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Holocene Climate in the Northern Great Plains Inferred from Sediment Stratigraphy, Stable Isotopes, Carbonate Geochemistry, Diatoms, and Pollen at Moon Lake, North Dakota

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Seismic stratigraphy, sedimentary facies, pollen stratigraphy, diatom-inferred salinity, stable isotope (δ^{18}O and δ^{13}C), and chemical composition (Sr/Ca and Mg/Ca) of authigenic carbonates from Moon Lake cores provide a congruent Holocene record of effective moisture for the eastern Northern Great Plains. Between 11,700 and 9500 ^{14}C yr B.P., the climate was cool and moist. A gradual decrease in effective moisture occurred between 9500 and 7100 ^{14}C yr B.P. A change at about 7100 ^{14}C yr B.P. inaugurated the most arid period during the Holocene. Between 7100 and 4000 ^{14}C yr B.P., three arid phases occurred at 6600–6200 ^{14}C yr B.P., 5400–5200 ^{14}C yr B.P., and 4800–4600 ^{14}C yr B.P. Effective moisture generally increased after 4000 ^{14}C yr B.P., but periods of low effective moisture occurred between 2900–2800 ^{14}C yr B.P. and 1200–800 ^{14}C yr B.P. The data also suggest high climatic variability during the last few centuries. Despite the overall congruence, the biological (diatom), sedimentological, isotopic, and chemical proxies were occassionally out of phase. At these times the evaporative process was not the only control of lake-water chemical and isotopic composition.

Key Words: **sedimentology; paleolimnology; diatoms; isotopes; geochemistry; northern Great Plains; Holocene; drought; hydrology; saline lakes; paleoclimate.**

INTRODUCTION

Paleolimnological studies from the Northern Great Plains show similar patterns of Holocene environmental change (Watts and Bright, 1968; Raddle *et al.*, 1989; Last and Schweyen, 1984; Last and Slezak, 1986; Kennedy, 1994; Valero-Garcés *et al.*, 1995; Laird *et al.*, 1996; Haskell *et al.*, 1996). During the early Holocene, a transition from freshwater to saline conditions parallels the replacement of woodland by prairie vegetation. In the mid Holocene, high salinity and a number of low lake stands are characteristic. The late Holocene is typified by a general increase in lake levels after 4000 yr B.P. and fluctuating conditions over the past few thousand years. In lakes where diatom-inferred salinity (Fritz *et al.*, 1991; Laird *et al.*, 1966) and sedimentological and isotopic techniques (Valero-Garcés *et al.*, 1995; Xia *et al.*, 1997) have been applied, more-complex patterns of hydrological change have been detected. Lake levels and solute concentrations in closed-basin lakes fluctuate in response to the ratio of precipitation to evaporation (P/E). These changes in the hydrologic budget are recorded in the sedimentary facies and in the isotopic and trace-element composition of authigenic carbonates. In this paper we use multiple independent proxies (pollen, diatom asemblages, sedimentary facies, trace-element geochemistry, and stable isotopes) to reconstruct the hydrologic history of Moon Lake, North Dakota

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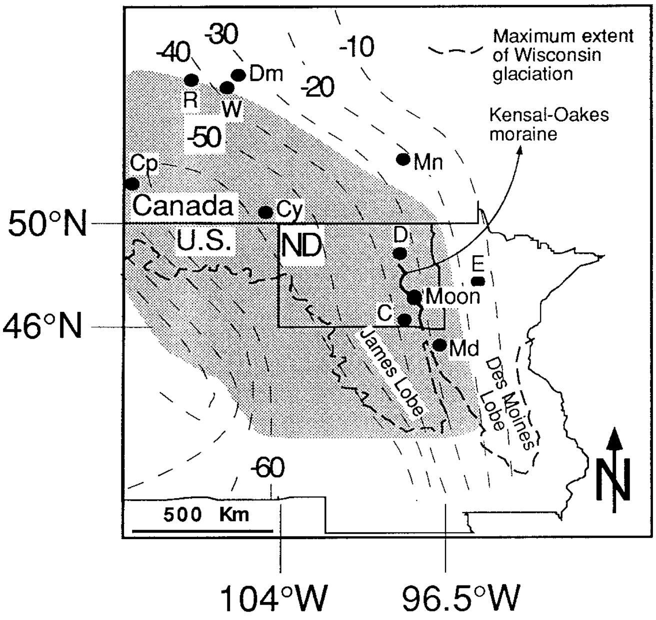


FIG. 1. Map showing location of Moon Lake in the Northern Great Plains (shaded area); other sites referred to in the text: Ceylon (Cy), Chappice (Cp), Coldwater (C), Deadmoose (Dm), Devils (D), Elk (E), Manitoba (Mn), Medicine (Md), Redberry (R), Waldsea (W), the Kensal–Oakes moraine (solid line), and the maximum extent of Wisconsin glaciation (dashed line) with the two main glacier lobes (Des Moines and James). Contours show present effective moisture (precipitation minus evaporation) in cm/yr.

and to infer moisture and environmental changes in the Northern Great Plains during the Holocene.

SITE DESCRIPTION

Moon Lake (46°51′27″ N, 98°09′30″ W, elev. 444 m), Barnes County, is a small (35-hectare) shallow (12.8 m maximum depth) lake with a relatively small watershed (1166 hectares) in the Missouri Coteau region of eastern North Dakota (Fig. 1). Present-day lake waters are saline (TDS: 5.81 g/L), alkaline (pH = 9.2), and of $Na–(Mg)–SO_4–CO_3$ type. Moon Lake is in outwash deposits associated with the Kensal–Oakes readvance of the Des Moines lobe (Kelly and Block, 1967). The lake has no outlet, and the hydrologic input includes direct precipitation, runoff, and groundwater influx. Water loss from Moon Lake is by evaporation and groundwater seepage. The annual temperature range in the region is large (−29° to 38°C), and average annual temperature is 6°C. Annual precipitation is 45.9 cm, and annual water deficit is about 35 cm/yr (Laird *et al.,* 1996). Climate is controlled by the interplay of three air masses: warm dry flow from the Pacific, cold dry Arctic air, and most tropical air from the Gulf of Mexico. Aridity is usually associated with summer precipitation deficits caused by high-pressure systems that block flow from the Gulf of Mexico and divert moisture to the east (Bradbury *et al.,* 1993).

