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A late Pleistocene–Holocene noble gas paleotemperature record in southern Michigan

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[1] Noble gas temperatures (NGTs) and ^{14}C derived ages in groundwaters of the Michigan Basin reveal a ground temperature of ~1°C toward the end of the Last Glacial Maximum (LGM) suggesting that groundwater recharge occurred under the Laurentide Ice Sheet (LIS) cover. In addition to the general warming observed since the LGM, the NGT record indicates an abrupt warming event between ~12.8 and 11.1kyrs BP, correlative to the Bølling-Allerød (BOA) warm phases. Ice-sheet-linked changes in freshwater delivery to the North Atlantic, together with changes in the North Atlantic Deep Water (NADW) circulation are possible causes of such abrupt climate shifts in northeastern US. Pleistocene waters yielding the lowest NGTs have the highest δ^{18}O and δD values, suggesting an atmospheric circulation pattern distinct from today, with a stronger moisture component from the Gulf of Mexico, possibly due to the presence of the LIS which weakened the Pacific westerly flow. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1829 Hydrology: Groundwater hydrology; 1833 Hydrology: Hydroclimatology; 1899 Hydrology: General or miscellaneous. **Citation:** Ma, L., M. C. Castro, and C. M. Hall (2004), A late Pleistocene–Holocene noble gas paleotemperature record in southern Michigan, *Geophys. Res. Lett.*, *31*, L23204, doi:10.1029/2004GL021766.

1. Introduction

[2] Late Pleistocene and Holocene paleoclimatic reconstructions through the use of noble gases dissolved in groundwater have been the object of numerous studies in recent years [e.g., *Kipfer et al.*, 2002; *Castro and Goblet*, 2003]. Unlike many other continental proxies, noble gas temperatures (NGTs) are a direct measure of the temperature at which groundwater equilibrated with the atmosphere during infiltration. This is because the solubility of noble gases in water, especially those of Ar, Kr and Xe is primarily dependent on the mean local atmospheric pressure (altitude of the recharge area) and temperature of the water at the time recharge took place [*Kipfer et al.*, 2002].

[3] With the exception of *Beyerle et al.* [1998] who conducted a paleoclimatic reconstruction using NGTs in a mid-latitude region that experienced ice-cover during the Last Glacial Maximum (LGM), all other available climate records based on NGTs come from permanently ice-free regions. In addition to a much improved understanding of past climate evolution and atmospheric circulation patterns, such paleoclimatic reconstructions in ice-covered regions during the LGM are critical to assess the impact of glaciation on groundwater recharge and dynamics.

[4] Here, we present a ~17kyrs (^{14}C derived ages) NGT and stable isotope record derived mostly from the Marshall aquifer in southern Michigan, a region covered by the Laurentide Ice Sheet (LIS) during the LGM and early deglaciation periods. Our NGT record reveals new aspects of late Pleistocene climate change in southern Michigan and provides new information on the occurrence of groundwater recharge under ice-sheet cover. The combined analysis of NGTs and δD and δ^{18}O shed new light into atmospheric circulation patterns in place during the early stages of deglaciation in this region.

2. Regional Setting

[5] The Marshall aquifer, a major groundwater flow system composed mostly of sandstones is located in the central portion of the Michigan Basin, a basin with an ovate shape occupying the Lower Peninsula of Michigan (Figure 1). The Bayport-Michigan confining units which are composed mostly of shale, overly the Marshall aquifer and are in turn overlain by the Saginaw aquifer, which mainly consists of sandstone [*Mandle and Westjohn*, 1989]. These formations subcrop at an altitude of ~300 m and are overlain by glacial deposits from the Wisconsinan and possibly older Pleistocene ages. In the Marshall aquifer in southern Michigan, groundwater flows gravitationally to the NE and NW (Figure 1), and groundwater discharges into Lake Huron and Lake Michigan, in the Saginaw and Michigan Lowlands area, respectively [*Vugrinovich*, 1986]. Flow in the Saginaw aquifer is toward the NE.

