Climatic effects of glacial Lake Agassiz in the midwestern United States during the last deglaciation

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ABSTRACT

Stable isotope and pollen analyses of a sediment core from Deep Lake, Minnesota, provide new information on the climatic effects of glacial Lake Agassiz in Minnesota and insights into the cause of the prominent *Picea* recurrence during the Younger Dryas in the southern Great Lakes region. Bulk-carbonate $\delta^{18}O$ exhibited large fluctuations between 12.0 and 9.1 ka (dates are in calendar years throughout this paper unless indicated otherwise), probably reflecting the effects of glacial Lake Agassiz superimposed on climatic warming related to large-scale climatic controls. In particular, a 3‰ decrease in $\delta^{18}O$ 11.2–10.2 ka interrupted the $\delta^{18}O$ enrichment of 1‰ from 12.0 to 11.2 ka and 3.5‰ from 10.2 to 9.1 ka. This $\delta^{18}O$ decrease coincided with the expansion of Lake Agassiz. We interpret this decrease as a result of decreased summer temperature and increased precipitation derived from the cold and isotopically light meltwaters of Lake Agassiz. During this $\delta^{18}O$ decline, *Pinus* pollen continued to increase at the expense of *Picea* pollen at Deep Lake, as at other Minnesota sites, providing evidence that climatic cooling induced by Lake Agassiz did not cause a reversal to a *Picea*-dominated vegetation. The absence of such a vegetational response implies that the prominent *Picea* recurrence during the Younger Dryas in the southern Great Lakes region was not caused solely by climatic cooling due to increased flux of meltwater from Lake Agassiz into the Great Lakes. Instead the *Picea* recurrence might have been driven primarily by the westward penetration of the Younger Dryas cooling.

INTRODUCTION

The release of meltwater from North American glacial Lake Agassiz has been recognized as a possible factor in the abrupt climatic changes that occurred during the last deglaciation. For example, meltwater influx to the Gulf of Mexico produced a distinct record in the isotope stratigraphy (Flower and Kennett, 1990) and may have had an effect on the regional climate (Overpeck et al., 1989). The abrupt diversion of Lake Agassiz meltwater to the St. Lawrence River and the North Atlantic is a possible cause for the Younger Dryas episode (Broecker et al., 1988). Despite the well-recognized potential of this immense proglacial lake as a climatic driver, its influence on the climate and vegetation of adjacent regions directly downwind has not been evaluated. The lake went through two major periods of expansion (13.9–12.6 ka and 11.0–10.0 ka; Lowell and Teller 1994) while being fed by meltwaters from fluctuating lobes of the Laurentide ice sheet (Teller and Clayton, 1983; Teller, 1987), which may have substantially altered the climate of the adjacent regions, including Minnesota (Bartlein and Whitlock, 1993). Such effects, however, are not conspicuous in the numerous existing paleorecords from these regions, probably because they lack adequate temporal resolution for the late glacial period or because the study sites are located too far from Lake Agassiz. Assessing these climatic effects and their vegetational consequences is necessary for understanding the controls of the regional paleoenvironments. Moreover, such information should offer insights into the controversial question of whether the *Picea* (spruce) recurrence contemporaneous with the Younger Dryas in the southern Great Lakes region was caused by