METHODS

Two cores were collected on January 31, 1986 in the deepest part of the basin (Fig. 2): core A was 11.83 m and core B was 11.16 m. The cores were split, photographed, and correlated by distinct lithologies (laminated and banded units). Chronology is based on linear interpolation between 14 AMS radiocarbon dates of terrestrial charcoal and plant macrofossils in core A (Fig. 3). All ages are given in radiocarbon years B.P. High-resolution seismic reflection data were acquired in August 1994 using a multifrequency (1–12 kHz) ORE Geopulse subbottom profiling system.

Century-scale analysis of diatom assemblages and pollen stratigraphy for the entire Holocene record of core B are reported elsewhere (Laird *et al.,* 1996). Quantitative changes in salinity are inferred from diatom assemblages following a two-step process. First, the relationship between modern diatom assemblages and water chemistry is modeled through weighted-average regression and calibration techniques that result in estimates of species optima to salinity. These modeled responses are then applied to the paleolimnological record to reconstruct salinity based on the species composition of a sample. Comparison between diatom-inferred and measured salinity shows strong correlation in data sets from the Northern Great Plains (Fritz *et al.,* 1991).

Organic, carbonate, and inorganic percentages were determined by loss-on-ignition analyses every 8 cm from samples in core B. Sedimentological, mineralogical, geochemical, and isotopic studies were performed on core A. Sedimentary facies were identified based on color, lithology, mineralogy, grain size, and sedimentological structures. Sediment mineralogy was characterized by X-ray diffraction. Stable isotope and trace element analyses were performed on samples from discrete, <1-mm-thick calcite and aragonite laminae from core A. Monomineralic composition, sharp laminae boundaries, and the euhedral prismatic shape of the crystals (scanning electron microscopy observations) indicate rapid precipitation from surface waters and confirm the primary nature of these carbonates (Kelts and Talbot, 1990; Valero-Garcés and Kelts, 1995). Oxygen and carbon isotopic composition were measured by a Finnigan MAT delta E mass spectrometer. The isotopic values are reported in the conventional delta notation relative to the PDB standard, and the precision was 0.2‰ for $\delta^{18}O$ and 0.1‰ for $\delta^{13}C$. Sr and Mg concentrations were determined from dried samples after 15 min leaching in 0.15 *M* acetic acid to restrict dissolution to calcite and aragonite. Elemental concentrations were measured by DC plasma atomic emission spectrometry.

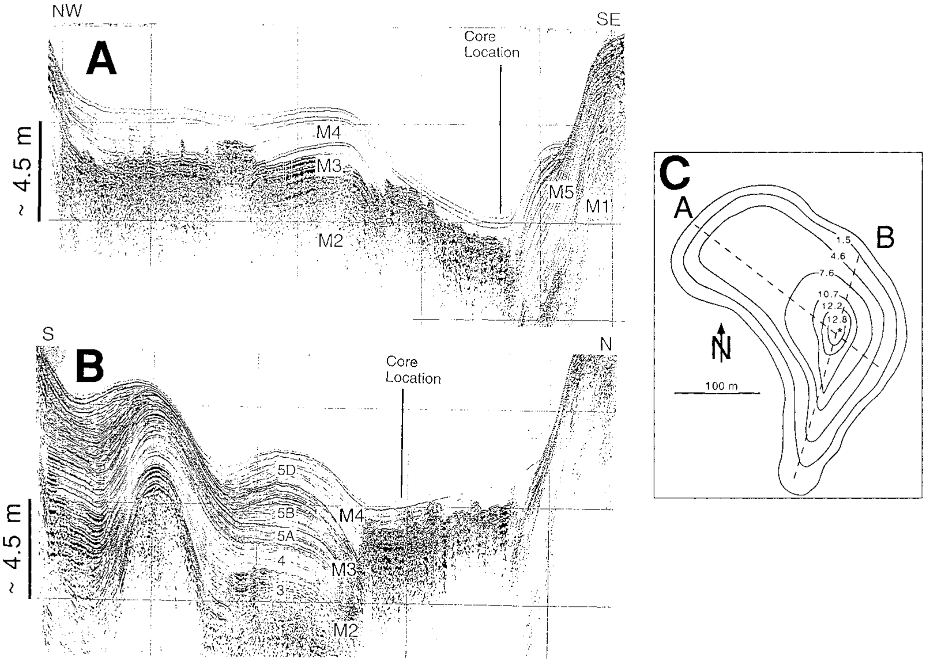


FIG. 2. Seismic profiles in Moon Lake showing an irregular basin morphology and variable sediment thickness. Each vertical division about 4.5 m. (A) Seismic units in a NW–SE profile. (B) Correlation of seismic and sedimentary units in a N-S profile. (C) Bathymetry, seismic profiles, and core location (*).

RESULTS

Seismic Stratigraphy

The seismic survey identified five units in the Moon Lake basin (Fig. 2) that are correlated with the lithostratigraphic core units (see below and Figs. 4D and 4E). Unit M1, characterized by strong and irregular reflectors, groups the clastic and massive Kensal–Oakes moraine sediments underlying the lacustrine units. Unit M2 does not have clear reflectors because of little pulse-energy penetration and the presence of gas. This unit comprises the laminated sediments of the lower part of the core (sedimentary units 2 and 3) deposited between 11,000 and 5000 ^{14}C yr B.P. M3 is characterized by alternation of strong and weak hummocky reflectors, which are irregularly spaced, and with numerous cut-offs towards the basin margins and the sills. The strong traceable reflectors defined internal subunits, which are correlated with lithostratigraphic core units 4 and 5A, 5B, and 5C. These features indicate changes in the composition of the sediments and more-frequent fluctuations in lake level since 5000 ^{14}C yr B.P. Seismic unit M4 displays more parallel, regularly spaced reflectors and is extensive over unit M3. Absence of cut-offs and regularity of reflectors indicate deposition during generally higher lake levels during the past 500 yr. Seismic unit M5 encompasses the prograding platform sediments at the southeastern margin of Moon Lake. Strong internal reflectors are interpreted as episodic slope activity and changes in lake level.

