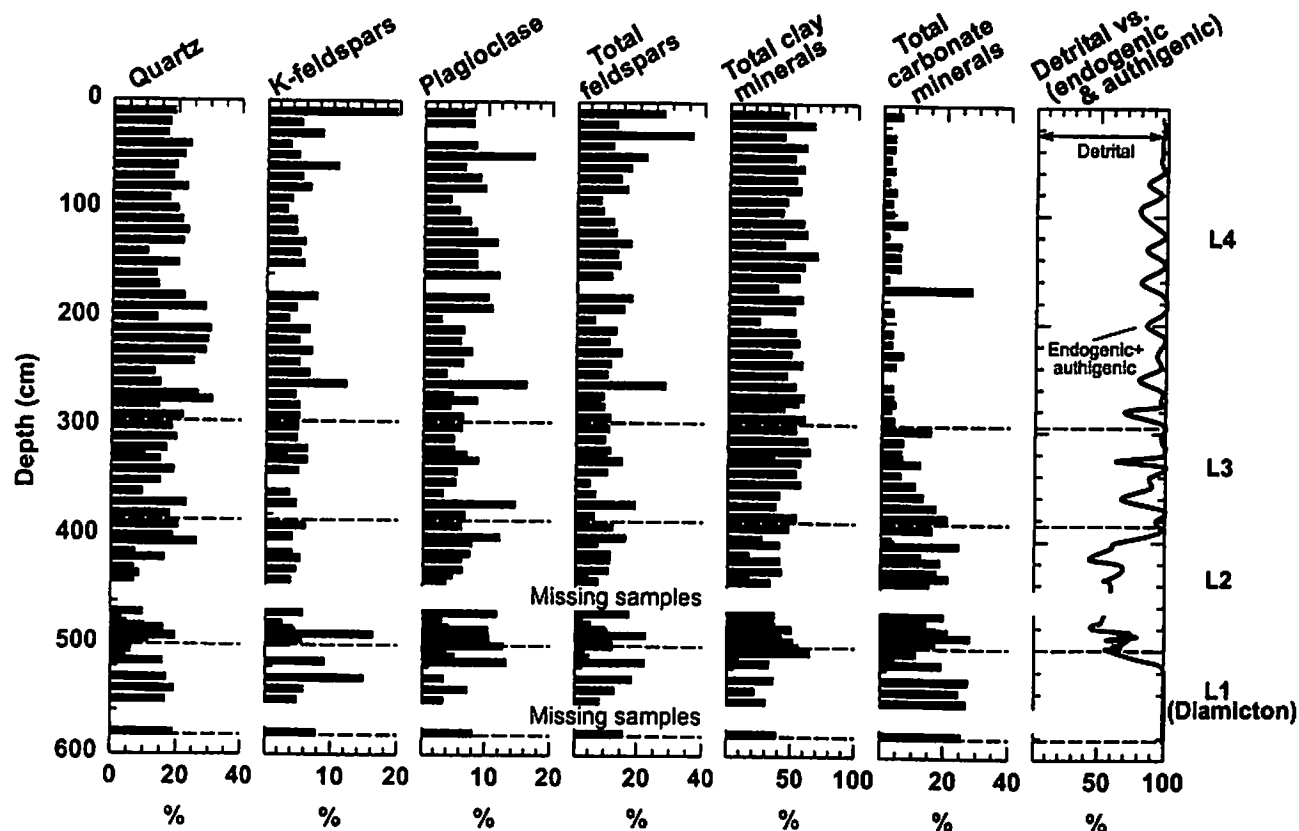

Figure 4. Stratigraphic variation in detrital quartz, feldspar minerals (potassium feldspars, plagioclase feldspars, total feldspars), total clay minerals, total carbonate minerals, and the proportion of detrital versus (endogenic + authigenic) mineral components. Letters and numbers in capitals on the right side of the figure (e.g. L1) and horizontal dashed lines refer to lithostratigraphic units.

magnesian calcite, and protodolomite contents, together with detrital calcite and dolomite. Discrete thin beds and laminae of fine to medium quartzose sand occur over the interval 470–420 cm within this unit.

Sediment accumulation in L2 occurred during the interval ca. 10 200–8150 BP. The laminated sediments are overlain by a 10 cm thick bed (390–400 cm depth) of sandy mud enriched in charcoal flakes and charred seeds. This horizon is associated with a pronounced reduction in the organic matter content, from about 20% to less than 5%.