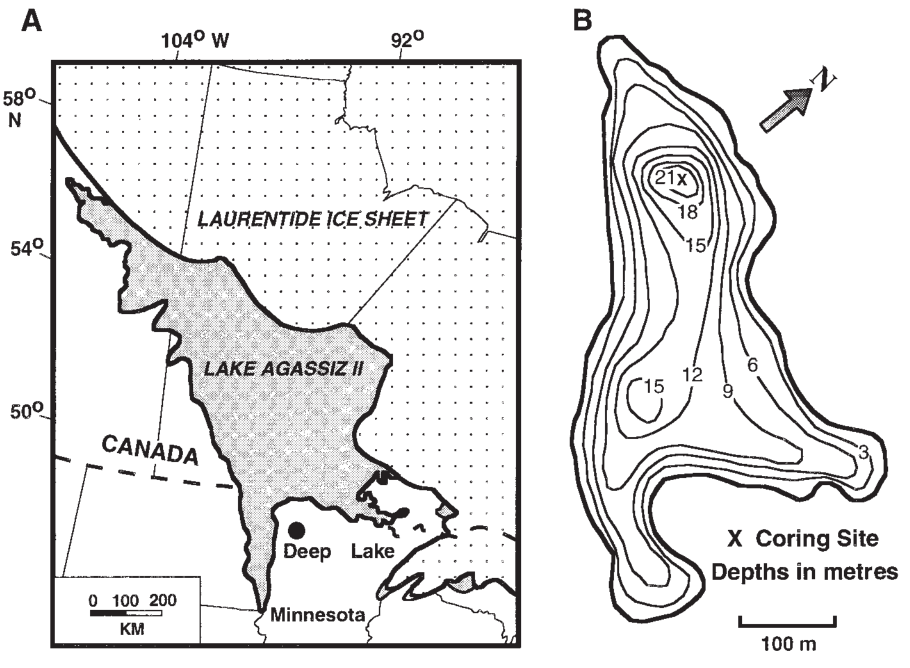

Figure 1. A: Map of Lake Agassiz II region (Teller, 1987). B: Bathymetry of Deep Lake.

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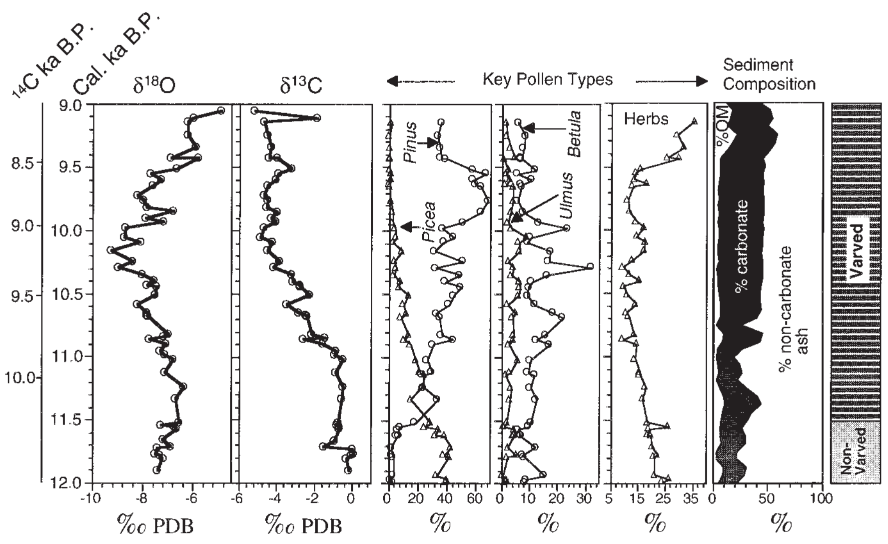

Figure 2. Stratigraphy of oxygen and carbon isotopes, pollen assemblages, sediment composition (OM: organic matter), and gross lithology, Deep Lake. Open circles and triangles in isotope and pollen curves represent sampling points. The ^{14}C age scale, which is provided for reference, is a straight conversion from the calendar age scale on the basis of Stuiver and Reimer (1993).

the penetration of the Younger Dryas cooling into the interior of North America (Shane, 1987; Wright, 1989; Shane and Anderson, 1993), or by the more local climatic cooling of the cold Lake Agassiz waters passing through the Great Lakes (Lewis and Anderson, 1989, 1992).