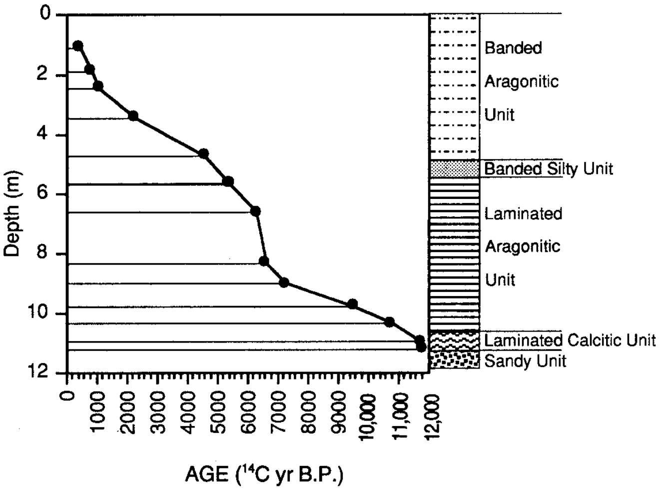
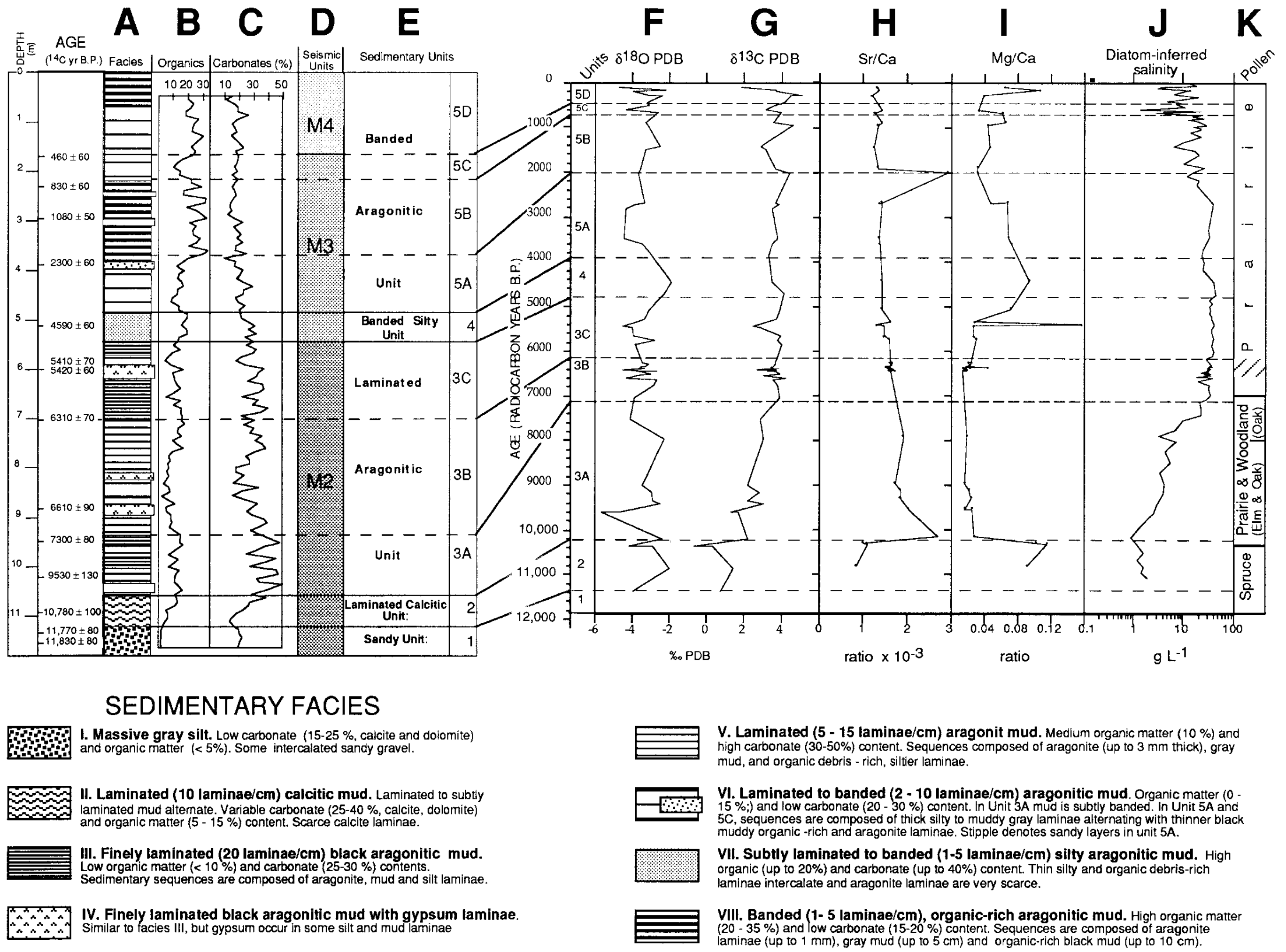


FIG. 3. Relationship between depth and ^{14}C age for Moon Lake core B.

Sedimentology

Based on 8 diagnostic facies, we defined five sedimentary units in Moon lake (Fig. 4A). The boundaries between sedimentary units are defined by grain size, sediment composition, mineralogy (calcite versus aragonite), and sedimentary structures (type of lamination, sedimentary sequences). The



SEDIMENTARY FACIES

I. Massive gray silt. Low carbonate (15-25 %, calcite and dolomite) and organic matter (< 5%). Some intercalated sandy gravel.

II. Laminated (10 laminae/cm) calcitic mud. Laminated to subtly laminated mud alternate. Variable carbonate (25-40 %, calcite, dolomite) and organic matter (5 - 15 %) content. Scarce calcite laminae.

III. Finely laminated (20 laminae/cm) black aragonitic mud. Low organic matter (< 10 %) and carbonate (25-30 %) contents. Sedimentary sequences are composed of aragonite, mud and silt laminae.

IV. Finely laminated black aragonitic mud with gypsum laminae. Similar to facies III, but gypsum occur in some silt and mud laminae

V. Laminated (5 - 15 laminae/cm) aragonit mud. Medium organic matter (10 %) and high carbonate (30-50%) content. Sequences composed of aragonite (up to 3 mm thick), gray mud, and organic debris - rich, siltier laminae.

VI. Laminated to banded (2 - 10 laminae/cm) aragonitic mud. Organic matter (0 - 15 %;) and low carbonate (20 - 30 %) content. In Unit 3A mud is subtly banded. In Unit 5A and 5C, sequences are composed of thick silty to muddy gray laminae alternating with thinner black muddy organic -rich and aragonite laminae. Stipple denotes sandy layers in unit 5A.

VII. Subtly laminated to banded (1-5 laminae/cm) silty aragonitic mud. High organic (up to 20%) and carbonate (up to 40%) content. Thin silty and organic debris-rich laminae intercalate and aragonite laminae are very scarce.

