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Speleothem evidence for Holocene fluctuations of the prairie-forest ecotone, north-central USA

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Abstract: Carbon and oxygen isotopic trends from seven Midwestern speleothems record significant offsets in the timing of middle-Holocene vegetation change. Interactions of dry Pacific and moist Gulf of Mexico air masses maintained a sharp moisture gradient across Iowa, Minnesota, and Wisconsin such that the arrival of prairie was offset by 2000 years between caves and pollen sites located only 50 km apart. Oxygen isotopes shift concomitantly with carbon in most cases, although these changes are believed to represent increased evaporative enrichment of 18O prior to infiltration during the prairie period.

Key words: Speleothems, oxygen isotopes, carbon isotopes, climatic change, vegetation change, prairie-forest ecotone, Holocene, Midwestern USA.

Introduction

Numerous studies have recognized a middle-Holocene warm and/or dry period in North America (Wright, 1968; Webb and Bryson, 1972; Chumbley et al., 1990; Baker et al., 1992; Dorale et al., 1992). One prominent response to this climatic shift was the displacement of deciduous forest by a tongue of prairie that extended east between northern Missouri and southern Minnesota into Illinois. That this ‘Prairie Peninsula’ migrated east instead of north or south suggests that increased aridity rather than elevated temperature was primarily responsible for these changes. Several studies have suggested that regional moisture balances were affected by changing atmospheric circulation patterns (Amundson et al., 1996; Yu et al., 1997) and that advancing prairie was driven by encroaching cool, dry Pacific air that displaced moist maritime air masses from the Gulf of Mexico (Bryson, 1966; Wright, 1968; Chumbley et al., 1990; Baker et al., 1992).

The timing and nature of Holocene vegetation change across the northern Midwest is recorded primarily by pollen sequences preserved in lakes and ponds formed north of the Wisconsinan glacial margin. South of the glacial margin, palaeoecological records are limited in number, geographic distribution and temporal resolution. Well-documented macrofossil records exist (e.g., Baker et al., 1996), but, as they allow only snapshots of time, they are less suitable for constraining the exact timing of vegetation change than continuous records. The isotopic chemistry of lake sediments has also been used to constrain palaeoclimatic conditions, but, during periods of increased aridity, complex interactions between recharge derived from precipitation versus groundwater complicate interpretations (Smith et al., 1997).

Caves are widespread across the region, however, and, because speleothems provide continuous records, can be precisely dated using uranium-series techniques, and record shifts in both site-specific (vegetation) and regional (mean annual temperature) climatic variables, they can offer unique, high-resolution records of continental climate and vegetation change (Dorale et al., 1992) that complement and clarify these other records.

Much of the northeastern margin of the prairie peninsula lacks abundant pollen records, and as a result its temporal and geographic distributions are not well understood. Some studies have suggested that the interaction between Pacific and Gulf of Mexico air masses stabilized an extremely steep moisture gradient, with drier conditions existing to the west of the prairie-forest ecotone (Baker et al., 1992). The sparsity of data sets from this boundary makes it difficult to examine the precise timing and lateral extent of the ecotone. The purpose of this paper is to correlate the carbon and oxygen isotopic compositions of speleothems from four caves clustered along the palaeomargin of the prairie-forest ecotone with area pollen sequences in order to construct a more complete...
picture of middle-Holocene vegetation change along the north-eastern border of the Prairie Peninsula.

**Setting**

Stalagmites from four caves were analysed in this study: (1) Cold Water Cave, Cresco, Iowa; (2) Mystery Cave, Wykoff, Minnesota; (3) Spring Valley Cave, Spring Valley, Minnesota; and (4) Crystal Cave, Spring Valley, Wisconsin. Cold Water Cave, Mystery Cave and Spring Valley Cave are located within 50 km of each other in southeast Minnesota and northeast Iowa (Figure 1). Crystal Cave is located in west central Wisconsin, approximately 130 km from Mystery Cave. Each of the caves is developed in early Palaeozoic carbonates. The caves span a stratigraphic interval of about 150 m from the upper Ordovician Dubuque and Stewardville Formations (Mystery Cave and Spring Valley Caverns) and Dunleith Formation (Cold Water Cave) to the middle of the lower Ordovician Prairie du Chien Group (Crystal Cave). All four caves are developed under local topographic highs adjacent to incised surface valleys and are about 30 m below the surface. The unconsolidated materials overlying the caves consist of residuum and weathered remnants of pre-Illinoian tills overlain by widely varying thicknesses of Wisconsinan loess. The sediments vary in thickness from 0 to ~10 m over each cave. The overlying soils are typically well-developed mollisols.