3. Sample Collection and Measurements

[6] Water samples were collected from 13 wells in the Marshall and 1 well in the Saginaw (sample 11) aquifers (see Figure 1) for measurement of noble gases (Ne, Ar, Kr and Xe), stable isotope ratios (δD and δ^{18}O), carbon isotopes (δ^{13}C and ^{14}C), and major elements (Table 1; see auxiliary material[1]). Noble gas concentrations and isotopic ratios, δD and δ^{18}O as well as major elements were measured at the University of Michigan. Excess air, air saturated water (ASW) components and NGTs were determined following *Ballentine and Hall* [1999]. ^{14}C activities of dissolved inorganic carbon were measured at the AMS facility at Woods Hole Oceanographic Institution. Five conventional correction models (see auxiliary material) using chemical and isotopic balances were applied to convert activity values into ^{14}C ages. They all yield consistent results, including sample 14 which belongs to a time

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL021766.

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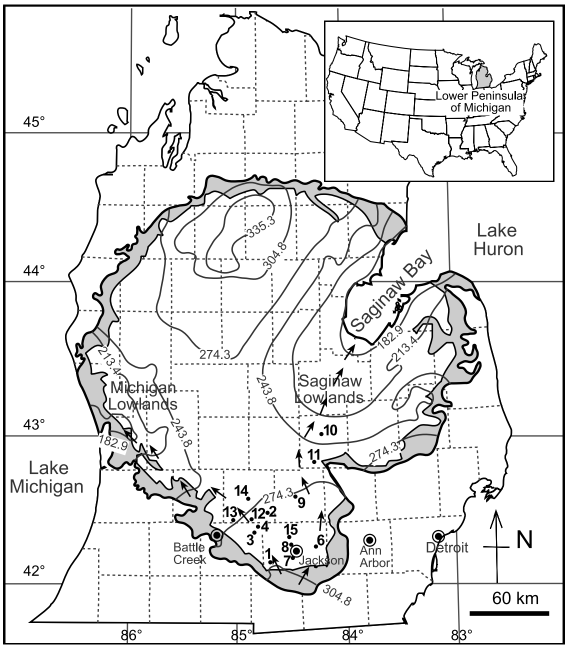

Figure 1. Study area and sample locations in southern Michigan [adapted from *Mandle and Westjohn*, 1989]. The Marshall aquifer subcrop (shaded area), equipotentials (m, contour lines), and direction of water flow (arrows) are indicated.

period during which the recharge area is believed to have been under glacial cover. Under such conditions, the potential for difficulties in the ^{14}C age interpretation (see auxiliary material) exists. However, it is likely that CO_2 production by bacteria beneath the glacier can provide a sufficient source of inorganic C and ^{14}C correction models should apply to recharge beneath an ice sheet (see auxiliary material). Except for sample 3, all ^{14}C ages here presented are those obtained using the *Fontes and Garnier* [1979] correction.

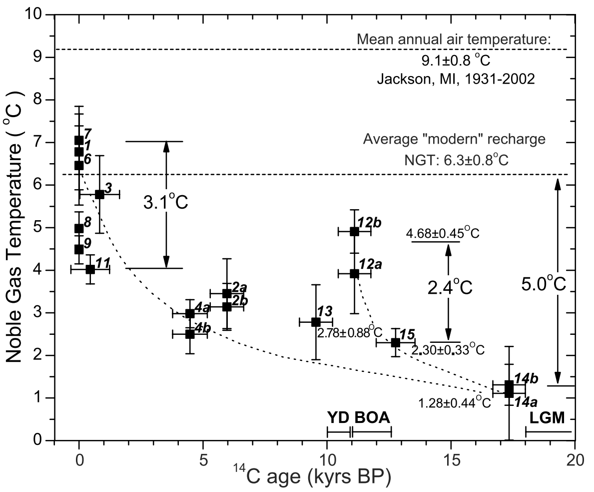

Figure 2. Noble gas temperatures (°C) versus ^{14}C ages. Mean annual air temperature is from http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.html; BOA: Bølling-Allerød warm phases; YD: Younger Dryas [after *Yu and Eicher*, 1998].