L3 — Calcareous clayey silt

This unit, extending from 390 to 295 cm depth, is a nonbedded, calcareous, clayey silt. The unit is distinguished from underlying L2 by its finer texture, high clay-mineral content, lack of bedding, and paucity of gypsum. As in L2, magnesian calcite and protodolomite dominate the endogenic carbonates. However, the composition of these carbonate

minerals differs from that in the underlying unit: the mc MgCO₃ within the magnesian calcite is relatively high the mol % CaCO₃ content of the protodolomite is l· Although gypsum is rare, unit L3 does contain spora occurrences of other sulphate salts. Sediment accumulat in L3 occurred during the interval 8150–5500 BP.

L4 — Clayey silt

The upper approximately 3 m of the section consists nonbedded, noncalcareous, clayey silt to silty clay. Hi quartz, feldspar, and clay mineral contents, low organic m; ter content, and an almost complete absence of detrital ca bonates characterize the composition of this unit. Slight coarser grained sediments occur in the intervals 230–295 c and 30–150 cm. Variation in mean grain size and standaı deviation in the upper 3 m suggest a regular alternation of re atively fine and relatively coarse sediment, although this not reflected by any visible bedding features.
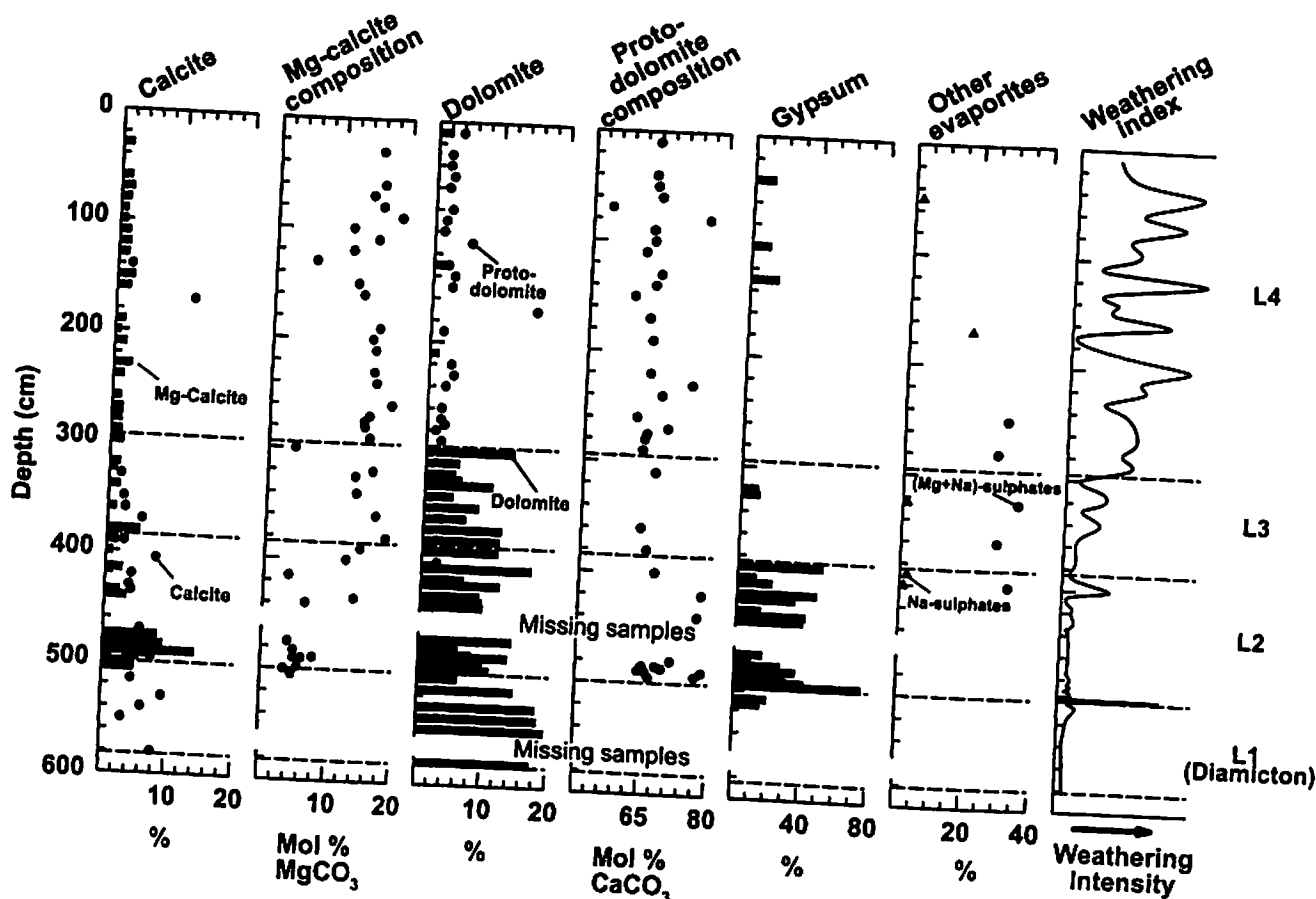