Two pollen and/or macrofossil sites from northern Iowa and eastern Minnesota were used as guidelines to trace the middle-Holocene prairie-forest border in this study. Roberts Creek and Kirchner Marsh span the presettlement prairie-forest border.

**Methods**

Stalagmites were sawn in half vertically, polished, and sampled for carbon and oxygen stable isotope pairs using a modified dental drill with a 500 μm diameter bit at intervals ranging from 1 to 3 mm. Carbon and oxygen isotopic analyses were performed at the University of Michigan Stable Isotope Laboratory using a MAT-251 gas-source mass spectrometer. Samples were converted to CO₂ by reacting them with phosphoric acid at 72°C. All values are reported in per mil (‰) with oxygen relative to SMOW and carbon relative to PDB; analytical precision is better than 0.1‰ for both carbon and oxygen.

Powders were similarly extracted for 230Th dating by thermal ionization mass spectrometry (TIMS) at the University of Minnesota for the Spring Valley, Mystery Cave and Crystal Cave speleothems (Table 1). Analytical procedures are modifications of those of Edwards et al. (1987) as discussed in Edwards et al. (1993). Ages have previously been reported for the Cold Water Cave speleothem 1S (Dorale et al., 1992) and 2SS and 3L (Denniston et al., 1999). Ages, determined using linear interpolation between dated intervals and linear extrapolation beyond dated intervals, are in years before present (yr BP) where present is 1994–1997, the years of these isotopic analyses.

**Climate signals in speleothem calcite**

Dissolution of CO₂ produced by plant respiration and decomposition of organic matter in the soil zone drives dissolution of carbonate bedrock during infiltration. Long-term changes in speleothem δ¹³C values should therefore reflect shifts in the type of vegetation overlying the cave. Plants utilizing the C₄ photosynthetic pathway respire and decompose into carbon dioxide with higher δ¹³C values than do C₃ plants. These two vegetation types are frequently found in close association, but C₃ plants are most abundant in cool and moist climates and C₄ plants predominate in warm, arid environments. Therefore, the δ¹³C values of speleothem calcite reflect climatic conditions (Dorale et al., 1992). However, because the CO₂ produced by both C₃ and C₄ vegetation ranges by approximately 10‰ (~32‰ to ~20‰ for C₃ and ~19‰ to ~9‰ for C₄) (Boutton, 1991), we do not attempt to constrain absolute C₃/C₄ ratios.

The oxygen isotopic signature of speleothem calcite is derived almost exclusively from infiltrating meteoric water. Evaporation prior to infiltration or in the cave can increase the δ¹⁸O values of water, but neither plant activity nor dissolution of carbonate bedrock significantly affects water isotopic composition. Assuming minimal evaporative enrichment of δ¹⁸O, the relationships between mean annual temperature and the oxygen isotopic composition of precipitation (higher δ¹⁸O at higher temperatures) can be used to extract palaeoclimatic signals from speleothem calcite (Hendy and Wilson, 1968). This effect is, in part, counteracted by fractionation during calcite precipitation which results in lower δ¹⁸O values at higher temperatures; however, the change in δ¹⁸O values of precipitation with temperature is larger than the change in δ¹³C values due to fractionation during precipitation so that the net result is higher speleothem δ¹⁸O values with higher temperature. Thus, a shift from a cooler and/or wetter climate to warmer and/or drier conditions may be recorded by increases in both δ¹³C values (as C₄ plants become increasingly abundant) and δ¹⁸O values (due to Rayleigh distillation processes in the atmosphere) of speleothem calcite. However, uncertainty regarding a number of variables including moisture source and seasonality of precipitation complicates determining absolute temperatures.

