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# Late Quaternary paleoenvironments of an ephemeral wetland in North Dakota, USA: relative interactions of ground-water hydrology and climate change

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**Abstract** This study of fossils (pollen, plant macrofossils, stomata and fish) and sediments (lithostratigraphy and geochemistry) from the Wendel site in North Dakota, USA, emphasizes the importance of considering ground-water hydrology when deciphering paleoclimate signals from lakes in postglacial landscapes. The Wendel site was a paleolake from about 11,500  $^{14}\text{C}$  yr BP to 11,100  $^{14}\text{C}$  yr BP. Afterwards, the lake-level lowered until it became a prairie marsh by 9,300  $^{14}\text{C}$  yr BP and finally, at 8,500  $^{14}\text{C}$  yr BP, an ephemeral wetland as it is today. Meanwhile, the vegetation changed from a white spruce parkland (11,500 to 10,500  $^{14}\text{C}$  yr BP) to deciduous parkland, followed by grassland at 9,300  $^{14}\text{C}$  yr BP. The pattern and timing of these aquatic and terrestrial changes are similar to coeval kettle lake records from adjacent uplands, providing a regional aridity signal. However, two local sources of ground water were identified from

the fossil and geochemical data, which mediated atmospheric inputs to the Wendel basin. First, the paleolake received water from the melting of stagnant ice buried under local till for about 900 years after glacier recession. Later, Holocene droughts probably caused the lower-elevation Wendel site to capture the ground water of up-gradient lakes.

**Keywords** Climate · Ground water · Pollen · Plant macrofossils · Geochemistry · North Dakota

## Introduction

The climate of the northern Great Plains of the USA today is semi-arid and droughts are common. As a result of this aridity, the native vegetation of North Dakota, South Dakota and Montana is grassland. During the late-glacial, however, the climate of the northeastern part of this region was cool and moist, supporting *Picea* A. Dietr. (spruce) vegetation in areas closest to the Laurentide Ice Sheet (e.g. Laird et al. 1998; Dean and Schwalb 2000). This climate, reconstructed from pollen and other proxy data, is thought to have resulted from the nearby ice sheet having both high albedo and a persistent high-pressure atmospheric cell that generated anticyclonic cold winds (Barnosky et al. 1987). This climatic effect was diminished farther west of

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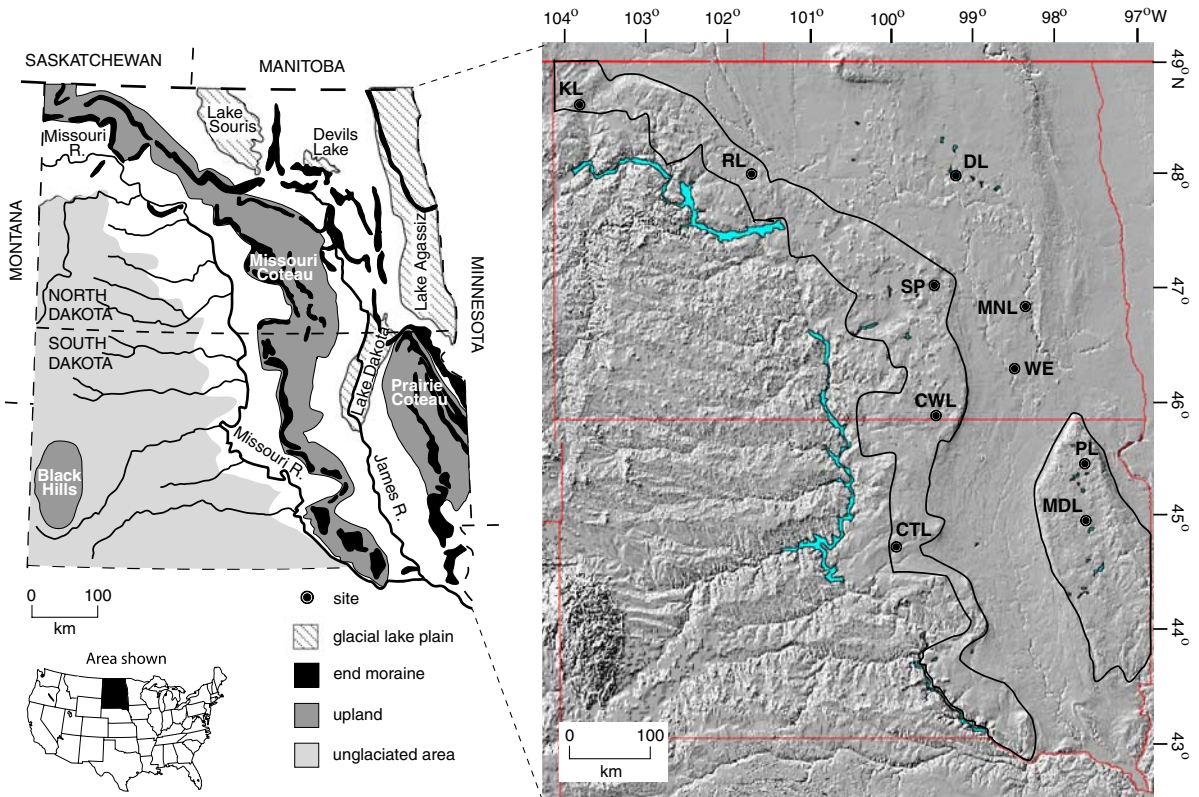
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the ice sheet, where grassland was established on the plains of Montana immediately after deglaciation, at about 12,200  $^{14}\text{C}$  yr BP (Barnosky 1989). This prairie vegetation was interpreted by Barnosky (1989) to indicate a direct response to greater summer insolation during the late-glacial. In contrast, the appearance of aridity was delayed in the eastern portion of the northern Great Plains (the eastern Dakotas), closer to the glacier, until the early Holocene (9,000–8,000  $^{14}\text{C}$  yr BP) when the ice receded to the northeast (Laird et al. 1998; Dean and Schwalb 2000; Grimm 2001; Clark et al. 2002). Thereafter, drought was a common occurrence in the region and grassland vegetation was widespread.

Few researchers have considered ground-water/lake interactions in their paleoclimatic

interpretations. Some exceptions include Smith et al. (1997) and Almendinger et al. (1999), who proposed that ground water flowed along a regional gradient to discharge into lower elevation lakes throughout the Holocene. Also, the contribution of subsurface meltwater to lakes during the Late Pleistocene from slowly ablating stagnant ice buried under till has long been recognized by geologists working in the region (Clayton 1967), but not by paleolimnologists.

In this paper, we use of a variety of paleoindicators to track past ground water and climate changes at the Wendel site in southeastern North Dakota, USA (Fig. 1), an ephemeral wetland that was once a paleolake. Our primary indicators include plant macrofossils, which have been shown to reliably represent past macrophyte



**Fig. 1** Location map displays the physiographic features of North Dakota and South Dakota. The inset shaded-relief map shows the locations of the study site (WE = Wendel site) and coeval fossil localities: KL = Kettle Lake (Clark et al. 2002); RL = Rice Lake (Grimm 2001); DL = Devils Lake (Haskell et al. 1996); SP = Seibold Pond (Newbrey and Ashworth 2004); MNL = Moon

Lake (Laird et al. 1996, 1998); CWL = Coldwater Lake (Yansa 2002); CTL = Cottonwood Lake (Barnosky et al. 1987; E. Grimm data on NAPD website, [www.ncdc.noaa.gov/paleo/napd.html](http://www.ncdc.noaa.gov/paleo/napd.html)); MDL = Medicine Lake (Radle et al. 1989); and PL = Pickerel Lake (Watts and Bright 1968; Dean and Schwalb 2000)