To address these issues, we conducted stable isotope and pollen analyses of a sediment core from Deep Lake (47°41'N, 95°23'W), northwestern Minnesota (Fig. 1). Deep Lake is strategically selected for the purposes of this study. First, the carbonate-rich sediments from this lake offer an excellent opportunity for paleoclimatic reconstructions on the basis of stable isotope records. Second, the lake is suitable for reconstructing vegetational changes on the surrounding landscape because of its small surface area (~4 ha) and the relatively small areas of pollen sources (Jacobson and Bradshaw, 1981). Third, the lake sediments for the period of interest are annually laminated (varved), providing a means for precise chronological determination. Fourth, and most important, Deep Lake has the potential to record the environmental effects of Lake Agassiz because of its proximity to the proglacial lake. Deep Lake is located in a moraine 45 km east of Lake Agassiz at the time of its second expansion 11.0–10.0 ka (herein termed Lake Agassiz II), and its varved sediments are old enough to encompass this expansion.

METHODS

Three overlapping cores were recovered from the deepest part of Deep Lake with a square-rod piston corer. The cores, mostly consisting of varved sediments (Fig. 2), were correlated with distinctive markers in the varve sequence. We anchored the chronology on a calibrated date of 8.986 ka (accelerator mass spectrometry ^{14}C date 8.090 ± 0.085 ka, Table 1) and extended it to 11.522 ka by varve counts easily made with the aid of a low-power (10X) microscope. Dates for the nonvarved section below were linearly interpolated between 11.522 ka and 12.610 ka (AMS ^{14}C date 10.700 ± 0.107 ka, Table 1). Subsamples of 0.5 cm^3 were taken with a calibrated sampler for the analyses of sediment composition, pollen, and stable isotopes of carbonates. Organic and carbonate contents (Fig. 2) were determined by loss on ignition at 550 °C and 950 °C, respectively. Pollen analysis followed standard procedures of Faegri et al. (1992), and at least 300 pollen grains were counted at each level. For the analyses of oxygen and carbon isotopes, bulk-carbonate samples were reacted at 25 °C for 1 hr with 104% H_3PO_4 made from ultra-pure P_2O_5 and triply distilled H_2O (McCrea, 1950); this reaction should not result in the substantial dissolution of detrital dolomite, which could complicate paleoclimatic interpretation of the data. The isotopic composition of the released CO_2 gas was analyzed with a Finnigan MAT delta E triple-collector mass spectrometer.

PALEOCLIMATIC INTERPRETATIONS OF OXYGEN ISOTOPE RECORDS

Because $\delta^{18}O$ records from lake sediments may have a number of controls, their climatic interpretations are complicated. Here we discuss the possible controls of $\delta^{18}O$ to facilitate the interpretation of the Deep Lake data in the following section. The controls of $\delta^{13}C$ are not discussed in detail because we use our $\delta^{13}C$ data only as supportive information for climatic inferences from the $\delta^{18}O$ record.

The $\delta^{18}O$ of authigenic calcite is a function of water temperature and lake water $\delta^{18}O$ (Stuiver, 1970), assuming isotopic equilibrium for carbonate precipitation from lake water. Changes in water temperature are relatively unimportant, because the coefficient is small (–0.24‰/°C) for the temperature-dependent fractionation between lake water and carbonate and because this effect can be easily compensated by evaporative changes in a closed basin (Talbot, 1990) such as Deep Lake. Before evaporative enrichment, the $\delta^{18}O$ of lake water is determined by the $\delta^{18}O$ of the source water modified by progressive temperature-dependent isotopic fractionation as the air mass passes over the continent (Dansgaard, 1964). The $\delta^{18}O$ in precipitation increases with air temperature at the rate of 0.6‰/°C for the midwestern United States (Rozanski et al., 1993). Shifting moisture sources related to the interplay of the air masses from the Arctic, Pacific, and Caribbean could be important, because Deep Lake is located near the junction of these air masses. However, both the Arctic and Pacific air masses are extremely dry, so the Caribbean is essentially the sole moisture source. We assume that this was the case for the period of interest. Nevertheless, changes in the more local moisture source through the expansion and reduction of Lake Agassiz could be an important driver of our isotopic trends, given the proximity of Deep Lake to this vast proglacial lake. Therefore we consider evaporation, air temperature, and regional moisture source as the major climatic controls of the $\delta^{18}O$ trends in the Deep Lake record.