**Results**

**Crystal Cave, Wisconsin**

Stalagmite CC-A was actively growing when collected from Crystal Cave, and its top is zero age. CC-A’s base dates to 2840 years BP, so that an average growth rate for this sample is 110 μm/year. The δ¹³C values in most of the stalagmite are relatively constant at about ~11.7‰ (Figure 2). The last 500 years are marked by a 1.5‰ increase to ~10‰. The δ¹³C record spiked up to ~7.5‰ between 1800 and 2000 yr BP and to ~8.5 at the bottom of CC-
A. Without a longer record it is impossible to determine whether the elevated \( \Delta^{13}C \) values at the bottom of the stalagmite represents a long-term shift in the overlying vegetation or a short-term peak. The \( \Delta^{13}C \) record in CC-A is relatively flat and averages about 23‰.

**Mystery Cave, Minnesota**

Stalagmite MC-28 was actively growing when it was collected from Mystery Cave. The age data in Table 1 indicate it began to grow shortly before 7270 years BP. The average growth rate of this sample is 40 m/year (Figure 2). The nearly identical \( \Delta^{13}C \) values of SV-2 decreased gradually from –6‰ to –8‰ during the middle Holocene and returned to 24.0‰ during the late Holocene.

**Cold Water Cave, Iowa**

Carbon isotopic compositions from Cold Water Cave stalagmites 1S (Dorale et al., 1992), 2SS and 3L increased simultaneously and by similar magnitudes (–5‰ to –3‰) at approximately 5900 years BP (Denniston et al., 1999) (Figure 2). Maximum \( \Delta^{13}C \) values during the middle Holocene approached 5.5‰ for all three samples. This interval of heavy carbon endured until 3300 years BP when \( \Delta^{13}C \) values began decreasing, stabilizing at approximately –7.5‰ by 2000 years BP. Although early and late Holocene \( \Delta^{13}C \) values are very similar among these three stalagmites, oxygen isotopic compositions vary significantly during the middle Holocene, with elevated \( \Delta^{18}O \) values in 1S, decreased \( \Delta^{18}O \) values in 2SS and largely unchanged \( \Delta^{18}O \) values in 3L. The similarity of carbon signatures coupled with the wide variability in \( \Delta^{18}O \) values between stalagmites lead Denniston et al. (1999) to suggest that this variability in oxygen isotopic composition is related to pre-infiltration evaporative effects or changes in precipitation seasonality.

**Discussion**

The nearly identical \( \Delta^{13}C \) values of the Cold Water Cave, Mystery Cave and Spring Valley Cave speleothems demonstrate that these

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**Table 1 Uranium and thorium isotopic ratios and \( ^{230}\text{Th}^{234}\text{U} \) ages**

<table>
<thead>
<tr>
<th>Sample</th>
<th>mm from</th>
<th>( ^{238}\text{U} ) (ng/g)</th>
<th>( ^{232}\text{Th} ) (pp/g)</th>
<th>( \delta^{234}\text{U} ) measured</th>
<th>( ^{230}\text{Th}^{234}\text{U} ) activity</th>
<th>( ^{230}\text{Th}^{235}\text{Th} ) atomic</th>
<th>Age †</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV-1</td>
<td>23</td>
<td>1260</td>
<td>2400</td>
<td>660 (3)</td>
<td>0.123 (1)</td>
<td>1.077 (1)</td>
<td>380 (90)</td>
</tr>
<tr>
<td>SV-1</td>
<td>76</td>
<td>1340</td>
<td>1340</td>
<td>650 (3)</td>
<td>0.116 (90)</td>
<td>1.913 (2)</td>
<td>7880 (60)</td>
</tr>
<tr>
<td>SV-1</td>
<td>200</td>
<td>1590</td>
<td>780</td>
<td>690 (4)</td>
<td>6.90e-2 (3)</td>
<td>2.31e-3 (2)</td>
<td>4510 (30)</td>
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<tr>
<td>SV-1</td>
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<td>2410</td>
<td>690</td>
<td>630 (2)</td>
<td>6.34e-2 (4)</td>
<td>3.65e-3 (60)</td>
<td>4300 (30)</td>
</tr>
<tr>
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<td>375</td>
<td>1570</td>
<td>480</td>
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<td>5.14e-2 (3)</td>
<td>2.75e-3 (3)</td>
<td>3400 (30)</td>
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<td>1920</td>
<td>4080</td>
<td>660 (3)</td>
<td>2.63e-2 (9)</td>
<td>2.04e-4 (8)</td>
<td>1700 (60)</td>
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<td>1730</td>
<td>2190</td>
<td>710 (5)</td>
<td>1.06e-2 (1)</td>
<td>1.37e-4 (2)</td>
<td>650 (10)</td>
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<tr>
<td>SV-2</td>
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<td>1800</td>
<td>1330</td>
<td>700 (4)</td>
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<td>2.13e-3 (6)</td>
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<td>1760</td>
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<td>7.16e-4 (74)</td>
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<td>2790</td>
<td>704 (3)</td>
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<td>2.40e-4 (2)</td>
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<tr>
<td>MC-28</td>
<td>9</td>
<td>1170</td>
<td>1100</td>
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<td>0.113 (1)</td>
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<td>550</td>
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<td>660</td>
<td>640 (3)</td>
<td>1.27e-2 (4)</td>
<td>1.05e-4 (3)</td>
<td>810 (30)</td>
</tr>
</tbody>
</table>