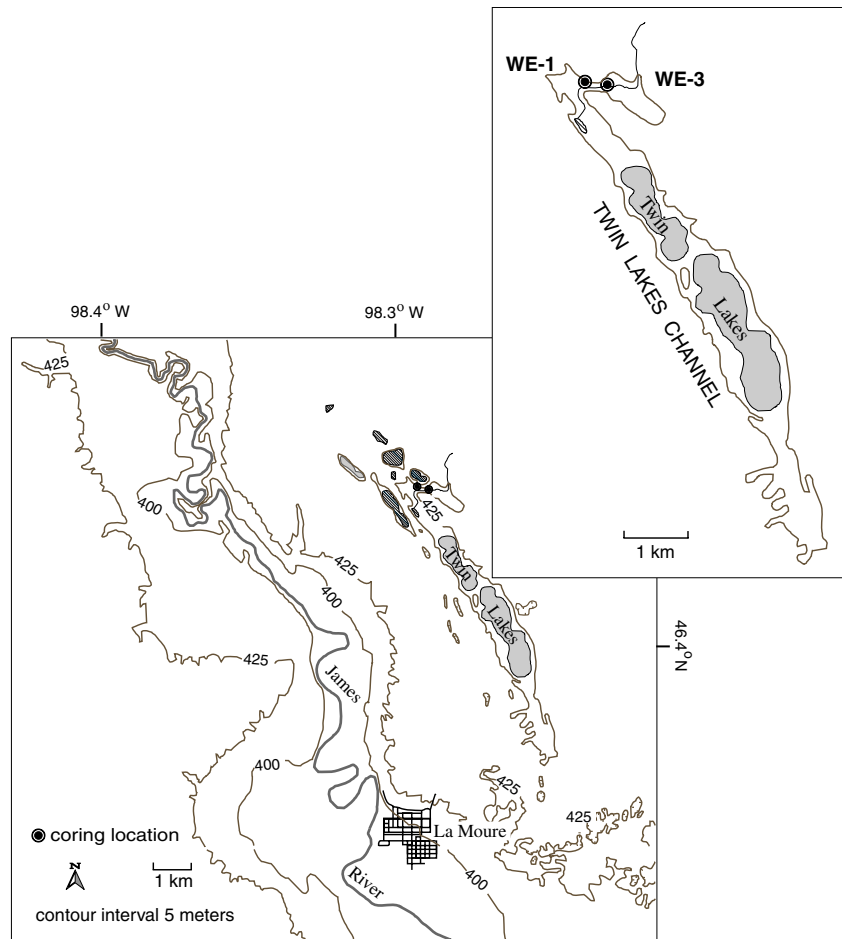
populations (e.g. Zhao et al. 2006), and have been used in a variety of paleoclimate studies (e.g. Dieffenbacher-Krall and Nurse 2005; Velle et al. 2005). We also employ fossil pollen and stomata to reconstruct local and subregional vegetation changes for the paleoclimate information they provide (e.g. Grimm 2001; Grimm and Jacobson 2004). In addition, we include fossil fish remains in our analysis, because fish populations are sensitive to lake chemistry, which is controlled by ground-water hydrology and climate (e.g. Newbrey and Ashworth 2004). The bulk geochemistry and organic carbon data we obtain indicate shifts in the levels of oxygen, nutrients and salts in the paleolake water, which provide information about the relative contribution of ground water and precipitation to the lake during various times in the past (e.g. Gorham et al. 1983; Dean and Schwalb 2000). By correlating these

proxy datasets we reconstruct the interplay between climate and ground-water hydrology and its effects on limnology, vegetation and fish from about 11,500 to 8,100  $^{14}\text{C}$  yr BP. During this time there was draw down of the lake, which caused subaerial exposure of part of the basin.

### Study area

The Wendel site (46°25' N, 98°20' W; 423 m asl) in LaMoure County, North Dakota (Fig. 2), temporarily holds water after snowmelt and heavy rainfall, and typically dries out by mid-summer. This site is situated at the northern end of a partly drained lake bed within a palimpsest meltwater channel situated on the Glaciated Till Plain (Fig. 2). We named this channel the Twin Lakes channel; it has a maximum relief of 14 m, an

**Fig. 2** Simplified topographic map (1:100,000 scale) with inset that shows the Twin Lakes channel and the locations of the WE-1 and WE-3 cores



average width of 610 m and length of 16 km, and runs roughly parallel to the James River valley.

The climate of the study area (eastern Dakotas) is classified as sub-humid continental. The meteorological station at LaMoure, North Dakota, for the climate normal years 1961–1990 reported average temperatures of  $-13.3^{\circ}\text{C}$  for January and  $21.6^{\circ}\text{C}$  for July, and a mean annual precipitation of 520 mm (Owenby and Ezell 1992). Most of this precipitation occurs during the spring and summer, but is lost through evapotranspiration, causing a moisture deficit (Winter 1989). Lake levels are controlled by the amount of autumn precipitation and snowmelt, because even though this accounts for less of the annual moisture, little of it is lost through evapotranspiration (Winter and Rosenberry 1995). Perennial lakes are thus rare in this region, but playas and ephemeral wetlands (sloughs or prairie potholes) are common. Summer droughts in the northern Great Plains occur whenever zonal westerly flow of the Pacific air mass dominates, because it diverts the Gulf moisture eastward into the Midwest (Bradbury et al. 1993).

The vegetation in the eastern Dakotas is mixed-grass prairie, which is a mixture of tall grass and forb species more common to the east and short-grass prairie plants of the western plains. Trees in the study area are restricted to

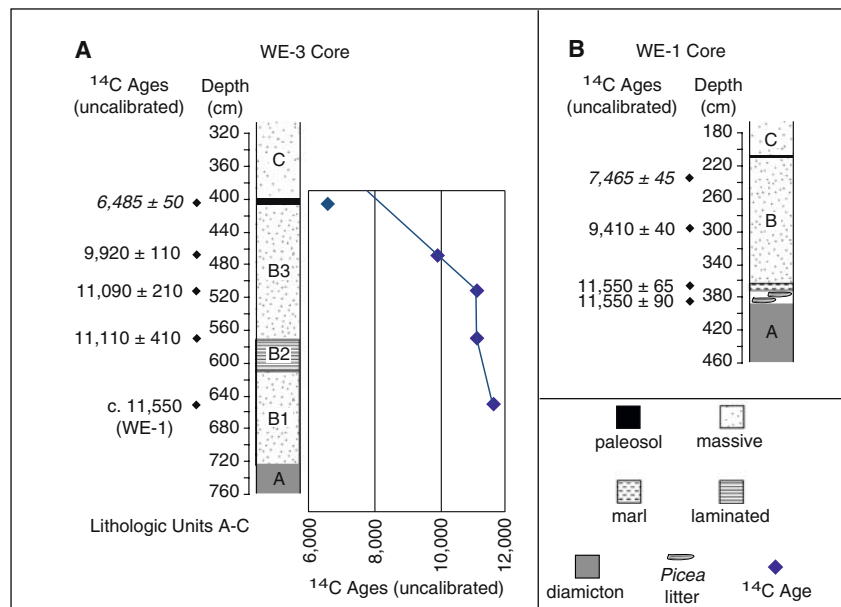
river valleys and around the few existing perennial lakes where the soils are moist. The most common tree species in these habitats are *Populus tremuloides* Michx. (quaking aspen), *Ulmus americanus* L. (American elm) and *Quercus macrocarpa* Michx. (bur oak) (Great Plains Flora Association 1986).

## Materials and methods

Sediment cores were collected at the Wendel site at two locations, 400 m apart (Fig. 2, inset), using a split-spoon core barrel attached to a CME™ hollow-stem drill rig. Based on lithologies and fossil assemblages, we consider the WE-1 core (6.1 m long) to represent a “nearshore” location and the WE-3 core (9.1 m long) as representative of an “offshore” location within a bay of a paleolake (Figs. 2 and 3). We analyzed pollen, plant macrofossils, stomata and fish fossils, as well as lithology and geochemistry from the sediments of the WE-3 core. For the WE-1 core, we only studied the plant macrofossils and fish remains to provide additional data.