Carbonate mineralogy is a nonclimatic or indirect climatic factor affecting $\delta^{18}O$ of sediments. Microscopic examinations show that the carbonates in the Deep Lake sediments are dominated by fine-grained calcite that probably precipitated from surface water, presumably as a result of algal photosynthesis during the summer. In addition, X-ray diffraction analysis of the sediment samples shows no correlation of mineralogical composition with our isotopic trends. Furthermore, $\delta^{18}O$ analysis of ostracode valves, which are present at several levels (A. Schwalb, 1996, personal commun.), shows a trend consistent with that of bulk sediment samples. We therefore assume that the carbonates in the Deep Lake sediments are primarily authigenic calcite for the period of interest.

CLIMATIC AND VEGETATIONAL RECONSTRUCTIONS FROM DEEP LAKE: EFFECTS OF GLACIAL LAKE AGASSIZ

Between 12.0 and 11.2 ka, $\delta^{18}O$ increased from –7.5‰ to –6.5‰ in the Deep Lake record (Fig. 2), probably as a result of climatic warming associated with increased insolation and decreased ice-sheet size (COHMAP Members, 1988). This interpretation is consistent with other climatic reconstructions from the midwestern United States. For example, many pollen records show a transition from *Picea* parkland to *Pinus* (pine) forests during this period (Webb et al., 1983; Wright, 1992). Using several statistical approaches, Bartlein and Whitlock (1993) estimated that increases in both July and January temperatures of ~7 °C were associated with this vegetation change at Elk Lake, northwestern Minnesota. A similar vegetational change occurred in the Deep Lake region, as evidenced by the decreasing *Picea* and increasing *Pinus* percentages in our pollen record (Fig. 2).

$\delta^{18}O$ decreased from –6.5‰ to –9.5‰ between 11.2 and 10.2 ka (Fig. 2), suggesting marked decreases in air temperature and evaporation, and/or a shift in moisture source. A temperature decrease resulting from large-scale climatic controls is unlikely, because at this time insolation increased greatly and caused the Laurentide ice sheet to retreat rapidly (COHMAP Members, 1988), and the pollen records throughout the midwestern United States indicate rapid climatic amelioration. The Younger Dryas cooling event, recorded especially in the North Atlantic area, occurred before Lake Agassiz II. The most plausible cause for the 3‰ reversal in $\delta^{18}O$ is the climatic effects of Lake Agassiz II, which is dated at 11.0–10.0 ka. Lake Agassiz expanded at this time when the Marquette glacial advance crossed the Superior basin to the Upper Peninsula of Michigan and blocked the eastern outlets (Teller and Clayton, 1983). The lake was fed by glacial meltwater in summer and was dotted by icebergs, which left prominent tracks on the clayey bottom (Clayton et al., 1965). This expansion probably resulted in cooler summers and greater precipitation in the downwind region in which Deep Lake was located, just as the North American Great Lakes (Norton and Boisenga, 1993; Gat et al., 1994) and Hudson Bay (Rouse, 1991) alter the climates to their lee today. Both cooler summers and greater precipitation would have contributed to the ^{18}O depletion in our record. In addition, the isotopically light glacial meltwaters in Lake Agassiz (–15‰ to –17‰ based on the valves of ostracode *Candona subtriangulata*, Last et al., 1994) as an important moisture source likely contributed to the ^{18}O depletion. A major decrease in lake-surface evaporation in summer probably occurred as a result of these climatic changes, as suggested by the highly significant covariance ($R^2 = 0.843$; $p < 0.001$) in the decreases of $\delta^{18}O$ and $\delta^{13}C$ (Fig. 2) in this closed basin (Talbot, 1990). Winter changes might not have been large, because Lake Agassiz was probably frozen in the winter as a result of the constant flux of cold meltwater from a broad expanse of the ice front in the summer, restricted heat storage in this relatively shallow lake (Teller and Clayton, 1983), and cool periglacial atmospheric temperatures. The relative importance of the contributing factors for the 3‰ $\delta^{18}O$ decrease cannot be separated with our data.