Figure 5. Stratigraphic variation in calcite, magnesian calcite, dolomite, protodolomite, gypsum, Na-sulphates, and (Na+Mg)-sulphates. Also shown are variations in the composition of the magnesian calcite and protodolomite, and the clastic weathering index. The weathering index is a ratio of the rela- tively chemically stable potassium feldspars to the less stable plagioclase feldspars. This ratio increases (to the right in the figure) under more intense chemical-weathering conditions in the watershed. Letters and numbers in capitals on the right side of the figure (e.g. L1) and horizontal dashed lines refer to lithostratigraphic units.

INTERPRETATION

The basal diamicton (L1) is most likely Late Wisconsinan Battleford Formation, on the basis of stratigraphic position and lithological characteristics (cf. Christiansen, 1971, 1992; Klassen, 1992). Subglacial erosion of Cretaceous marine sandstone and shale and Paleozoic carbonate rocks beneath the Laurentide Ice Sheet is reflected in the dominance of detrital carbonate minerals and siliciclastics in this lithostratigraphic unit. Like elsewhere on The Missouri Coteau, thick supraglacial debris resulting from thrusting at the ice margin would have insulated the glacier surface from direct radiation and may have allowed stagnant ice to persist for several thousand years following retreat of active ice from the site. Down-wasting of the ice surface, accompanied by active resedimentation of supraglacial debris, generated a multitude of internally drained depressions within hummocky moraine (Gravenor and Kupsch, 1959; Clayton, 1967).

Coarse organic debris present at the top of L1 (vegetation zone II of Yansa and Basinger, 1999), together with charcoal and charred wood and seeds, suggest fire may have temporarily disrupted the vegetation cover of the landscape surrounding the depression ca. 10 200 BP. The resulting destabilization of watershed soils would serve to increase runoff and erosion.

The sharp contact between the poorly sorted mineral and organic detritus of L1 and the fine-grained laminated evaporites of L2 implies a relatively rapid transition to high-salinity lacustrine conditions. The fine, undisturbed lamination, relatively fine grain size, and high organic-matter content of L2 also indicate deposition in quiet water conditions. Although these sedimentary features are similar to those characterizing present-day offshore (deep-water) facies of perennial and meromictic saline lakes in the region (Schweyen and Last, 1983; Van Stempvoort et al., 1993; Valero-Garcés et al., 1995), finely laminated, organic-rich evaporitic sediments can also be generated and preserved in shallow playa basins (Last and Vance, 1997).

The endogenic mineral suite of L2 is dominated by gypsum, protodolomite, and magnesian calcite. Comparison with modern analogues on the northern Great Plains indicates that the genesis of these minerals occurs in basins having salinities ranging from about 10 to 40 g·L⁻¹ (Last, 1994; Last and Vance, 1997; Vance et al., 1997). Variation in ionic composition of the lake water, from Ca-sulphate dominated to (Mg+Ca)-bicarbonate enriched, is required to facilitate the contemporaneous deposition of gypsum and carbonates. High Mg/Ca ratios (10-100) and elevated alkalinities are indicated by the presence of magnesian calcite and protodolomite. Sulphate salts also occur sporadically within the uppermost 20 cm of L2 and occasionally in overlying L3, suggesting that the basin experienced brief periods of hypersalinity (TDS greater than 40 g·L⁻¹) in the early Holocene. Although there is nothing in the sediment to indicate complete drying and desiccation, the lake likely experienced significant fluctuations in water level, from deep and possibly meromictic conditions to shallow ephemeral

conditions, during this 1200-year period. This interval was terminated abruptly by deposition of a 10 cm thick bed (390–400 cm depth) of sandy mud enriched in charcoal flakes and charred seeds. This episode, which corresponds to vegetation zone IV of Yansa and Basinger (1999), is also interpreted to reflect an increase in erosion due to prairie fires destabilizing the vegetation cover of the watershed. This period of increased detrital accumulation is bracketed by radiocarbon ages of 8800 BP at 410 cm depth and 7700 BP at 395 cm depth.