†Ages are to the time of measurement, 1994–1996. Ages are calculated using a modification of the standard age equations (Broecker and Thurber, 1965) modified to correct for initial \( ^{230}\text{Th}^{234}\text{U} \) assuming an initial \( ^{230}\text{Th}^{234}\text{U} \) ratio of \( 4.4 \times 10^{-6} \) (±2.2 × 10−6). Half lives are those used in Edwards et al. (1987). Although analytically precise, uncertainty associated with drilling large (~1 g) samples increases the effective error of these dates.
Figure 2. Carbon (solid lines) and oxygen (dotted lines) isotopic trends for each stalagmite discussed in this study. The scales for both carbon and oxygen have ranges of 6‰ for all speleothems except for SV-1. The scale for SV-1 has a range of 8‰ for both isotope ratios. The absolute distance representative of a 1‰ change is constant throughout the figure. Solid lines crossing all samples define the beginning of the arrival or departure of prairie from each site. '?' refers to the projected timing of the vegetation shift. Horizontal bars represent radiometric ages and vertical lines are the 2σ errors. Ages for individual carbon and oxygen isotope values are calculated using linear interpolation between radiometric dates.
speleothems crystallized under equilibrium conditions which preserved the vegetation signal in cave dripwater $\delta^{13}$C values and that the nature of middle Holocene vegetation change was similar at each site. Dorale et al. (1992) linked the onset of heavier speleothem carbon compositions at Cold Water Cave to arrival of prairie at the site, a conclusion supported by macrofossil evidence at nearby Roberts Creek (Baker et al., 1996) (Figure 1). However, the arrival of a prairie signal at Spring Valley occurred approximately 2000 years earlier than at Cold Water Cave. The Mystery Cave carbon signal appears to have behaved similarly to the Spring Valley record, although the shifts are subdued and the sequence does not extend far enough to record the shift to higher $\delta^{13}$C values seen in Spring Valley stalagmites at ~8000 yr BP. Mystery Cave also lies in between Cold Water Cave and Spring Valley, and this may have been a transition zone between prairie and forest that remained with little change during this part of the middle Holocene.

Two pollen and plant macrofossil sequences, one on each side of this proposed ecotone, show clearly the delay in arrival of prairie along the eastern edge. These records are summarized here using the sum of pollen from all trees versus all herbs (Figure 3). At Kirchner Marsh (Wright et al., 1963), the tree pollen began to decrease as herb pollen increased approximately 9000 cal. yr BP when prairie taxa apparently first entered the area. Prairie became dominant approximately 6500 to 4500 cal. yr BP. Following this period, tree pollen increased and forests moved back into the area.

The Roberts Creek record of tree and herb pollen shows a similar but offset pattern (Baker et al., 1996). Tree pollen was dominant in the early Holocene, but its decline was more precipitous and delayed by nearly 2000 years. Prairie was well established at Roberts Creek from 6200 to 3800 yr BP. Trees, mainly oaks, returned to Roberts Creek after 3800 yr BP but were apparently intermixed with prairie in a savannah habitat until Euro-American settlement.

These two pollen sequences are typical of the pollen sites along this mid-Holocene ecotone. Combined with other sites in the Midwest, it is apparent that prairie moved rapidly from the eastern Dakotas eastward through central Iowa and Minnesota between about 11000 and 10000 yr BP and then stalled in southeastern Minnesota and eastern Iowa for several thousand years along a sharp, mainly N–S boundary. Several sites suggest that the warmest and/or driest part of this episode was between about 6500 and 5500 yr BP. On the east side of this boundary, closed deciduous forest was present.