An alternative interpretation for the $\delta^{18}O$ decline 11.2–10.2 ka at Deep Lake is a cooling event immediately following the Younger Dryas, as hypothesized by Anderson et al. (1997). In a study at Seneca Lake, one of the Finger Lakes in New York, Anderson et al. (1997) suggested that a 1‰ decline in $\delta^{18}O$ values 11.7–9.2 ka (10.1–8.2 ^{14}C ka) was correlated with meltwater pulse IB of Fairbanks et al. (1992), and that this represented extensive melting of the ice sheets and influx of meltwater to the Great Lakes, which reduced summer temperatures in the area. However, the duration of the $\delta^{18}O$ reversal at Deep Lake was much shorter; here $\delta^{18}O$ resumed its increase 10.2 ka and became enriched by 3.5‰ by 9.1 ka (see below). Considering the temporal coincidence of the $\delta^{18}O$ decline at Deep Lake with Lake Agassiz II and the potential climatic effects of this huge proglacial lake, we prefer to interpret the Deep Lake record as a manifestation of the more local Lake Agassiz expansion.

TABLE 1. RADIOCARBON DATES AND RELEVANT INFORMATION, DEEP LAKE, MINNESOTA

Core depth (cm)	AMS ^{14}C date (ka B.P.)	Calibrated calendar age (ka B.P.)	Dated material	^{14}C lab identification
3180	8.090 ± 0.085	8.986	Wood	AA17064
3529	10.700 ± 0.107	12.610	*Picea* needles	AA18347

Note: AMS is accelerator mass spectrometry; calibration is based on Stuiver and Reimer (1993).

The pollen assemblages at the onset of Lake Agassiz II (Fig. 2) suggest that the vegetation of the Deep Lake region was at a *Picea-Pinus* forest ecotone, which should be susceptible to climatic forcing. However, during the first phase (11.2 and 10.4 ka) of the isotopic decrease, *Pinus* pollen percentages continued to increase at the expense of *Picea* pollen, as they do elsewhere in Minnesota. This suggests that climatic changes related to Lake Agassiz II did not alter the direction of vegetational transition from *Picea* to *Pinus* dominance around Deep Lake. However, as $\delta^{18}O$ dropped to its minimum values between 10.4 and 10.0 ka, *Pinus* pollen percentages decreased gradually, mostly in favor of hardwood taxa *Betula* (birch) and *Ulmus* (elm).

Starting at 10.2 ka, $\delta^{18}O$ gradually increased to –6.0‰ by 9.1 ka (Fig. 2). This 3.5‰ enrichment probably reflected the cessation of Lake Agassiz effects and resumption of large-scale insolation controls (COHMAP Members, 1988) over the climate of the Deep Lake region, which would have resulted in increased summer temperature, decreased annual precipitation, and the resulting increase in evaporation. Such a climatic trend was probably responsible for the initial expansion of *Pinus*, the population density of which reached a maximum between 10.0 and 9.5 ka, as inferred from its maximum pollen percentages. In the following 400 yr, $\delta^{18}O$ continued to increase, and it reached a maximum of –6.0‰ at 9.1 ka. However, *Pinus* pollen percentages declined markedly as the pollen percentages of herbaceous taxa increased. These isotopic and pollen changes were probably caused by increased evaporation and the consequent effective-moisture deficit, which led to the decline of *Pinus* forests and the establishment of prairie. These changes are typical of the vegetational and climatic histories (Webb et al., 1983; Bartlein and Whitlock, 1993) of this region.