Methods used in fossil analysis followed standard procedures for pollen (Faegri and Iverson 1975) and plant macrofossils (Birks 2001). Sampling intervals were every 5 cm for pollen

**Fig. 3** Lithostratigraphy and  $^{14}\text{C}$  ages of the cores analyzed: **(A)** the WE-3 core and **(B)** the WE-1 core. An age model was only constructed for the WE-3 core and is shown in Fig. 3A. The  $^{14}\text{C}$  ages in italics (*6,485 ± 50* for the WE-3 core and *7,465 ± 45* for the WE-1) are not included in the age model for the reasons discussed in the Results section



(1 cm<sup>3</sup> volume) and every 2.5 cm for plant macrofossils (50 cm<sup>3</sup>). Cyperaceae, members of the sedge family, occupy both upland and lowland habitats. The exceedingly high pollen counts for Cyperaceae and the numerous seeds of *Carex* spp. (sedges), *Scirpus* spp. (bulrushes), and other members of this family suggest that most of the Cyperaceae pollen grains are probably of wetland types. Hence the Cyperaceae pollen data were excluded from the pollen sum, which is based on the total pollen count of upland plants. Macrofossil data are counts, except for leaves and stems of a species of *Drepanocladus* (C. Mull.) G. Roth (sickle-branch moss), statoblast of *Cristatella mucedo* Cuvier (a bryozoan), and bones of *Perca flavescens* Mitchell (yellow perch), which were evaluated using relative abundance on a 0–4 scale. In Tilia™ spreadsheets, macrofossil data were entered and pollen percentages were calculated based on counts of about 300 pollen grains of upland taxa (excluding Cyperaceae) per sample. Abundance data of the more common taxa identified from pollen and plant macrofossils were plotted using a combination of Tilia.graph™, TGView™, and Adobe Illustrator™. CONISS was used to distinguish the plant macrofossil and pollen zones in the diagrams (Grimm 1987). Plant taxonomy and habitat information were based on the Great Plains Flora Association (1986). Terrestrial plant materials were used to obtain <sup>14</sup>C ages from both cores (Table 1).

A fossil specimen of *Esox lucius* L. (northern pike) was recovered in 1971 during excavation of a livestock watering hole at the site (A. Ashworth pers. commun.). Decades later we collected the WE-1 core within 50 m of this watering hole. Bones of *Perca flavescens* from the WE-1 and WE-3 cores were identified by M. Newbrey (pers. commun.) from the same samples analyzed for plant macrofossils.

The entire length of the WE-3 core was sampled for geochemistry and organic carbon at 20-cm intervals. The results of samples younger than 7,800 <sup>14</sup>C yr BP are not reported here, because they provided an invariant signal, presumably due to homogenizing of the sediment by erosion and redeposition within what was then an ephemeral wetland. Dried samples were

analyzed for weight percentages of total carbon (TC) and inorganic carbon (IC) by coulometric titration of carbon-dioxide following extraction from the sediment by combustion at 950°C and acid volatilization, respectively (Engleman et al. 1985). Percent total organic carbon (TOC) was calculated as the difference (TC–IC), and percent CaCO<sub>3</sub> was calculated as

$$\text{CaCO}_3 = \text{IC}/0.12 \quad (1)$$

where 0.12 is the fraction of carbon in CaCO<sub>3</sub>. The accuracy and precision of this method, determined from hundreds of replicate standards, usually are better than 0.10 wt % for both TC and IC.

Samples were analyzed for 40 major, minor, and trace elements by inductively coupled, argon-plasma, atomic emission spectrometry (ICP-AES) by SGS Laboratories, Toronto, Canada. Rock standards (USGS) were included with the sediment samples, and 10% of the samples were duplicated. The precision, determined by analyzing rock standards and duplicate sediment samples, is better than 10%, and usually is better than 5%, at a concentration of ten times the limit of detection. Only results for phosphorus (P), manganese (Mn), molybdenum (Mo), and nickel (Ni) will be discussed here.

## Results

### Lithology and dating

The lithologies of the WE-1 and WE-3 cores contain three stratigraphic units (from bottom to top): diamicton (Unit A); fossiliferous silty clay (Unit B); and massive sandy clay lacking plant and fish fossils (Unit C) (Fig. 3A, B). Unit A, a very dark gray (Munsell™ 5Y 3/1) diamicton composed of sandy clay with pebbles and gravel, is essentially barren of fossils.

The contact between units A and B in the WE-1 core (Fig. 3B) is delineated by two closely spaced *Picea glauca* (white spruce)-needle litter layers (identified to species based on needle stomata and seed wings), which provide <sup>14</sup>C ages of 11,550 ± 90 yr BP and 11,550 ± 65 yr BP (Table 1). This litter layer is absent in the “offshore”

**Table 1** Results of radiocarbon age determinations with reference to stratigraphic depth, lab sample number ( $^{14}\text{C}$  laboratory and #), AMS  $^{14}\text{C}$  age (with one standard deviation and corrected for  $\sigma^{13}\text{C}$  fractionation), calendar age (using the INTCAL98 calibration curve of Stuiver et al. (1998)), and the materials dated. Seeds used to obtain some of these ages are of terrestrial plants, not those of aquatics

Core	Depth (cm) below surface	Lab number	AMS age ( $^{14}\text{C}$ yr BP)	Calibrated age (cal yr BP) $2\sigma$ range (50% mean probability)	Materials dated (# of Seeds)	Comments
WE-1	388.5–391	AA34340 <sup>a</sup>	11,550 ± 90	13,938–13,205 (13,570)	<i>Picea glauca</i> needles	Litter layer
WE-1	366–368.5	AA34339 <sup>a</sup>	11,550 ± 65	13,903–13,215 (13,560)	<i>Picea</i> wood & <i>Picea glauca</i> needles	Litter layer
WE-1	295–300	CAMS114471 <sup>b</sup>	9,410 ± 40	10,794–10,553 (10,670)	Seeds: <i>Typha</i> (9); <i>Scirpus nevadensis</i> (1); <i>Scirpus validus</i> (12); <i>Lycopus americanus</i> (2); <i>Chenopodium rubrum</i> (11); <i>Chenopodium</i> cf. <i>C. berlandieri</i> (2); <i>Rubus idaeus</i> (1)	First appearance of <i>Ruppia</i> (aquatic plant)
WE-1	235–250	CAMS114470 <sup>b</sup>	7,465 ± 45 <sup>c</sup>	8,414–8,231 (8,320) <sup>c</sup>	Terrestrial plant rootlets & seeds: <i>Scirpus validus</i> (1); <i>Typha</i> (2)	Truncation of fossil record
WE-3	576.5–579	AA34342 <sup>a</sup>	11,110 ± 410	14,148–11,787 (12,970)	Seeds: <i>Potentilla</i> (3); <i>Mentha arvensis</i> (1); <i>Chenopodium rubrum</i> (6); <i>Carex</i> cf. <i>C. C. sychnocephala</i> (4); <i>Scirpus validus</i> (2); <i>Lycopus americanus</i> (2)	Lack of dateable materials beneath
WE-3	515.5–518	AA46442 <sup>a</sup>	11,090 ± 210	13,542–12,842 (13,190)	Seeds: <i>Scirpus validus</i> (1); <i>Lycopus americanus</i> (6); <i>Typha</i> (10)	Onset of lake shallowing
WE-3	470–472.5	AA34341 <sup>a</sup>	9,920 ± 110	11,815–11,171 (11,490)	Seeds: <i>Typha</i> (23); <i>Scirpus nevadensis</i> (2); <i>Lycopus americanus</i> (4); <i>Rumex maritimus</i> (3)	Spruce decline
WE-3	401–408.5	CAMS114472 <sup>b</sup>	6,485 ± 50 <sup>c</sup>	7,529–7,337 (7,430) <sup>c</sup>	Terrestrial plant rootlets	Truncation of fossil record