The cause of the sharp boundary between prairie and forest in the mid-Holocene is probably a long-term boundary separating zonal flow (Pacific air masses) where prairie was present and meridional flow (Gulf of Mexico air masses) where mesic forests were growing. Such enduring, sharp transitions in modern biomes are not unprecedented. In northwestern Minnesota, for example, McAndrews (1966) showed that prairie, deciduous forest and conifer-hardwood forest have remained compressed for 4000 years across what is presently a steep moisture gradient and a moderate temperature gradient (~25–50 mm precipitation and ~1°C in growing season temperature in 40 km). Although fire is also considered to have been important in controlling the prairie-forest border (Grimm, 1984), fire frequency is also a function of climate.

Covariance of speleothem carbon and oxygen has been traditionally interpreted as indicating non-equilibrium crystallization of speleothem calcite (Fornaca-Rinaldi et al., 1968; Fantidis and Ehnhalt, 1970) owing perhaps to evaporation of dripwater (causing $^{18}$O enrichment with concomitant CO$_2$ outgassing resulting in higher $^{13}$C/$^{12}$C ratios) in an arid cave environment. However, the similarity of both carbon isotopic trends and $\delta^{13}$C values between caves suggests that the carbon isotopic signatures of these speleothems record a regional event (i.e., replacement of deciduous forest by prairie), while the oxygen signatures may be reflecting local pre-infiltration evaporative effects in response to increased middle-Holocene aridity and the loss of tree canopies capable of sheltering not-yet-infiltrated water from sun and wind. While air mass interactions could theoretically stabilize steep moisture gradients, it appears unlikely that such a steep temperature gradient could be sustained. If we assume that evaporative effects are not significant, we can combine the temperature dependence of calcite-water fractionation factors with relationships linking latitude and precipitation $\delta^{18}$O (see Dorale et al., 1992) and calculate that mean annual temperature at Cold Water Cave would have been more than 3°C warmer than at Spring Valley between 8000 and 6000 years BP. As such a large temperature gradient is unlikely, we argue instead for increased evaporative effects which disguised the $\delta^{18}$O temperature signal.

In contrast to the large offsets in the timing of the advance of prairie during the early middle Holocene, the similar timing of

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**Figure 3** Pollen sequences from two sites on opposing sides of the middle-Holocene prairie-forest border illustrating the ~2000 year offset in the arrival of prairie. Pollen data and chronologies were compiled from the North American Pollen Database (National Geophysical Data Center, NOAA Paleoclimatology Program).
the shift from heavy to lighter speleothem carbon during the late middle Holocene suggests that prairie retreated rapidly from each site. While the increased $\delta^{13}C$ values at the very bottom of Crystal Cave stalagmite CC-A may record a regional shift from prairie back to deciduous forest at the end of the middle Holocene dry period, the extremely light carbon compositions ($\sim$12‰) between 2700 and 500 years BP suggest that local vegetation was C$_4$-rich. A change to heavier carbon at Crystal Cave (CC-A), Spring Valley (SV-1), and Cold Water Cave (1S) suggests that this increase was also regional, although whether it reflects cultivation of C$_4$ crops such as corn, shifts in plant communities driven by wildfires set accidentally or deliberately by Native Americans before European settlement, or a climatic signal is unclear because age uncertainty does not allow a precise comparison of these recent events. Fluorescent banding studies are in progress, however, that may shed light on the synchronicity of these shifts.

**Conclusions**

Speleothem $\delta^{13}C$ values indicate that the prairie-forest ecotone remained roughly stationary (within tens of kilometres) for approximately 2000 years during the early and middle Holocene. The position of this boundary appears to have been determined by a steep moisture gradient caused by the eastward encroachment of Pacific air into the northern Midwest which decreased effective moisture during the growing season. Although oxygen isotopic compositions of speleothem calcite increased during this prairie period, higher $\delta^{18}O$ values do not appear to reflect an increase in mean annual temperature because temperature gradients would have to have been extremely steep ($\sim$1°C/15 km) between Cold Water Cave and Spring Valley Cave.

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