VIII. Banded (1- 5 laminae/cm), organic-rich aragonitic mud. High organic matter (20 - 35 %) and low carbonate (15-20 %) content. Sequences are composed of aragonite laminae (up to 1 mm), gray mud (up to 5 cm) and organic-rich black mud (up to 10 cm).

FIG. 4. Palaeoenvironmental proxies in Moon Lake core. (A) Sedimentary facies and ^{14}C dates. (B) Organic matter content. (C) Carbonate content. (D) Seismic units. (E) Sedimentological units. (F) Oxygen isotope composition (δ^{18}O). (G) Carbon isotope composition (δ^{13}C). (H) Sr/Ca ratio. (I) Mg/Ca ratio. (J) Diatom-inferred salinity. (K) Pollen stratigraphy.

basal sandy and silty Unit 1 (11,830–11,390 ^{14}C yr B.P.) is interpreted as representing deposition in a periglacial, well-mixed freshwater lake originating from the melting of buried ice blocks in the Kensal–Oakes moraine. Moon Lake during this time was likely to have had both a surface outlet and inlet and a much larger volume and surface area than today. A sharp change from massive sandy sediments to laminated calcitic muds marks the boundary with Unit 2 (11,390–10,200 ^{14}C yr B.P.). The progressive increase in carbonate and organic matter (Figs. 4B and 4C) contents could reflect a decrease in detrital influx caused by changes in the surface drainage or increased algal productivity. The onset of authigenic calcite formation indicates that lake waters reached carbonate saturation. Good preservation of laminae in Unit 2 suggests that bottom anoxia occurred frequently.

The onset of deposition of laminated, aragonite-rich facies defines the lower boundary of Unit 3 and represents a major limnological change in Moon Lake. The switch from calcite to aragonite precipitation indicates increasing Mg/Ca ratio in lake waters, probably caused by evaporative concentration and hydrologic closure. Following deposition of massive aragonitic muds (10,200–9530 ^{14}C yr B.P.), sedimentation in Moon Lake was characterized by the accumulation of laminated (up to 15 laminae per cm) to finely laminated (>15 laminae per cm) muds. These cycles of laminated and finely laminated muds represent an alternation of a hyposaline well-mixed lake with saline conditions and frequent anoxia (Fig. 4A). The lower proportions of carbonate and organic matter in the laminated aragonitic muds (Unit 3B, 7070–6170 ^{14}C yr B.P.) could be a reflection of increased clastic input at the coring site during low lake stands and greater precipitation of gypsum. The gypsum-bearing silty muds, with very low organic and carbonate content, correspond to a short interval (6600–6200 ^{14}C yr B.P.) of high sedimentation rate (0.56 cm/yr, Fig. 3) and indicate a period of low lake level and saline waters. Deposition of finely laminated aragonitic muds with higher carbonate and organic matter contents in Unit 3C (6170–4810 ^{14}C yr B.P.) suggests decreased clastic input and a return to higher lake levels. Another gypsum-rich interval occurred from 5520 to 5310 ^{14}C yr B.P.

During the transition from Unit 3 to 4 at about 4810 ^{14}C yr B.P., an abrupt change occurred in Moon Lake. Sediments changed from finely laminated to massive or branded, with fewer aragonite laminae. Unit 4 (4810–3950 ^{14}C yr B.P.) represents a period of generally low lake levels as shown by the dominance of silty, massive sediments and the presence of abundant, aquatic, littoral plant fragments. The conspicuous absence of gypsum in Unit 4 may result from post-depositional dissolution rather than nondeposition. Absence of individual aragonite laminae and the banded nature of the facies indicate a decrease in the extent of hypolimnetic anoxia.

After 3950 ^{14}C yr B.P. deposition in Moon Lake switched to a period characterized by banded facies (Unit 5). The occurrence of *Ruppia* pollen, the silty nature of the sediments, abundant laminae rich in plant debris, and the presence of silty laminae are all evidence for generally low lake level between 3950 and 2010 ^{14}C yr B.P. (Unit 5A). A longer low stand is inferred from the presence of a 6-cm-thick sandy silt layer at 2300 ^{14}C yr B.P. Better preservation of sedimentary lamination in Unit 5B indicates more frequent hypolimnetic anoxia and suggests a relative rise in lake level after 2010 ^{14}C yr B.P. Organic matter content increases significantly, fluctuating at the 25% level, possibly as a result of increased lake productivity and better preservation. Another episode of generally lower lake levels occurred in the upper part of Unit 5B (about 1300 ^{14}C yr B.P.) as shown by more abundant plant remains and siltier facies. Massive, organic-poor muds, devoid of plant remains and with scarce aragonite laminae, suggest deposition in a well-mixed lake for Unit 5C (720–480 ^{14}C yr B.P.). Mainly banded organic and carbonate-rich sediments were deposited during the last 500 yr (Unit 5D), although fluctuating lake levels are suggested by the occurrence of siltier layers.

Pollen

The pollen stratigraphy shows that the spruce forest was replaced by a parkland of mixed deciduous forest dominated by elm and oak with opening of grasses (Poaceae) and *Artemisia* at about 10,300 ^{14}C yr B.P., slightly before the onset of aragonite deposition in Unit 3 (Figs. 4E and 4K). The early Holocene abundance of *Ulmus* (Elm), which thrives best on poorly drained soils, suggests that the regional water table was considerably higher and that a much larger area than today would have been flooded (Laird *et al.*, 1996). Elm gradually disappeared when Ambrosia began to increase sharply about 8000 ^{14}C yr B.P. *Quercus* (oak) remained until 7000 ^{14}C yr B.P. suggesting a climate not sufficiently dry to eliminate scattered oak groves. About 7000 ^{14}C yr B.P., the appearance of *Ruppia* indicates shallow high-salinity waters and an arid climate. During the mid Holocene, a short interval of rapid deposition (6600–6200 ^{14}C yr B.P.) coincides with peaks in *Iva annua, Ruppia,* and *Picea* (spruce) pollen. This pollen spectrum indicates significantly warmer temperatures (*Iva annua*) and shallower waters (*Ruppia* and *Iva*) and suggests redeposition of older sediments exposed during lower lake levels (*Picea*). Prairie vegetation has characterized the region to the present.