The effects of the expansion and reduction of Lake Agassiz on the climate and vegetation of the adjacent regions have not been documented by previous studies. Despite the existence of numerous pollen records, only the pollen record from Elk Lake, which was substantially farther away from Lake Agassiz II (~75 km) than Deep Lake, has sufficient temporal resolution to assess the effects of Lake Agassiz. On the basis of numerical climatic analyses of the pollen record from Elk Lake, Bartlein and Whitlock (1993) speculated that Lake Agassiz II might have been the cause of increased annual precipitation and decreased July and January temperatures. However, as these authors acknowledged, this interpretation is problematic because the chronology is insecure and because pollen changes responsible for the reconstructed climatic changes occurred throughout much of the midwestern United States. Stable-isotope analyses at this site (Dean and Stuiver, 1993) focused on the environmental reconstructions of the Holocene, the late glacial being represented by a few samples at coarse temporal resolution.

IMPLICATIONS FOR THE CAUSE OF THE LATE GLACIAL CLIMATIC FLUCTUATIONS IN THE GREAT LAKES REGION

Palynological studies in the southern Great Lakes area provide evidence for vegetational changes contemporaneous with the Younger Dryas episode of cooling. In particular, the recurrence of *Picea* was a striking feature in the pollen diagrams from the till plains of northern Ohio (Shane, 1987; Shane and Anderson, 1993). Here *Picea* pollen percentages declined a great amount ca. 15.4–12.9 ka, in association with increases in the pollen percentages of *Fraxinus* (ash), *Quercus* (oak), and other temperate hardwood species as a result of climatic warming. *Picea* pollen then increased along with *Abies* (fir) and *Larix* (larch) and then *Pinus* during the Younger Dryas, which is interpreted as a result of a climatic reversal from the previous warming. Two alternative causal mechanisms have been hypothesized:

(1) a westward extension of the Younger Dryas cooling from the North Atlantic (Shane, 1987; Wright, 1989), and (2) local "lake-effect" cooling due to increased flow of meltwater through the Great Lakes basins at this time (Lewis and Anderson, 1989, 1992), following the diversion of glacial Lake Agassiz drainage from the Gulf of Mexico to the St. Lawrence Valley.

These hypotheses can be evaluated in the context of our conclusion about the climatic effects of Lake Agassiz II and the vegetation response in the Deep Lake region, because similar processes were involved in these two cases, even though the *Picea* recurrence in the southern Great Lakes area occurred 1000 yr before Lake Agassiz II. The magnitude of climatic cooling caused by Lake Agassiz II in adjacent Minnesota should be at least as great as that induced by increased meltwater influx to the Great Lakes for several reasons. First, Lake Agassiz II was far larger than all the Great Lakes combined (Teller and Clayton, 1983). Second, Deep Lake was much closer to Lake Agassiz II (~45 km) than the till plains sites were to the Great Lakes (up to several hundred kilometres). Third, Lake Agassiz meltwater, when passing through the Great Lakes, should be warmer, or at least not colder, than that in Lake Agassiz II itself because of surface warming during transit. Although the vegetation around Deep Lake was somewhat different from that of northern Ohio and Indiana for the respective periods of concern, it was at a *Picea-Pinus* ecotone that should be suitable for a *Picea* recurrence similar to that in the southern Great Lakes region. However, our results show that climatic changes in the Deep Lake region due to the expansion of Lake Agassiz, although enough to affect the stable isotope record, did not reverse the trend toward the replacement of *Picea* by *Pinus*. This implies that climatic cooling south of Lake Michigan due to the increased influx of meltwaters to the Great Lakes alone did not cause the *Picea* recurrence in the downwind region to the south. This striking palynological anomaly probably resulted from the westward penetration of the Younger Dryas cooling from the North Atlantic superimposed on the more local cooling that might be attributed to lake effects.

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