4. Results and Discussion

[7] Samples range in age from modern to ~17.4 kyrs BP and yield NGTs between 7.05 ± 0.80°C (sample 7) and 1.28 ± 0.44°C (samples 14a,b) (Figure 2). Samples close to the recharge area (1, 6, 7, 8; Figure 1) displaying negative corrected ^{14}C "apparent" ages yield an average NGT of 6.3 ± 0.8°C. This value is ~3°C lower than the average annual air temperature of 9.1 ± 0.8°C for Jackson (1931–2002) (Figure 1). Although ^{14}C ages indicate that samples 1, 6, 7, and 8 are "modern", these waters could possibly be hundreds of years old and representative of a cooler period instead. NGTs over several degrees cooler than present were recorded elsewhere at the beginning of the last millennium [*Castro and Goblet*, 2003]. Samples close to the recharge area together with samples 3, 9 and 11 indicate similar NGT variations, up to ~3°C within the last thousand years (Figure 2). Lack of age resolution through ^{14}C, however, does not allow for a detailed paleoclimatic reconstruction within this period. Estimation of NGTs in the recharge area will be needed to assess the present ground temperature and determine if such a value is higher and closer to the mean annual air temperature (MAAT). In the discussion that follows and for comparative purposes, our reference to "modern" recharge temperature potentially representative of an average for the last millennium is 6.3 ± 0.8°C.

[8] Our NGT record displays a smooth general warming trend between the late stages of the LGM at ~17.4 kyrs BP and present time (Figure 2), trend interrupted by an abrupt warming event between ~12.8 and 11.1 kyrs BP. Of particular interest is the NGT record representative of the late stages of the LGM (14a, b; Figure 2), a period during which the LIS reached its maximum extent, penetrating into central Indiana and Ohio, far south of the Marshall subcrop (Figure 3). The LIS experienced several subsequent fluctuations near its maximum extent and retreated rapidly at a later time into the Great Lakes basins, at ~14 kyrs BP [*Dyke et al.*, 2002]. Chronology of the LIS suggests that the Marshall recharge area was under glacial cover until ~15.5 kyrs BP. Our NGT record indicates an average

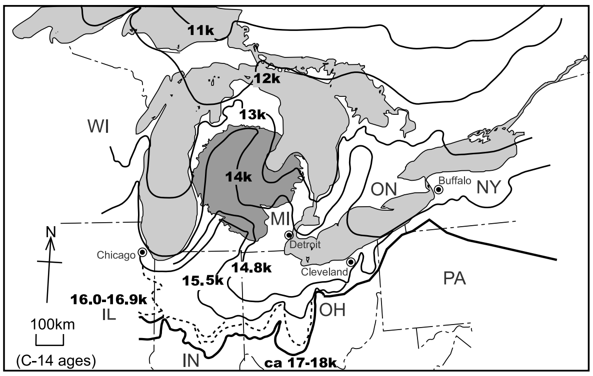

Figure 3. Laurentide Ice Sheet extent and deglaciation history (^{14}C ages) in the Great Lakes region since the Last Glacial Maximum [after *Prest*, 1969; *Fullerton*, 1986]. The Marshall aquifer is indicated (dark shaded area) as well as present Great Lakes location (light shaded areas).