<sup>a</sup> AA—University of Arizona AMS  $^{14}\text{C}$  Laboratory/NSF Facility

<sup>b</sup> CAMS—Center for Acceleratory Mass Spectrometry, Lawrence Livermore National Laboratory

<sup>c</sup> These dates are rejected as being too young, because they were obtained mainly or exclusively from terrestrial plant rootlets (see Results section for discussion)

WE-3 core where the contact between units A and B is gradational (Fig. 3A), and dateable terrestrial organics are absent (Fig. 4). Hence, we assign the age of 11,500 <sup>14</sup>C yr BP from the WE-1 core (Fig. 3B) to the base of the plant macrofossil and pollen records (Figs. 4 and 5) of the WE-3 core (Fig. 3A). Seeds from the WE-3 core provide an age of 11,100 ± 410 <sup>14</sup>C yr BP (Table 1) for the top of a laminated section in Unit B (Fig. 3A). Radiocarbon ages for levels upcore are shown in Table 1 and are displayed in Fig. 3A.

Unit B in the WE-3 core is divided into three subunits based on lithologies and fossils. The basal Unit B1 is comprised of massive, olive gray (Munsell™ 5Y 4/2) silty clay containing few macrofossils, which may have been redeposited (Fig. 4). The pollen record (Fig. 5) begins abruptly in the upper part of this unit with exceedingly rare and degraded grains at depths below. Fossil abundance and species diversity are greatest from the sediments of the subunits B2

(laminated sediment, 5Y 4/2 and 3/2) and B3 (massive sediment, 5Y 3/2), as evident by the macrofossil and pollen assemblages and abundant bones of *Perca flavescens* (Figs. 4 and 5).

The contact between units B (top of B3) and C is delineated by a paleosol (Fig. 3). In the WE-3 core, this buried soil is 5-cm thick, includes a root cast, and occurs at a depth of 405–400 cm. This paleosol is thinner in the WE-1 core and is found at a depth of 215 cm. The overlying massive sediment of Unit C (5Y 3/2) contains no preserved plant or fish fossils, but gastropod shells and oogonia of *Chara* L. (stonewort, a green alga) are found at certain levels.

Above the depth of 470 cm (<9,920 <sup>14</sup>C yr BP) in the WE-3 core, no seeds, wood or charcoal were recovered. So terrestrial plant rootlets were dated from the paleosol (Table 1; Fig. 3A), providing an age of 6,485 ± 50 <sup>14</sup>C yr BP, which we suspect to be too young based on several reasons. First, rootlets can penetrate to some depth, providing

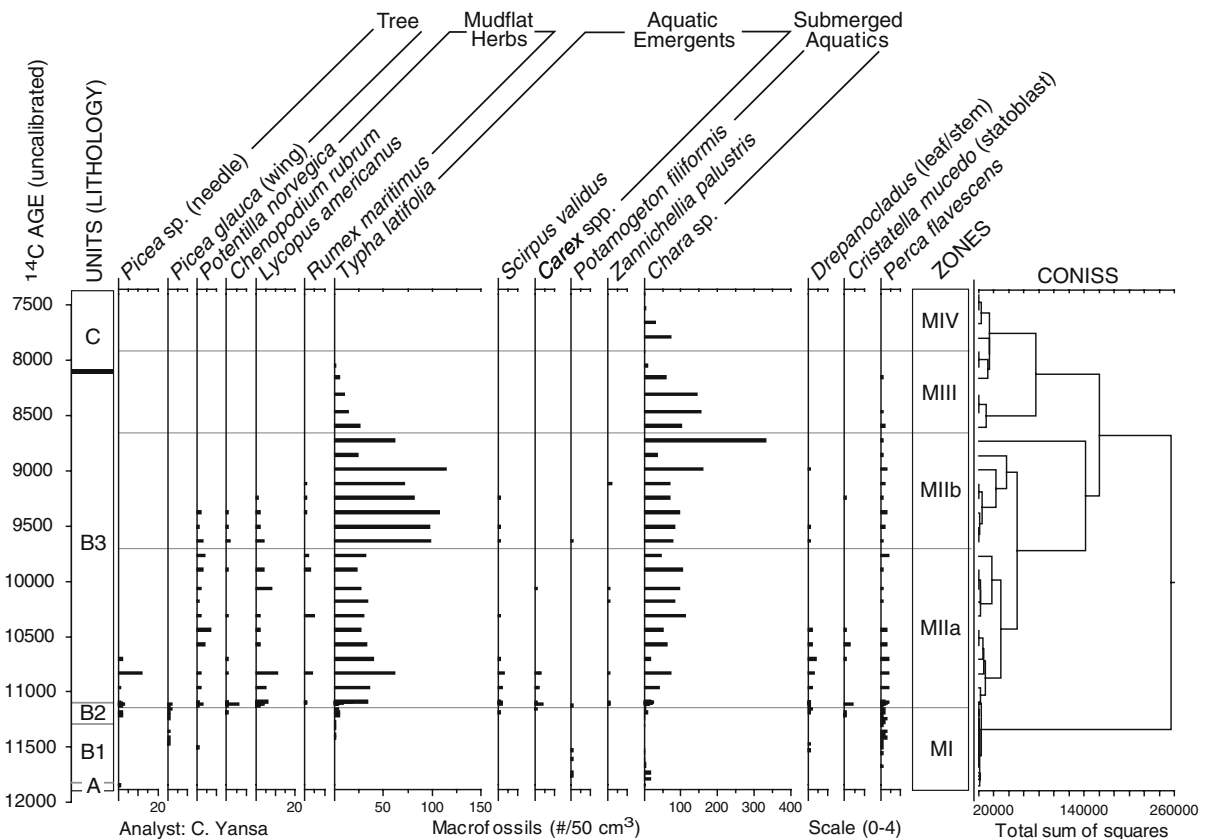
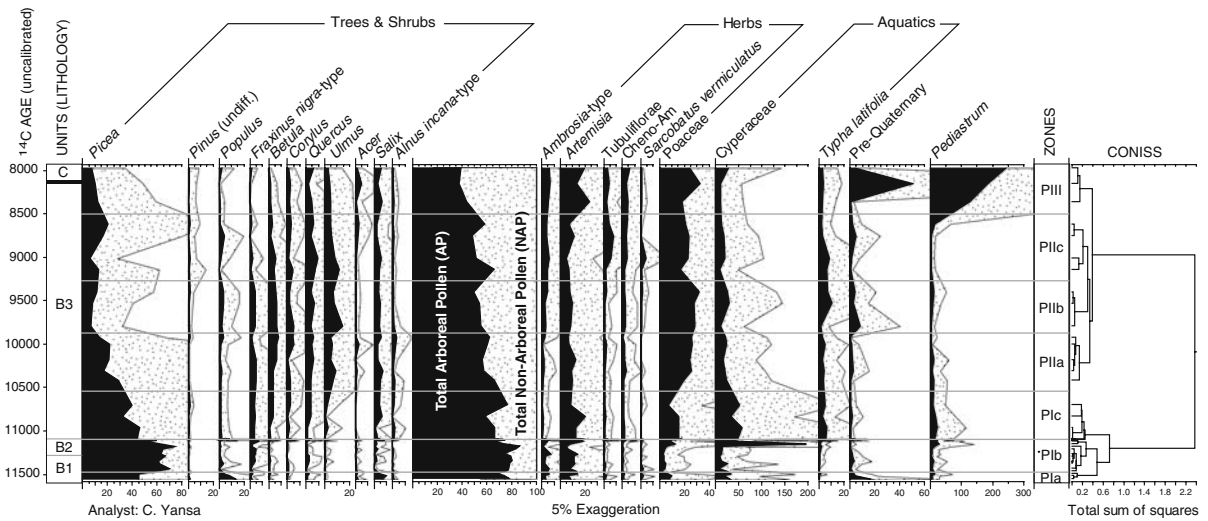