Diatoms

Century-scale analysis of the diatom record showed that salinity dramatically fluctuated during the Holocene (Laird *et al.*, 1996). In the early Holocene (ca. 11,000 to 7300 ^{14}C yr B.P.) the lake changed from a freshwater (<3 g/L) to a highly saline (>20 g/L) system (Fig. 4J). This shift from fresh to saline conditions occurred in two stages. First was a gradual transition (10,000–8100 ^{14}C yr B.P.) from 1 to 4 g/L which corresponds to deposition of Units 2 and the lower part of 3A. Afterward, a more rapid transition from 5 to >20 g/L (upper part of Unit 3A) culminates by 7300 ^{14}C yr B.P. The mid-Holocene period (ca. 7300–4700 ^{14}C yr B.P.; Units 3B and 3C) is characterized by very high salinity, indicative of arid conditions. Poor diatom preservation characterized a transitional period from ca. 4700–2200 ^{14}C yr B.P., which corresponds to deposition of Units 4 and 5A. Finally, the last 2200 yr is a period of variable salinity, indicative of large fluctuations in effective moisture (Units 5B, 5C, and 5D).

The δ^{18}O Record

The δ^{18}O record does not show a general trend comparable to the diatom-inferred salinity or to the environmental changes interpreted from sedimentary facies. As in many other cases (Chivas *et al.*, 1993), the δ^{18}O curve cannot be interpreted as a function of simple evaporation from a closed system that would be related to salinity. Other controls, including temperature and changes in the sources of water, have to be considered in determining the contemporaneous δ^{18}O values (Siegenthaler and Eicher, 1986; Kelts and Talbot, 1990; Talbot, 1990; Valero-Garcés *et al.*, 1995).

Isotopic trends and relative values within different units in the core provide evidence about past hydrological changes (Fig. 4F). The δ^{18}O values (from -6 to -2‰) are generally more negative than those from the nearby hypersaline Medicine Lake (Valero-Garcés *et al.*, 1995), suggesting a shorter residence time. We interpret these data to reflect greater groundwater recharge and seepage in the Moon Lake system rather than differences in precipitation or evaporation between the two lakes.

The oldest isotopic sample in Moon Lake ($\delta^{18}O$ = −3.93‰) is a bulk carbonate in which detrital contamination is suspected. The composition of the first calcite laminae (−1.97‰) is the second heaviest of the whole core, which seems unexpected in a freshwater lake, as interpreted for Unit 2. Low water temperatures during calcite precipitation in summer of an ice-melt lake might explain the heavier oxygen isotopic compositions. The 2‰ negative shift in $\delta^{18}O$ values during the time of deposition of Unit 2 suggests increasing freshwater inputs (runoff and groundwater) and more positive hydrologic balance.

The $\delta^{18}O$ composition of the aragonite laminae in Unit 3A is about 2‰ heavier than the calcite laminae from Unit 2. The accompanying change in mineralogy from calcite to aragonite suggests chemical concentration in the lake waters and supports an interpretation of increased evaporative concentration. A period of high effective moisture in the early Holocene is indicated by the large negative excursion in $\delta^{18}O$ between 10,200 and 9500 ^{14}C yr B.P. The oxygen isotopic record between 6590–6170 ^{14}C yr B.P. (Unit 3B) suggests a low effective moisture period, but not the most intense as pollen and sedimentological evidence indicate. The high variability in $\delta^{18}O$ during the mid Holocene suggests high-frequency fluctuations in the water budget. Deposition of gypsum in Unit 3C inaugurated a millennium-long (5400 to 4400 ^{14}C yr B.P.) increasing trend in $\delta^{18}O$ values (−4.46 to −1.89) and $\delta^{13}C$ (2.53 to 4.13) that extends into Unit 4 (Fig. 4F), reflecting a decrease of effective moisture.

Decreasing $\delta^{18}O$ values in the lower parts of Units 5A and 5C and the upper part of Unit 5D are interpreted as a more positive hydrologic balance in the lake. Increasing values, between 2900 and 2700 ^{14}C yr B.P., and the transition from Unit 5C to 5D, indicate a more negative water budget. The relatively heavy isotopic compositions of Unit 5B samples are unlikely the result of evaporative processes, because diatom-inferred salinity decreased during this time. Therefore, a change in water sources seems necessary. Frequent negative and positive excursions of $\delta^{18}O$ in the upper two units suggest large hydrologic fluctuations.

The $\delta^{13}C$ Record

Changes in the $\delta^{13}C$ of authigenic lacustrine carbonate reflect variations in the dissolved inorganic carbon (DIC) pool from which the carbonate (calcite or aragonite) precipitated (Håkansson, 1985). Carbon isotopic compositions of Unit 2 samples are the lightest in the whole core and show a decreasing up-core trend (Fig. 4G). Low $\delta^{13}C$ values suggest that most DIC in Moon Lake was derived from light carbon sources (Valero-Garcés *et al.*, 1995): recycling of terrestrial carbon from the surrounding boreal forest (C3 plants $\delta^{13}C$ values between −25 and −32‰), lacustrine plants and plankton (values between −40 and −20‰), or marine carbonate and shale fragments from the till (typical $\delta^{13}C$ values of ca. 0‰ PDB).

The abrupt increase in $\delta^{13}C$ compositions from Unit 2 to Unit 3 (2.9‰) and the relatively heavier $\delta^{13}C$ compositions during the early Holocene in Moon Lake can be attained by mechanisms such as preferential $^{12}CO_2$ outgassing, equilibrium with atmospheric CO_2, increased algal productivity, or changes in inflow DIC compositions (Valero-Garcés *et al.*, 1995). Exchange with atmospheric CO_2 would have increased as a result of hydrological closure and longer residence time. The increasing dominance of C4 (prairie grass) versus C3 (boreal forest) plants (Laird *et al.*, 1996) would both contribute to heavier DIC in groundwaters. A similar pattern of increasing $\delta^{13}C$ into the Prairie Period occurred in Elk Lake, Minnesota (Dean and Stuiver, 1993), and Coldwater Lake, North Dakota (Xia *et al.*, 1997). The fluctuations during Unit 3B and the large $\delta^{13}C$ negative excursion between 5520 and 5310 ^{14}C yr B.P. are in phase with the oxygen isotope variations (Fig. 4F and 4G), as expected in lakes with longer residence periods. A change in this covariant pattern and the onset of a decreasing trend coincides with deposition of organic-rich, banded facies about 2000 ^{14}C yr B.P. (Unit 5B). The large negative shift during the last 200 yr could reflect changes in the management of the watershed after European settlement in the area.