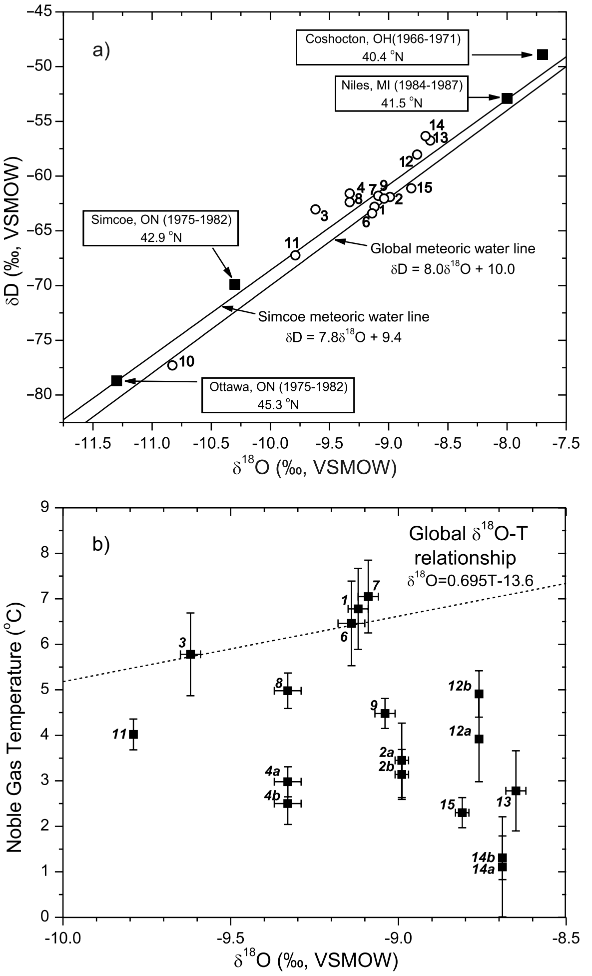

Figure 4. (a) δD vs. δ^{18}O in Michigan groundwaters; mean annual values for Ottawa, Simcoe, Niles and Coshocton, as well as the Simcoe meteoric water line from http://isohis.iaea.org. Global water meteoric line is from *Craig* [1961]. (b) Noble Gas Temperatures versus δ^{18}O values; global δ^{18}O-T relationship is from *Dansgaard* [1964].

recharge temperature of 1.28 ± 0.44°C (14a, b; Figure 2) at an earlier time, strongly suggesting the occurrence of subglacial groundwater recharge. Our results support findings by *Hoaglund et al.* [2004] in which numerical groundwater flow simulations (and δ^{18}O anomalies) in the Michigan Basin suggest a reversal of the groundwater flow system in the Saginaw Lowlands area due to ice-induced hydraulic loading and resultant occurrence of subglacial recharge. By contrast, based on a calculated groundwater age gap between ~17 and 25 kyrs BP, *Beyerle et al.* [1998] concluded that local groundwater recharge in the Glatt Valley aquifer, Switzerland, was prevented by overlying glaciers during the LGM. Although the impact of glaciation on groundwater flow behavior is not fully understood, a number of studies have shown that glaciers can dramatically change groundwater flow patterns [e.g., *Siegel*, 1991]. Such impact might be of different nature depending on the geological/tectonic history, and thus, hydrogeological system of the region considered. Our NGT record provides important direct support for the existence of subglacial recharge in Michigan and indicates a temperature underneath glaciers at ~1°C. It further suggests a ground temperature at the late stages of the LGM 5°C cooler than that of "modern" recharge (Figure 2). Temperature differences between the ground and the atmosphere, however, have the potential to be much greater due to a possible insulation effect of the ground from colder air temperatures by glacier cover. Such effect has been observed in snow covered regions [*Pollack and Huang*, 2000]. Beetle assemblages during the LGM from regions south of the LIS suggest mean January and July temperatures 10–19°C and 11–12°C cooler than present, respectively [*Elias et al.*, 1996]. Additional NGTs that span the full interval of the LGM will be needed to assess whether or not groundwater recharge occurred continuously during this time period.

[9] Another important aspect of our NGT record is the observed abrupt warming between ~12.8 (15) and 11.1 kyrs BP (12a, b) of ~2.4°C (Figure 2) immediately following deglaciation in the region (Figure 3). Taking into account the general warming trend between the LGM and present time, as well as the trend suggested by sample 13 at ~9.6 kyrs BP (Figure 2), such warming period seems to be followed by a rapid climate reversal. Similar broad-scale climate oscillations within the North Atlantic region were observed within the same time period (~13–10 kyrs BP). Here, an initial general warming corresponding to the Bølling-Allerød (BOA) warm phases (~13–11 kyrs BP) was found. This event is contemporaneous with global deglaciation and was followed by a climate reversal correlative to the Younger Dryas (YD) at ~11.0–10.0 kyrs BP, prior to a return to warmer conditions [*Alley and Clark*, 1999]. In northeastern US, such abrupt warming began at ~12.4 kyrs BP to peak at ~11 kyrs, followed by a cold phase (YD) from ~10.8–10 kyrs BP [*Peteet et al.*, 1993]. In the Great Lakes region, similar paleoclimatic oscillations have been identified based on a variety of proxies. Pollen records in northern Ohio indicate a mean annual temperature increase of 8°C at ~13–11 kyrs BP, followed by a cold period with a temperature decrease of 2–5°C and 1–2°C in January and July, respectively, suggesting the possible westward extension of the YD into the Great Lake regions [*Shane and Anderson*, 1993]. Based on stable isotopes, pollen records, and plant macrofossils from lake sediments in Ontario, *Yu and Eicher* [1998] further demonstrate that late glacial-to-early Holocene climate oscillations occurred in the Great Lakes region with the onset of BOA at ~12.5 kyrs BP down to 11.0 kyrs. Although our NGT increase of ~2.4°C is not as pronounced as the one suggested by pollen records, the NGT record has undoubtedly captured the occurrence of climatic oscillations during the late glacial period, in particular, the BOA warm phases.