Fig. 4 Plant macrofossil abundance diagram for the WE-3 core





**Fig. 5** Pollen percentage diagram for the WE-3 core

younger ages. Second, it seems unlikely that deposition of about 70 cm of sediment took as long as 3435  $^{14}\text{C}$  years, given the sedimentation rates of nearby lakes and ponds (e.g. Laird et al. 1998). And, finally, correlation of the pollen record from the WE-3 core to those of other lakes in the region indicate that truncation of the fossil record of the Wendel site occurred before 8,000  $^{14}\text{C}$  yr B.P. (e.g. Laird et al. 1996, 1998; Grimm 2001). Thus, for the WE-3 core we excluded the age of  $6,485 \pm 50$   $^{14}\text{C}$  yr BP from our linear interpolation between dates and thus estimate the age of the paleosol at about 8,100  $^{14}\text{C}$  yr BP (Fig. 3A). The youngest age we obtained for the “nearshore” WE-1 core,  $7,465 \pm 45$   $^{14}\text{C}$  yr BP, is for a depth of 20 cm below the paleosol (Table 1, Fig. 3B). This date was obtained from mainly terrestrial plant rootlets with a few *Typha* L. and *Scirpus* L. seeds and thus is probably younger than its true age for this depth.

### Fossils

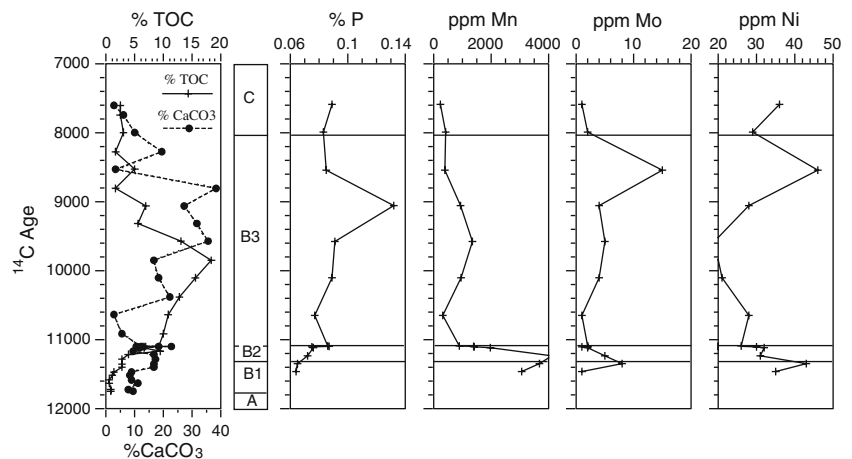
The first vegetation recorded at the Wendel site is indicated by the plant macrofossils (Zone MI in Fig. 4), pollen (zones PIa and PIb in Fig. 5), and stomata of the upper part of subunit B1, which dates from c. 11,500 to 11,100  $^{14}\text{C}$  yr BP. These data indicate that *Picea glauca* (white spruce) and herbs were the major constituents of the vegeta-

tion, whereas deciduous trees (some pollen tentatively identified as *Populus tremuloides*) were minor elements. The macrofossil flora also indicates an abundance of wetland plants (Fig. 4). Bones (ribs, vertebrae, otoliths, etc.) of *Perca flavescens* (yellow perch) are also common (Fig. 4), as well as those of unidentified minnows, indicating early colonization of the Wendel paleolake by fish (M. Newbrey pers. commun.). Stratigraphic provenance of the sole specimen of *Esox lucius* (northern pike) collected over 30 years ago is uncertain, but it was buried under several meters of sediment near the WE-1 coring location (A. Ashworth pers. commun.). Therefore, we can assume that it was coeval with its prey, yellow perch.

The vegetation and limnology underwent a transition from c. 11,100 and 10,500  $^{14}\text{C}$  yr BP, driven by warming temperatures and lowering of the local water table. As indicated by Fig. 4 (lower part of Zone MIIa) and Fig. 5 (Zone PIIc), deciduous trees became more common and local abundance of spruce began to decline. There was a dramatic increase in the coverage of aquatic and emergent herbs. Yellow perch still inhabited the lake at this time.

A parkland of deciduous trees and herbs occupied the area from about 10,500 to 9,300  $^{14}\text{C}$  yr BP, as indicated by the pollen zones PIIa and PIIb (Fig. 5) and from plant macrofossils (the

**Fig. 6** Geochemical, organic carbon and nutrient data obtained from the WE-3 core. Plots show the percentages of Total Organic Carbon (%TOC) and phosphorus (P) as well as the amounts (expressed as ppm) of manganese (Mn), molybdenum (Mo) and nickel (Ni)



upper part of Zone MIIa and lower part of Zone MIIb in Fig. 4). The drying trend continued during this phase, as indicated by an increase in species diversity and coverage of herbs that occupy shallow-water, shoreline, and upland habitats. The fish populations were probably disseminated during this phase.

With the disappearance of deciduous trees in the area around 9,300  $^{14}\text{C}$  yr BP, grassland became the exclusive vegetation cover, as indicated by Zone PIIC (Fig. 5). The Wendel basin in the coring locations contained shallow water, first as an extensive prairie marsh (9,300–8,700  $^{14}\text{C}$  yr BP; Zone MIIb in Fig. 4) and subsequently as a seasonal (ephemeral) wetland (zones MIII and MIV in Fig. 4). A soil formed by about 8,100  $^{14}\text{C}$  yr BP (Figs. 3–5), truncating the fossil record.

### Geochemistry

Initially, the waters of the Wendel paleolake waters were well oxidized, as indicated by high concentrations of Mn in Unit B1, most likely as manganese oxyhydroxides, and high concentrations of adsorbed Mo and Ni (Fig. 6). Nutrient levels were low (low concentrations of P) so productivity was low (low concentrations of TOC; Fig. 6). By about 11,250  $^{14}\text{C}$  yr BP, the time that laminated sediments of Unit B2 were deposited, nutrients had increased, stimulating higher productivity in the lake and increased burial of TOC. Lakes in the eastern Dakotas have high concentrations of dissolved sulfate (Gorham et al. 1983), so sulfate reduction caused the sediments and

possibly the bottom waters in the Wendel site basin to become anoxic. Such an event is indicated by the abrupt decrease in Mn in the laminated sediments of Unit B2 (Fig. 6) as manganese oxyhydroxides were reduced, releasing adsorbed Mo and Ni. This change in dissolved oxygen levels occurred during the spruce parkland phase. Lake productivity was still fairly high during the transition from spruce to deciduous parkland vegetation (lower part of Unit B3; Fig. 6), but subsequently declined, as indicated by a marked decrease in TOC. In contrast, the influx of nutrients (P) continued to increase during the deciduous parkland phase, probably because of upslope soil erosion. These nutrients were utilized by increasing populations of aquatic emergents (Fig. 4). The abundance of *Chara* also increased, which increased the amount of  $\text{CaCO}_3$  in the sediments, peaking at about 8,700  $^{14}\text{C}$  yr BP (Fig. 6). There may have been a period of anoxia at about 8,500  $^{14}\text{C}$  yr BP, as indicated by high concentrations of Mo and Ni, followed by decreasing concentrations of these elements (Fig. 6). The continued low concentrations of Mn indicate that Mo and Ni were being precipitated as sulfides and were not adsorbed on manganese oxyhydroxides as they were in sediments deposited prior to 11,250  $^{14}\text{C}$  yr BP.