The abundance of endogenic minerals in L3 is lower than that of L2, but the presence of both Mg-calcite and protodolomite in L3 indicates continued high alkalinity and moderate salinity. The significant increase in mol % MgCO₃ in the endogenic calcite (and a corresponding decrease in calcium content in protodolomite) of L3 relative to L2 suggests an increase in Mg/Ca ratios. The gradual upward increase in allogenic components continues into the upper 3 m of the section (unit L4). This upper portion is also characterized by an increase in the weathering intensity index, suggesting more humid and/or warmer climatic conditions after ca. 5900 BP. Overall, however, the mid- to late Holocene record in this sequence does not appear to be especially sensitive to environmental changes. Except for broadly spaced shifts in mean grain size and sorting, and the rare occurrence of sulphates, the mineralogical composition and organic matter content of L4 are homogeneous.

DISCUSSION

The mineralogical and textural data from the Andrews site generally correspond well with the interpreted lake history deduced from paleobotanical evidence at the site (Yansa, 1995, 1998; Yansa and Basinger, 1999). Nonetheless, differences between the two records are apparent. Yansa (1998) and Yansa and Basinger (1999) proposed that the lake shifted gradually from a permanent, deep-water (>2 m) pond environment ca. 10 000 BP to an alkaline and brackish, shallow, semipermanent wetland by 8800 BP. In their reconstruction, the local onset of maximum Holocene aridity did not occur until after 8800 BP. This interpretation is not supported by the mineralogical data presented here. Rather, the rapid transition to highly saline conditions at the L2-L3 boundary (ca. 10 000 BP) suggests an earlier phase of severe aridity that is consistent with records of several other sites in the region. For example, lake records from three sites within the Palliser Triangle all suggest an interval of severe aridity in the Late Pleistocene–early Holocene. At Clearwater Lake, about 100 km northwest of the Andrews site, Last et al. (1998) recognized a saline to hypersaline phase (salinities approximately 20–70 g·L⁻¹) between 9800 and 8600 BP. Oro Lake, located about 50 km south of the Andrews site, recorded an abrupt change from fresh-water conditions to a hypersaline, meromictic lake ca. 9400–9000 BP (Vance and Last, 1996). Salts preserved in North Ingebrigt lake, a hypersaline playa about 250 km west of the Andrews site, document much lower atmospheric relative humidities ca. 9800 BP (Shang and Last, 1999). Elsewhere on the Canadian Prairies, a shift from fresh to saline conditions occurred between 10 000 and

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9000 BP at Moore Lake, in east-central Alberta (Hickman and Schweger, 1993). In the United States, a salinity maximum was recorded between 10 200 and 9500 BP in Pickerel Lake, South Dakota, one of the longest stratigraphic records from the Great Plains (Schwalb and Dean, 1998). Similarly, Radle et al. (1989), Kennedy (1994), and Valero-Garcés et al. (1995) showed that Medicine Lake, South Dakota was a highly saline basin at 9500 BP, while Xia et al. (1997) interpreted an increase in salinity ca. 9000 BP in Coldwater Lake, North Dakota.

Such differences, however subtle, illustrate the value of interpretations based upon integration of multiple-proxy indicators. Although neither changes in sediment mineralogy nor plant macrofossils are a direct record of climate change, the mineralogical record does allow detailed reconstruction of past brine chemistry. And although brine chemistry may relate, in part, to changes in groundwater regime (e.g. Remenda and Birks, 1999), the setting of the Andrews site suggests that climate will remain a dominant factor. It is noteworthy that the peak salinities observed in the mineralogical record at the Andrews site correlate well with the peak occurrences of *Chenopodium salinum* (saline goosefoot; cf. Fig. 4 *in* Yansa and Basinger (1999)), one of the most important halophytic species on the Prairies. The fact that signals of maximum aridity from different proxy indicators may occur at different times at the same site largely reflects the differing response times of hydrological, ecological, and geomorphic systems.

CONCLUSIONS

The transition from cool, moist, late-glacial environments to warmer and drier, early Holocene environments is recorded in the lithostratigraphy of postglacial sediments at the Andrews site. Melt-out of stagnant glacial ice and the collapse of overlying supraglacial debris contributed to the formation and initial flooding of a lacustrine basin in hummocky moraine prior to 10 200 BP. Laminated, fine-grained lacustrine sediments, rich in organic matter and endogenic precipitates, were deposited in this basin over the interval ca. 10 000–8000 BP. Salinities may have reached 40 $g \cdot L^{-1}$, alkalinities were high, and the water was dominated by Mg^{2+}, Ca^{2+}, and SO_4^{2-} ions. After ca. 8000 BP, the water composition changed to generally lower salinity, with little sulphate but high Mg/Ca ratios. The increasing relative abundance of detrital clay minerals, quartz, and feldspar minerals in these sediments reflects an increase in the rate of erosion in the lake's watershed and corresponds to an increase in the intensity of chemical weathering, probably due to a warmer and more humid climate after ca. 8000 BP.

ACKNOWLEDGMENTS

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