The Sr/Ca and Mg/Ca Records

The Sr/Ca and Mg/Ca ratios of ostracods have been applied as direct paleosalinity indicators in a variety of environments (Chivas *et al.*, 1993; Fritz *et al.*, 1994; Xia *et al.*, 1997). Authigenic inorganic calcite and aragonite carry the same signal as biogenic precipitates, but the difficulties in obtaining pure monomineralic carbonate samples in most lake sediments have restricted their applicability.

In Moon Lake, the Sr/Ca ratio in the carbonate laminae reflects changes in mineralogy and in past lakewater chemistry (Fig. 4H). Samples from calcitic Unit 2 have low Sr/Ca ratios (about 1×10^{-3}) because the calcite can accommodate less Sr than the aragonite lattice (Fritz *et al.*, 1994; Haskel *et al.*, 1996). The shift to aragonite precipitation in Unit 3 doubled the Sr/Ca values up to 2.8×10^{-3}. After 10,200 ^{14}C yr B.P., Sr/Ca values decreased sharply and reached 1.7×10^{-3} at about 9000 ^{14}C yr B.P. This period corresponds to the abrupt chemical change in the lake from a freshwater to a saline system. The rest of the record shows a gradual decrease with only a major excursion at the base of Unit 5B (about 2000 ^{14}C yr B.P.). After 9000 ^{14}C yr B.P., the small range in Sr/Ca ratios suggests that Moon Lake was a groundwater-dominated system.

The Mg/Ca record shows a more complex behavior than Sr/Ca record (Fig. 4I). Unit 2 samples have elevated values (>0.09) because of the high-magnesium calcite mineralogy. The shift to aragonite precipitation about 10,200 ^{14}C yr B.P. greatly decreased the Mg/Ca ratio (<0.03) because aragonite incorporates much less Mg than calcite (Haskell *et al.*, 1996;

Xia *et al.,* 1997); consequently, from 10,200 to 6400 ^{14}C yr B.P. values remained low (0.03–0.01). After the appearance of the gypsum-rich facies about 6400 ^{14}C yr B.P., values started to increase, first slowly until 5200 ^{14}C yr B.P. (occurrence of gypsum-rich muds and an anomalous high value of 0.16), and then sharply until a maximum value of 0.09 was reached at 4400 ^{14}C yr B.P. Values remained high during the deposition of Unit 4 and 5A, but decreased afterward, reaching a minimum value of 0.03 about 2000 ^{14}C yr B.P. We interpret the increasing Mg/Ca ratios between 6400 and 4400 ^{14}C yr B.P. to be the result of increasing chemical concentration of the lake. The decreasing values during Unit 5A reflect a progressive refreshening of the lake waters until the onset of deposition of Unit 5B. The increasing trend up to 0.1 during the past 2000 yr is interrupted by a negative excursion during deposition of Unit 5C, interpreted as another period of lowered chemical concentration in the lake.

RECONSTRUCTION OF SHIFTS IN EFFECTIVE MOISTURE

Deglaciation

Unit 1 (11,830–11,390 ^{14}C yr B.P.) represents deposition in a periglacial, well-mixed freshwater lake surrounded by mature spruce forest. All the proxies are consistent with a cool and moist climate and high effective moisture. The transition from Unit 1 to Unit 2 at about 11,390 ^{14}C yr B.P. corresponds to a hydrological change caused by final melting of dead ice and isolation of the lake. Oxygen and carbon isotopic values in Unit 2 display a clear covariant trend (Figs. 4F, 4G, and 5) diagnostic of primary carbonates formed in a hydrologically closed lake (Talbot, 1990). However, although some of the oxygen values are among the most positive in the core, sedimentologic and diatom evidence favor an open system. An alternative mechanism for the isotope covariance involves increased input of isotopically light groundwater in a hydrologically open system. However, this scenario is not consistent with the heavy ^{18}O values seen in this interval.

The Early Holocene

The deposition of laminated, aragonite-rich facies characterizes the onset of subunit 3A (10,200 ^{14}C yr B.P.). Between 10,200 and 9500 ^{14}C yr B.P., lake level was high and salinity low, as indicated by low diatom-inferred salinity, a large negative shift in δ^{18}O, and decreasing Sr/Ca values. The onset of finely laminated facies, a large positive oxygen excursion, and the stabilization of Sr/Ca values at 9500 ^{14}C yr B.P. correlate with decreased percentages of birch and are probably associated with climatic warming, increased primary production, and evaporative concentration of lake waters. An abrupt increase in diatom-inferred salinity between 8100 and 7300 ^{14}C yr B.P. is synchronous with a deposition of laminated facies, an increase in *Ambrosia,* and a disappearance of elm. However, δ^{18}O values are lower than before. Decreasing δ^{18}O values coincident with increasing salinity could result from increased input of lighter δ^{18}O as a result of either a change in the seasonal distribution of precipitation (more winter than summer precipitation) or increased influx of an isotopically light groundwater source. Increasing salinity and predominance of finely laminated facies suggest increased hydrologic closure during Unit 3A, so we consider isotopic covariance (Fig. 5) to be a reflection of closed basin dynamics.

Kennedy (1994) and Valero-Garcés and Kelts (1995) documented an abrupt limnological shift at the forest/prairie transition between 9200 and 9000 ^{14}C yr B.P. in Medicine Lake as a threshold response to changes in the hydrologic regime. In Medicine and Moon lakes, hydrological changes and the establishment of closed-basin conditions are undoubtedly driven by climatic warming, associated with increased summer insolation, as well as the regional climatic effects of the retreating Laurentide ice sheet and dissipation of the large, cold Lake Agassiz. Other sites in the Northern Great Plains also experienced low water levels and high salinity during the early Holocene (Fritz *et al.,* 1991; Vance *et al.,* 1992; Laird *et al.,* 1996), although these data indicate that maximum Holocene aridity occurred ca. 6500, and not at 9000 ^{14}C yr B.P., as GCM simulations suggest (Webb *et al.,* 1993). Changes in location and intensity of atmospheric features not considered by the models, such as the southwest summer low, would have brought moisture to the Plains during this period, allowing lakes to remain relatively high during the early Holocene (Harrison, 1989).