### Discussion

The Wendel site record offers new insights into distinguishing between local hydrological influences on lakes compared to those caused by

**Table 2** The timing and duration of vegetation and hydrologic changes at the Wendel site compared to those of other fossil localities in the region

Earliest date ( <sup>14</sup> C yr BP) or duration for	Wendel site, ND (46°25' N, 98°20' W)	Moon L., ND (46°51' N, 98°09' W)	Coldwater L., ND (46°01' N, 99°05' W)	Cottonwood L., SD (44°50' N, 99°54' W)	Pickrel L., SD (45°30' N, 97°19' W)	Medicine L., SD (44°49' N, 97°21' W)
Spruce vegetation & high-lake level	11,500–10,500	11,800–10,300	10,800–10,600	c. 12,300–c. 11,200 <sup>b</sup>	11,200 – 10,670	10,940 – 10,000 <sup>a</sup>
Deciduous parkland	10,500–9,300	10,300–9,500	10,300–9,500	c. 11,200 –c. 10,800 <sup>b</sup>	10,670 – 9,400 <sup>a</sup>	10,000 – 9,260 <sup>a</sup>
Closing of basin (increase in lake salinity)	11,000–9,300 (no salinity increase)	9,500–9,000	9,500–8,900	N/A	9,300 – 8,900	c. 9,000 <sup>a</sup>
Grassland (widespread)	9,300	9,500	c. 9,500	c. 10,800 <sup>b</sup>	9,400 <sup>a</sup>	c. 9,260 <sup>a</sup>
<i>Ambrosia</i> peak (prehistoric)	—	8,000	8,100	c. 9,500 <sup>b</sup>	8,200	c. 8,800 <sup>ab</sup>
Peak lake salinity (geochemistry)	—	8,100–7,300	c. 6,200	N/A	c. 8,100	<c. 8,200 <sup>a</sup>
Reference(s)	This paper	Laird et al. (1996, 1998)	Xia et al. (1997); Yansa (2002)	Barnosky et al. (1987); Grimm's data from the NAPD	Watts and Bright (1968); Dean and Schwalb (2000)	Radle et al. (1989)

<sup>a</sup> Date from organic sediment "corrected" for the hardwater effect by use of a correction factor (e.g. obtain a <sup>14</sup>C date for the sediment associated with the European *Ambrosia* rise (1870 in this area) and subtract this difference in years for the sediment dates downcore)

<sup>b</sup> We interpret the <sup>14</sup>C age by extrapolating between dates posted on a pollen diagram, which is available from a published paper or on the NAPD website

—, no evidence at site

N/A, no data available

NAPD, North American Pollen Database (<http://www.ncdc.noaa.gov/paleo/napd.html>)

regional atmospheric processes, because this record is the first for the extensive Glaciated Till Plain. Previously, our understanding of the regional paleoclimate was derived from the proxy records from lakes in other hydrologic settings (Table 2). These settings included: kettle lakes and ponds situated in the hummocky moraine uplands of the Missouri Coteau (Coldwater, Kettle, Rice, and Cottonwood Lakes and Seibold Pond) and the Prairie Coteau (Pickerel and Medicine Lakes); an isolated kettle lake in an outwash channel (Moon Lake); and a remnant of a glacial lake (Devils Lake). Timing of terrestrial and lacustrine events at the Wendel site is comparable to those of other lakes in the region, as shown in Table 2.

Spruce parkland and paleolake (>11,500–10,500  $^{14}\text{C}$  yr BP)

The Wendel site probably does not record the earliest stages of primary plant succession and lake development, because of initial landscape instability associated with deglaciation. Well-log data in the Wendel site area indicate that underneath the Twin Lakes Channel lies a larger tunnel valley, which extends to a depth of at least 250 m. Bluemle (1979) proposed, after mapping the study area, that this valley was ridden over and partially filled with ice and debris when the James Lobe of the Laurentide glacier briefly readvanced to the southwest during the latter part of local deglaciation. The surface expression of this partly-filled tunnel valley (see Patterson 1998) is the Twin Lakes Channel. With subsequent ice retreat, the surface in the vicinity of the WE-3 coring location was eroded by glacial meltwater prior to the formation of a paleolake in the Twin Lakes channel. In some places, such as where the WE-1 core was collected, small kettles and other ice-disintegration features are visible (Bluemle 1979). Thus, the water source for this paleolake was probably initially derived from the surficial accumulation of meltwater and later supplemented by the slow melting of buried ice protected from insolation by thick supraglacial debris.

We interpret that the white spruce trees and the other plants were rooted in till overlying blocks of stagnant ice within the Twin Lakes

channel and that the melting of this ice provided a reliable moisture source to the local vegetation for several centuries. Detritus of these plants were probably redeposited locally into the Wendel paleolake, as indicated by white spruce litter at the base of the WE-1 core. This interpretation has been previously used to explain the existence of “trash layers” of spruce macrofossils at the bottoms of kettle lakes in the region (e.g. Wright 1976; Dean and Schwalb 2000; Grimm 2001). Pollen grains at the Wendel site were thus deposited by airborne accumulation and slope-wash during this phase, and so the high *Picea* values of 41–74% for zones PIa and PIb (Fig. 5) should not directly compared to modern pollen rain data. Consequently, based on these data we interpret that the late-glacial vegetation was more open, that of a spruce parkland instead of a forest, which is described further in Yansa (2006).

The *Picea glauca* trees at the Wendel site, and presumably those of upland lakes within the region, were probably restricted to where soils were consistently moist, such as along lakeshores, whereas the drier soils upslope were covered by prairie/steppe vegetation. Species of Cyperaceae (sedge family), mudflat herbs (e.g. *Mentha arvensis* L. (field mint)), and *Salix* L. (willow) were also important constituents of the flora, particularly in local wetlands. The suite of shallow-water aquatics was limited to *Chara* (stonewort) and two species of *Potamogeton* L. (pondweed).

Other pollen studies of lakes on the northern Great Plains likewise report pioneering spruce vegetation associated with a high regional water table at approximately the same time as at the Wendel site, 11,500 to 10,500  $^{14}\text{C}$  yr BP (see Table 2). A high water table across the region was probably derived from the melting of glacial ice, because paleoclimate models simulate a low precipitation regime during the late-glacial (e.g. Bartlein et al. 1998). These models also propose that winters were cooler than modern, and summers were relatively mild for the time, though still a few degrees cooler than today.

The water of the Wendel paleolake was fresh during the spruce phase, as it was at other lake sites throughout the northeastern Great Plains (Table 2). The productivity of the Wendel paleolake increased through time because of 1) soil

erosion, which flushed nutrients into the water body, and 2) gradual warming and lengthening of the growing season. These events are suggested by abrupt increases in TOC and P in the sediments of Unit B2 (Fig. 5). The lake waters were initially well oxidized, as suggested by high concentrations of Mn in Unit B1, with high concentrations of adsorbed Mo and Ni. The abrupt decrease in Mn in the overlying laminated sediments of Unit B2 (Fig. 6), indicates anoxic conditions in the sediments and possibly in the water column.

This increased lake productivity supported fish populations in the Wendel paleolake. Initial waterway interconnections between the Wendel site basin and other waterbodies explain how minnows (unidentified), *Perca flavescens* (Fig. 4) and *Esox lucius* entered the basin before the water-table dropped, trapping them in a closed paleolake within the Twin Lakes channel (Fig. 2). A similar explanation was used to explain the presence of early Holocene fish fossils recovered from Seibold Pond (Fig. 1), a kettle pond located on the Missouri Coteau in central North Dakota (Newbrey and Ashworth 2004).