[10] Ice-sheet-linked changes in freshwater delivery to the North Atlantic, as well as changes in the North Atlantic Deep Water (NADW) circulation are possibly at the origin of such abrupt climate shifts in the northeastern US. BOA warming was accompanied by an increase of NADW formation, suggesting a link between heat transport to the North Atlantic region and NADW production. Decrease of continental freshwater fluxes to the North Atlantic and diversion of fresh water to the Gulf of Mexico via the Mississippi River due to fluctuations of the southern LIS margin could generate more vigorous deep water circulation, and lead to the BOA warm phases [*Clark et al.*, 2001].

[11] Samples 2a,b and 4a,b follow the general warming trend, with a possible slight temperature increase of ~0.7°C at ~6 kyrs BP (2a,b), relative to the long-term warming.

[12] Stable isotope analyses for all samples yield δD and δ^{18}O varying between −56.3 and −77.3‰, and −8.6 and −10.8‰, respectively (Figure 4a). All δD and δ^{18}O lie close to both the global [*Craig*, 1961] and local (Simcoe, Ontario, Canada) meteoric water lines (Figure 4a), indicating that δD and δ^{18}O were not significantly modified by isotope exchange within the aquifer.

[13] In eastern and central North America, mean annual δD and δ^{18}O precipitation values have a pronounced latitude effect, with depletion of δ^{18}O and δD with increased latitude (Figure 4a), a depletion that is likely related to mean annual air temperature decrease [*Dansgaard*, 1964]. Surprisingly, and unlike most of our "modern" samples, early Holocene and late Pleistocene waters follow no particular relationship with temperature (Figure 4b). Importantly, late Pleistocene samples (12–15) with some of the lowest NGT temperatures, yield the highest δD and δ^{18}O values, and thus present an opposite trend to that normally expected (Figure 4b). Such a decoupling between δ^{18}O and local temperature precipitation was previously found in Pleistocene waters and attributed, respectively, to a milder climate [*Siegel*, 1991] and to prevailing atmospheric circulation patterns distinct from those in place today [*Plummer*, 1993].

[14] Precipitation in southern Michigan is currently controlled by two distinct moisture sources [*Bryson and Hare*, 1974]: a depleted Pacific source from the west, as well as a more enriched Gulf of Mexico source from the south, reaching the Midwest with a δ^{18}O value of −10.8‰ and −7.2‰, respectively [*Simpkins*, 1995]. Thus, both an increase in the contribution from the Gulf of Mexico moisture and/or a decrease of contribution from Pacific moisture has the potential to generate precipitation with enriched δ^{18}O values in southern Michigan, masking the local precipitation temperature effect. This suggests that during the LGM and early deglaciation periods a different atmospheric circulation pattern was in place in southern Michigan, with a dominant moisture source originating in the Gulf of Mexico. Possible causes for this distinct pattern might be related to the presence of the LIS, which could deflect the Pacific westerly flow, thus, weakening its influence on local Michigan precipitation [*Amundson et al.*, 1996].

5. Concluding Remarks

[15] Noble gases hold great potential at identifying with relative accuracy major global climatic oscillations, at least since the LGM. Here, the BOA warm phases are recognized for the first time through NGT records. Such records hold also great promise for ascertaining whether or not groundwater recharge occurs under ice-covered regions. Together with stable isotope analysis, they allow for a better understanding of past atmospheric circulation patterns.

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