Mid-Holocene Aridity

Across the transition from Unit 3A to Unit 3B (about 7000 ^{14}C yr B.P.), δ^{18}O values increase (−3.89 to −2.64‰), oak pollen disappears, and *Ruppia* pollen appears (Fig. 4K). This transition to grassland vegetation correlates with increasing diatom-inferred salinities (20 to 35 g/L). The highest diatom-inferred salinity values correspond with the heaviest oxygen isotopic compositions, the occurrence of gypsum, and high Mg/Ca values, and these data suggest evaporative concentration caused by elevated aridity. Evidence for increased residence time and closed-basin behavior during deposition of Unit 3B comes from stronger isotopic covariance (Fig. 5). Pollen spectra, sedimentary facies, and Mg/Ca ratios identify the short interval between 6600–6200 ^{14}C yr B.P. as the interval of lowest effective moisture during the Holocene. The dominance of diatoms of the *Chaetoceros muelleri* complex, which have a salinity optimum of 11 gL^{-1} and are common in shallow saline systems, also supports this interpretation (Laird *et al.,* 1966).

Subunit 3B represents prairie expansion in the Moon Lake area and the onset of an arid interval from ca. 8000 to 5000

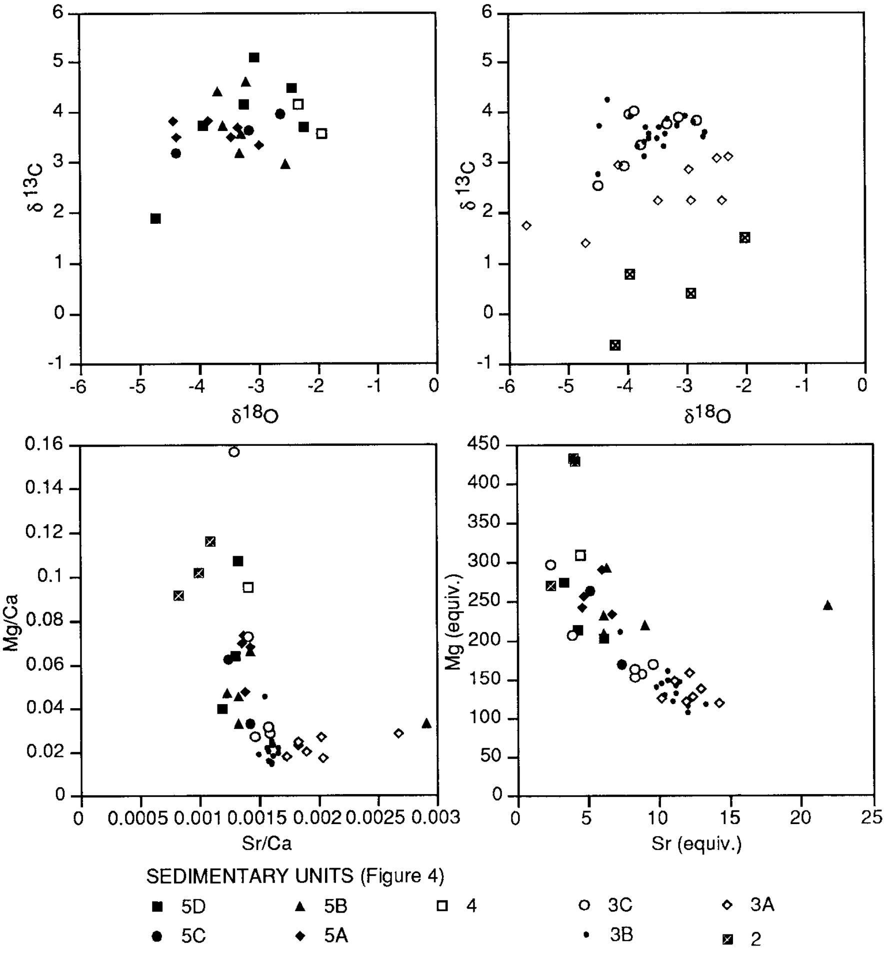


FIG. 5. Isotopic (δ^{18}O and δ^{13}C) and chemical (Sr and Mg compositions and Sr/Ca and Mg/Ca ratios) values of Moon Lake authigenic aragonite samples plotted by sedimentary unit.

^{14}C yr B.P. (Wright, 1992). The extreme low lake levels in Moon Lake at about 6500 ^{14}C yr B.P. correlate with loess deposition elsewhere in North Dakota (Clayton *et al.*, 1976) and maximum Holocene aridity at several sites in north-central North America (Watts and Bright, 1968; Bartlein *et al.*, 1984; Bradbury *et al.*, 1993; Laird *et al.*, 1996). Thus, moisture patterns in the eastern Dakotas are more similar to those in the upper Midwest than to those in the Rocky Mountains region and areas farther west (Thompson *et al.*, 1993). This mid-Holocene aridity likely was a result of an increased frequency of westerly flow that blocked summer moisture from the Gulf of Mexico (Webb *et al.*, 1983).

The decreasing δ^{18}O values, increased organic and carbonate content, and good preservation of laminations in the lower part of Unit 3C are evidence for increased lake levels after the low stand of Unit 3B. However, diatom-inferred salinity remained very high (35–40 g/L) and constant, and Mg/Ca ratios increased. We speculate that lake transgression could have dissolved former precipitated salts, thereby maintaining high salinity. Hypolimnetic anoxia during relatively low lake levels would promote the preservation of finely laminated facies in this unit. Gypsum occurs in very finely laminated facies at a time (ca. 5520–5310 ^{14}C yr B.P.) when peaks in Mg/Ca and Sr/Ca ratios occur, but all other proxies do not indicate increased aridity. The abundance of plagioclase and abraded gypsum grains in these laminae favors a detrital origin for the gypsum. Supporting this hypothesis, aragonite interbedded with gypsum-bearing laminae show the lightest oxygen isotopic values of Unit 3C.

Diatom-inferred salinity, δ^{18}O and Mg/Ca records, and sedimentary facies favor decreasing effective moisture across the transition from Units 3C to 4. Unit 4 represents another interval of low lake level, as shown by the dominance of littoral facies and the occurrence of the highest δ^{18}O and high Mg/Ca values. Poor diatom preservation and the detrital nature of the sediments during this period may have been caused by increased turbulence and sediment mixing as a result of lowered lake level.

The Late Holocene

The progressive transition to banded and muddy facies in the upper part of Unit 4 and the onset of a decreasing trend in δ^{18}O and Mg/Ca ratios at 4400 ^{14}C yr B.P. indicate an increase in effective moisture and the end of the persistent aridity of the mid-Holocene period. Relatively large fluctuations in δ^{18}O together with fairly constant δ^{13}C values (about 3.5‰) illustrate a new noncovariant isotopic pattern in Moon Lake (Fig. 5) that suggests a hydrological change. Climatic amelioration is also suggested by the fact that the earliest cultural complex extensively represented in North Dakota developed at this time (Artz, 1995).