At the Wendel site, a transitional phase in vegetation and limnology was identified from c. 11,100 to 10,500  $^{14}\text{C}$  yr BP. Warmer summers explain the declining pollen values for spruce and corresponding greater abundance of those of deciduous trees and herbaceous plants (Zone PIc in Fig. 5). The residual meltwater source derived from the slow melting of stagnant ice was probably diminished at the Wendel site by 11,100  $^{14}\text{C}$  yr BP, based on several indicators of lake shallowing. For example, there is a pronounced pollen spike of Cyperaceae (top of Zone WE-3 PIb in Fig. 5), associated with macrofossils of this family, *Carex* cf. *C. sychnocephala* Carey. (long-beaked sedge) and *Scirpus validus* Vahl. (common bulrush) (MIIa in Fig. 4), which indicate the expansion of shallow-water areas along the lake shore. Also occupying this habitat were the aquatic-emergent *Typha latifolia* (common cattail) and the fen-type moss *Drepanocladus*. Strobilasts of *Cristatella mucedo* are restricted to Zone MIIa (Fig. 4), and indicate that colonies of this freshwater bryozoan were attached to the submerged stems of emergent plants. Submerged

aquatics, such as *Potamogeton filiformis* Pers. (slender-leafed pondweed), *P. vaginatus* Turcz. (sheathed pondweed, not shown in Fig. 4), and *Zannichellia palustris* L. (horned pondweed) occupied the shallow water along the lakeshore. Bones of *Perca flavescens* from Zone MIIa (Fig. 4) are as common as before and indicate continued fish mortality.

The upcore abundance increase in macrofossils of damp-ground herbs (Fig. 4) indicates the areal expansion of a mudflat along the shore with declining lake levels. This shallowing also resulted in the spreading out of *Chara* beds, leading to the formation of a marl layer closer to shore (evident in WE-1 core, Fig. 3B), and the incorporation of  $\text{CaCO}_3$  from *Chara* in the offshore sediments (WE-3 core, Fig. 6). Increasing concentrations of TOC and P in the sediments (Fig. 6) also suggest that the productivity of the lake remained high.

#### Holocene deciduous parkland and lake shallowing (c. 10,500–9,300 $^{14}\text{C}$ yr BP)

The fossils (plant and fish), sediments (TOC and P), and stratigraphy of the Wendel site indicate that this trend of warming temperatures and increasing lake productivity continued into the early Holocene. Local populations of white spruce trees were extirpated at about 9,900  $^{14}\text{C}$  yr BP (boundary between zones PIIa and PIIb in Fig. 5), whereas *Populus* (poplar) and other deciduous trees that arrived earlier became more abundant in the local area. Most significant are the pollen spikes of *Ulmus* and *Betula* (Zone PIIb in Fig. 5), which along with moderate values for the shrubs *Salix* and *Corylus* (hazelnut), are good indicators of high soil moisture, at least locally. Grasses (members of Poaceae) and herbs, such as *Artemisia* L. and *Ambrosia* L.-type, became more numerous and widespread, indicating the expansion of dry upland habitats within the Glaciated Till Plain.

The shift from spruce parkland to deciduous parkland at the Wendel site (at 10,500  $^{14}\text{C}$  yr BP) is coeval to those reported for nearby upland sites in North Dakota (Table 2). This vegetation change has been attributed to the transition from cool late-glacial to warmer post-glacial climates (see Grimm and Jacobson 2004; Webb et al.

2004). The precipitation regime was probably still low (e.g. Bartlein et al. 1998) and the hardwoods were most likely restricted to the lakeshore with prairie on the uplands, as before.

Lowering of the regional water table during the deciduous parkland phase is reported for the Wendel site and multiple other localities in the northern Great Plains (Table 2). At the Wendel site, the abundant mudflat herbs contributed to the declining water table (Fig. 4). These herbs are today called “draw-down weeds” for their ability to significantly lower local water tables in the prairie marshes of North Dakota (Kantrud et al. 1989). Numerous seeds and pollen of *Typha latifolia* L. (broad-leaved cat-tail) (zones MIIa and MIIb in Fig. 4) indicate that the water depth in the coring location was probably about 0.5 m, considering that this is the optimal depth for peak seed production of this species (Kantrud et al. 1989). The bay of the Wendel paleolake, thus, was becoming a shallow prairie marsh. These and other aquatic-emergent and aquatic plants contributed to the greater precipitation of  $\text{CaCO}_3$  in the sediments (Fig. 6). This process presumably occurred both by plant transpiration, which increased the concentration of  $\text{CaCO}_3$  in the lake, and by photosynthesis, which reduced dissolved  $\text{CO}_2$  concentrations, thereby increasing the pH and hence causing calcite precipitation (McConnaughey et al. 1994). Evapotranspiration rates must have been extremely high, considering that the early and mid-Holocene summers were warmer than those of historic times (where evapotranspiration exceeds precipitation) (e.g. Barnosky et al. 1987; Bartlein et al. 1998).

The fish population in the Wendel paleolake was probably decimated during this phase, because the bones in overlying sediments (Zone MIII in Fig. 4) show signs of taphonomy. The fish die-off was most likely in the form of winter kills, resulting from low dissolved oxygen levels under the ice in what was then a shallow lake. Winter fish kills commonly occur today in shallow lakes and ponds in North Dakota and adjacent areas (Tonn and Magnuson 1982). Lake productivity also declined as indicated by a marked decrease in TOC, although influx of nutrients (P) continued to increase upcore probably because of upslope soil erosion (Fig. 6).

Grassland and development of an ephemeral wetland (c. 9,300–8,100  $^{14}\text{C}$  yr BP)

Shortly after 9,300  $^{14}\text{C}$  yr BP, the deciduous trees in the vicinity of the Wendel site disappeared, because of the continued aridity (upper part of Zone PIIc in Fig. 5). These trees were replaced by prairie herbs and possibly some shrubs. The transition from deciduous parkland to grassland at the Wendel site occurred at about the same time as at other lakes in the region (Table 2).

By this time, the Wendel site was a prairie marsh and with continued lowering of the local water table it became an ephemeral wetland at about 8,500  $^{14}\text{C}$  yr BP. Despite the draw down of the lake there is a surprising lack of salinity indicators in the geochemical and plant macrofossil records of the Wendel site (Figs. 4, 6). In contrast, the paleolimnology of kettle lakes on the coteaus documents the onset of saline and hypersaline conditions at about this time (Table 2). The exception is Pickerel Lake, South Dakota, which has a geochemistry that indicates that it received reliable ground water inflow to counteract its evaporative losses under a warm and dry climatic regime (Schwalb and Dean 1998). Similarly, we interpret the Wendel site as receiving ground-water discharge, which mediated the signal of atmospheric (precipitation) input to this basin.

There is some evidence for fluctuating water levels during the transition from prairie marsh to ephemeral wetland at the Wendel site. Shallow, eutrophic and calcareous water conditions prevailed at c. 8,800–8,700  $^{14}\text{C}$  yr BP, as indicated by a peak of *Chara* oogonia (Fig. 4), which correlates with a maximum concentration of  $\text{CaCO}_3$  in the sediments (Fig. 6). This input of carbonate probably diluted the TOC contents of the sediments.

Geochemical data suggest that there may have been a period of anoxia at c. 8,600  $^{14}\text{C}$  yr BP, as indicated by high concentrations of Mo and Ni, followed by decreasing concentrations of these elements (upper part of Unit B3 in Fig. 6). The continued low concentrations of Mn indicate that Mo and Ni were not adsorbed on manganese oxyhydroxides as they were in sediments deposited prior to 11,000  $^{14}\text{C}$  yr BP. Another line of

evidence to suggest that local soils were moist at about 8,600  $^{14}\text{C}$  yr BP is a decrease in P levels in the uppermost sediments (Fig. 6), which suggests a decrease in soil erosion.

This interpretation is further supported by the pollen data, particularly by a peak of *Artemisia* (sage) pollen, which dates between 8,500 and 8,100  $^{14}\text{C}$  yr BP (Fig. 5). Greater abundance of this deep-rooted plant indicates sufficient winter precipitation in the region (Grimm 2001) and, according to Winter and Rosenberry (1995), lake levels in North Dakota are controlled by the amount of snowmelt rather than rainfall. The existence of moist soils in the Wendel basin until about 8,100  $^{14}\text{C}$  yr BP is also indicated by the high pollen values for Poaceae (grass family), considering that the exine (pollen wall) of grass are known to deteriorate readily when soils are oxidized (Hall 1981). High values for *Pediastrum* (an alga) also support our interpretation for moist soils and stagnant pools of water in the drying lake bed. Water probably persisted longer in the lowest elevation areas within the Twin Lakes channel than at our coring sites.

There are also several indicators for the erosion, redeposition and periodic oxidation of sediments in the area where the WE-3 core was collected, starting at about 8,500  $^{14}\text{C}$  yr BP. By this time, sediment filled in about half of the Wendel basin, reducing its water-holding capacity. Macrofossil abundance and species diversity declined dramatically at this time (Zone MIII in Fig. 4). A spike of pre-Quaternary palynomorphs in Zone PIII (Fig. 5) indicates that the till underlying the upland soil was exposed and particles of which (containing the Cretaceous-age microfossils) were redeposited in the Wendel basin along with some older pollen grains (especially those of *Picea*). Some of the grains in this uppermost zone are deteriorated, which occurs when sediments undergo repeated drying/wetting cycles (Hall 1981).

A root cast associated with a paleosol indicates that a shrub invaded the vicinity of the WE-3 coring location to tap into the lowering water table at c. 8,100  $^{14}\text{C}$  yr BP. The fossil record at the Wendel site is truncated by this paleosol and the only plant fossils preserved in the overlying Unit C sediments are a few oogonia of *Chara* (Zone MIV in Fig. 4), and occasional gastropod shells.

The estimated age of c. 8,100  $^{14}\text{C}$  yr BP for the paleosol is further substantiated by the regional pollen spectra. A peak of *Ambrosia*-type (ragweed) pollen at about 9,000–8,000  $^{14}\text{C}$  yr BP (Table 2) characterizes the pollen records of Kettle, Rice, Moon, and Coldwater Lakes (Fig. 1; Laird et al. 1996, 1998; Grimm 2001; Yansa 2002; Clark et al. 2002). In contrast, the Wendel site pollen record lacks this ragweed peak (Table 2), which suggests that this record was truncated before this drought-adapted herb became widespread.

The complete Holocene records of the deeper kettle lakes in the Missouri and Prairie Coteau uplands report low and fluctuating lake levels beginning at about 9,000–8,000  $^{14}\text{C}$  yr BP, with salinity maxima occurring somewhat later. This aridity ensured that fossil preservation ceased for the later part of the Holocene at the Wendel site. After 8,100  $^{14}\text{C}$  yr BP, however, the local water table at the Wendel site must have been sufficiently high to have preserved the fossils of Unit B in saturated sediments. Again, this suggests at least some ground-water discharge into the Wendel basin, although we recognize that precipitation undoubtedly occurred.

## Summary and conclusions

Our ability to distinguish between local hydrologic and regional atmospheric influences on lakes relies upon comparison of our dataset from the Glaciated Till Plain with those of upland kettle lakes in the region. In particular, similarities in the sequence and timing of terrestrial and lacustrine changes shared between the Wendel site record and those of other (kettle) sites in the region provide a climate (temperature and precipitation) signal, whereas differences indicate the relative influences of local ground-water hydrology (Table 2, Fig. 1). These changes at the Wendel site were reconstructed by the study of fossils (pollen, plant macrofossils, stomata and fish) and sediments (lithostratigraphy and geochemistry) from two sediment cores collected from this site in southeastern North Dakota.

The environmental changes we reconstructed for the Wendel site include: 1) establishment of a

paleolake within a palimpsest meltwater channel at c. 11,500  $^{14}\text{C}$  yr BP, which was colonized by fish and had a shoreline that was inhabited by a white spruce parkland vegetation; 2) lake level lowering, beginning at c. 11,100  $^{14}\text{C}$  yr BP, associated with the replacement of spruce by deciduous trees along the lake shore, expansion of prairie herbs, and fish kills; 3) transition to an exclusive grassland vegetation occurred at c. 9,300  $^{14}\text{C}$  yr BP, which was coeval with continued lake shallowing, forming a prairie marsh and eventually an ephemeral wetland; and 4) formation of a paleosol at about 8,100  $^{14}\text{C}$  yr BP. Many of the upland kettle records are not truncated, as is the Wendel site record, but they too report the onset of peak aridity at this time (Laird et al. 1996; Last et al. 1998; Dean and Schwab 2000).

Differences in the proxy data from the Wendel site, compared to those from most of the kettle lakes of nearby uplands (Table 2), provide a local ground-water signal, which is not often recognized by researchers who reconstruct paleoclimate records. We hypothesize that a “residual meltwater effect” from the slow melting of buried ice blocks contributed to the initial high lake stands in the region. For some time it provided a source of water in addition to the melting of surficial ice and precipitation for the Wendel paleolake and presumably other lakes. The results of this study provide, for the first time, a minimal age range for this subsurface source of ground water on the Glaciated Till Plain. Rapid shallowing of the Wendel paleolake was first evident at about 11,100  $^{14}\text{C}$  yr BP by a remarkably high spike (190%) of Cyperaceae pollen, which may signal termination of meltwater contribution to this lake in the subsurface. Deglaciation of the study area is not dated, but we estimate from Clayton and Moran’s (1982) ice margin chronology and the establishment of vegetation at nearby Moon Lake (Table 2; Laird et al. 1996, 1998) that the Wendel site was deglaciated at about 12,000  $^{14}\text{C}$  yr BP. Thus, it took approximately 900 years for buried stagnant ice to melt at the Wendel site, which is roughly comparable to a previous estimate of 1000–3000 years for the melting of supraglacial ice on the Missouri Coteau by Clayton (1967).

Furthermore, to have preserved fossils (dated from 11,500 to 8,100  $^{14}\text{C}$  yr BP) at the Wendel site through subsequent dry spells, we reason that this site must have received some ground-water discharge from the recharging uplands (Missouri and Prairie Coteaus). Our interpretation is based on earlier work in North Dakota by Smith et al. (1997) and Almendinger et al. (1999), who suggest that severe mid-Holocene droughts caused the ground-water capture areas to change. Specifically, they proposed that lower-elevation lakes began to access catchment waters of up-gradient lakes (causing those lakes to go dry) and so were able to maintain their water levels.

Our paleoenvironmental data for the Wendel site are most similar to those obtained for Pickerel Lake, South Dakota, by Dean and Schwab (2000). Their geochemical and ostracode study provided an invariant paleoclimate signal, compared to other upland kettle lakes in the area, which Dean and Schwab (2000) attributed to the influence of more-or-less continual ground-water seepage into this lake. We propose that ground-water discharge into the Wendel basin also occurred, because of (1) the lack of salinity indicators in the geochemistry and fossil assemblages of the early Holocene and (2) preservation of fossils below the local water table.

In summary, the fossil and geochemical records of the Wendel site provide valuable information about late-glacial and early postglacial terrestrial and lacustrine environmental changes for the Glaciated Till Plain, a large (>60,000 km<sup>2</sup>) area of the northern Great Plains which up until now lacked a detailed multi-proxy study. Furthermore, we were able, in part, to distinguish local hydrologic influences from atmospheric influences (precipitation) on the terrestrial and aquatic environments of the Wendel basin. The results of this investigation emphasize the importance of considering the relative influence of local ground-water hydrology upon lakes in glaciated landscapes when detecting paleoclimate signals from proxy data.

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