Lake-level fluctuations were frequent during the past 4000 yr, as evidenced from the seismic record (Fig. 2), changes in facies (Fig. 4A), and large variations in diatom-inferred salinity (Fig. 4J). Subunit 5A (3950–2020 ^{14}C yr B.P.) was deposited during a period of low, but fluctuating lake levels. More-negative δ^{18}O values in the lower part of unit 5A (3900 and 3500 ^{14}C yr B.P.) and decreasing Mg/Ca ratios through the whole unit suggest decreasing chemical and isotopic concentration. The appearance of *Ruppia* pollen, the silty nature of the sediments, the abundant laminae rich in plant debris, the presence of sandy layers, and the relatively heavier δ^{18}O values are evidence for episodes of low lake level between 3500 and 2000 ^{14}C yr B.P.

Late Holocene low stands also occurred in Waldsea Lake, Saskatchewan, between 2800 and 2200 ^{14}C yr B.P. (Last and Schweyen, 1985) and in several nearby lakes: Devils Lake, between 3500 and 2000 ^{14}C yr B.P. (Fritz *et al.*, 1991), Medicine Lake (Valero-Garcés *et al.*, 1995), and Coldwater Lake (Xia *et al.*, 1997). These low stands also correlate with a period of increased loess deposition in North Dakota tentatively dated at 3500 yr B.P. (Clayton *et al.*, 1976). The regional scale of these events indicates that periods of severe aridity punctuated any general trend toward somewhat wetter and/or cooler conditions.

A sedimentary facies change at about 2000 ^{14}C yr B.P. (Unit 5B) is accompanied by a negative shift in δ^{13}C, the onset of an increasing trend in Mg/Ca values, and better preservation of diatoms. This phase of relatively high lake levels (Unit 5B) correlates with the second period of dynamic cultural development in the Northern Great Plains at about 2500 ^{14}C yr B.P. when pottery and mound-mortuary ceremonialism first appeared, and participation in inter-regional exchange increased (Artz, 1995).

Lake levels decreased after 1200 ^{14}C yr B.P. as shown by the more abundant plant remains, massive and siltier facies in the upper part of Unit 5B, and increasing diatom-inferred salinity. Oxygen isotopes maintain generally high values as before. Low lake levels at about 1000 ^{14}C yr B.P. occur in several other sites in the Northern Great Plains: Chappice Lake (about 1000–600 ^{14}C yr B.P.) (Vance *et al.*, 1993), Waldsea Lake (about 1000–700 ^{14}C yr B.P.) (Last and Slezak, 1988), Redberry Lake (about 1000–900 ^{14}C yr B.P.) (Stempvoort *et al.*, 1993), Deadmoose Lakes (Last and Slezak, 1986, 1988), and Coldwater Lake (Xia *et al.*, 1997), and another period of loess deposition has been dated at about 800 ^{14}C yr B.P. (Clayton *et al.*, 1976). This period correlates with the Medieval Warm Period in Europe (ca. 950–750 yr B.P.).

The lowest diatom-inferred salinity since the late-glacial/early-Holocene transition and negative excursions in δ^{18}O, δ^{13}C, and Mg/Ca values during Unit 5C suggest a period of more positive water balance from ca. 720 to 480 ^{14}C yr B.P. This was followed by gradual decrease in lake levels and an increase in salinity from 450 to 300 ^{14}C yr B.P. as evidenced by siltier sediments, the increase in diatom-inferred salinity, and higher δ^{18}O and Mg/Ca values. Fluctuating, but generally lower, diatom-inferred salinities, lower δ^{13}C and δ^{18}O, and Mg/Ca suggest relatively higher effective moisture during the past few centuries.

CONCLUSIONS

Integration of the results of studies of δ^{18}O, δ^{13}C, Sr/Ca, and Mg/Ca ratios, diatom-inferred salinities, and changes in sedimentary facies provide a basis for interpreting the salinity, evaporation, and chemical history of the Moon Lake system better than if each of these techniques was applied in isolation. Fairly constant Sr/Ca ratios during most of the Holocene suggest that Moon Lake has been groundwater-controlled since its establishment as a topographically closed basin. The Moon Lake record contains examples of periods when biological, chemical, and sedimentological proxies were out of phase. Biological (diatom-inferred salinity) and geochemical (δ^{18}O and Mg/Ca) indicators track each other more closely during saline and low lake level stages, when the isotopic and chemical composition of lake water is mostly driven by evaporative processes. Dissolution of previously deposited saline minerals (gypsum) within the lake, or within its surface or groundwater catchment as lake level rose, could explain some of the discrepancies during saline and low lake level stages (Units 3C and 4). Changes in relative amounts of rainfall and groundwater and evaporated waters during freshwater stages may result in large isotopic shifts without changes in salinity, because the different water sources are all of low salinity. These results stress the importance of interpreting variations in δ^{13}C and δ^{18}O with other environmental proxies such as sedimentary facies, pollen assemblages, and diatoms.

The similarities between the records from Moon Lake and other sites in the region indicate that Moon Lake reflects the climatic history of the eastern Northern Great Plains. Between 11,700 and 9500 ^{14}C yr B.P., lake level remained high and salinity low. A gradual decrease in effective moisture occurred between 9500 and 7100 ^{14}C yr B.P., at a time when the region had a mosaic of prairie and decidous woodland. A change to more extreme aridity occurred about 7100 ^{14}C yr B.P., with salinity higher than 30 g/L, very low lake levels, a positive shift in oxygen isotopic values, and the expansion of prairie vegetation. This abrupt change inaugurates the most arid period of the Holocene, dated between 7100 and 4000 ^{14}C yr B.P. Three especially arid phases occurred between 6600 and 6200, 5400 and 5200 and 4800 and 4600 ^{14}C yr B.P. The last 4000-yr period is characterized by large fluctuations in lake level and lakewater chemistry, including intervals when water was fresher than at any time during the mid Holocene, as well as periods of high salinity and low lake stands.

The reconstructed alternation of moist and arid periods suggests large temporal climatic variability in the Northern Great Plains during the Holocene. Changes in boundary conditions and global atmospheric circulation alone cannot explain the complexity of moisture availability reconstructed from the Holocene Moon Lake record. Shifts in location and variable strength of smaller atmospheric features would explain these patterns of century-scale fluctuations.

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