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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 ^{18}O 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

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picture of middle-Holocene vegetation change along the northeastern 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 Stewartville 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 mid-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 CO_2 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 ^{238}U-^{234}U-^{230}Th 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.

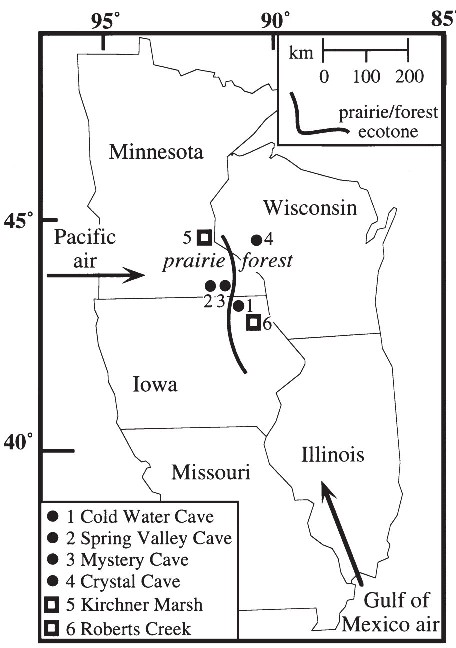

Figure 1 Map of the northern Midwest showing site locations and interpreted middle-Holocene prairie-forest ecotone.

Climate signals in speleothem calcite

Dissolution of CO_2 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 $\delta^{13}C$ values should therefore reflect shifts in the type of vegetation overlying the cave. Plants utilizing the C_4 photosynthetic pathway respire and decompose into carbon dioxide with higher $\delta^{13}C$ values than do C_3 plants. These two vegetation types are frequently found in close association, but C_3 plants are most abundant in cool and moist climates and C_4 plants predominate in warm, arid environments. Therefore, the $\delta^{13}C$ values of speleothem calcite reflect climatic conditions (Dorale *et al*., 1992). However, because the CO_2 produced by both C_3 and C_4 vegetation ranges by approximately 10‰ (–32‰ to –20‰ for C_3 and –19‰ to –9‰ for C_4) (Boutton, 1991), we do not attempt to constrain absolute C_4/C_3 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 $\delta^{18}O$ values of water, but neither plant activity nor dissolution of carbonate bedrock significantly affects water isotopic composition. Assuming minimal evaporative enrichment of ^{18}O, the relationships between mean annual temperature and the oxygen isotopic composition of precipitation (higher $\delta^{18}O$ 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 $\delta^{18}O$ values at higher temperatures; however, the change in $\delta^{18}O$ values of precipitation with temperature is larger than the change in $\delta^{18}O$ values due to fractionation during precipitation so that the net result is higher speleothem $\delta^{18}O$ 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 $\delta^{13}C$ values (as C_4 plants become increasingly abundant) and $\delta^{18}O$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ record spiked up to –7.5‰ between 1800 and 2000 yr BP and to –8.5 at the bottom of CC-

Table 1 Uranium and thorium isotopic ratios and ^{230}Th/^{234}U ages

Sample¶	mm from* bottom	^{238}U (ng/g)	^{232}Th (pg/g)	δ^{234}U§ measured	^{230}Th/^{238}U activity	^{230}Th/^{232}Th atomic	Age†
SV-1	23	1260	2400	660 (3)	0.123 (1)	1.07e-3 (1)	8340 (90)
SV-1	76	1340	1340	650 (3)	0.116 (90)	1.91e-3 (2)	7880 (60)
SV-1	200	1590	780	690 (4)	6.90e-2 (3)	2.31e-3 (2)	4510 (30)
SV-1	277	2410	690	630 (2)	6.34e-2 (4)	3.65e-3 (60)	4300 (30)
SV-1	375	1570	480	670 (10)	5.14e-2 (3)	2.75e-3 (3)	3400 (30)
SV-1	535	1920	4080	660 (3)	2.63e-2 (9)	2.04e-4 (8)	1700 (60)
SV-1	602	1730	2190	710 (5)	1.06e-2 (1)	1.37e-4 (2)	650 (10)
SV-2	188	1800	1330	700 (4)	9.63e-2 (21)	2.13e-3 (6)	6300 (140)
SV-2	466	1710	1760	670 (4)	4.48e-2 (36)	7.16e-4 (74)	2930 (240)
SV-2	540	1280	2790	704 (3)	3.19e-2 (1)	2.40e-4 (2)	2020 (20)
MC-28	9	1170	1100	740 (2)	0.113 (1)	1.99e-3 (3)	7270 (70)
MC-28	176	1370	210	820 (4)	7.74e-2 (1)	8.10e-3 (50)	4700 (70)
CC-A	8	340	550	680 (4)	4.38E-2 (11)	4.44e-4 (10)	2840 (80)
CC-A	139	390	230	650 (3)	2.38E-2 (3)	6.59e-4 (17)	1560 (20)
CC-A	225	330	660	640 (3)	1.27e-2 (4)	1.05e-4 (3)	810 (30)

¶Analyses of Cold Water Cave stalagmite 1S are tabuluated in Dorale *et al.* (1992).
*The total length of SV-1 = 635 mm; SV-2 = 560 mm; MC-28 = 317 mm; CC-A = 311 mm.
§$\delta^{234}U_{measured} = [(^{234}U/^{238}U)_{measured}/(^{234}U/^{238}U)_{eq} - 1] \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ is the secular equilibrium atomic ratio: $\lambda_{238}/\lambda_{234} = 5.472 \times 10^{-5}$. Values in parentheses are 2σ uncertainties.
†Ages are relative 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}Th assuming an initial ^{230}Th/^{232}Th ratio of 4.4×10^{-6} ($\pm 2.2 \times 10^{-6}$). 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.

A. Without a longer record it is impossible to determine whether the elevated Δ^{13}C values at the bottom of the stalagmite represents a long-term shift in overlying vegetation or a short-term peak. The δ^{18}O 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. These high-precision age data confirm Lively's (1983) alpha counting dates from this sample. The average growth rate of this sample is 40 μm/year. From the present back to about 1500 yr BP, the δ^{18}O values in the stalagmite remained relatively constant at about 24‰. The δ^{18}O values decreased steadily from 26‰ to 24‰ between 5000 and 1500 years BP. The oldest part of this record shows short-term fluctuations of up to 1‰ about a value of approximately 26‰. The carbon isotopes in MC-28 display only weak evidence of significant shifts between the present and 7270 years BP. The δ^{13}C values for the entire speleothem average -5.5 ± 0.4‰ (1σ). The average δ^{13}C value for the top half of MC-28 (0 to 3500 years BP) is -6.0 ± 0.4‰ while the value for the bottom half (3500–7280 yr BP) is -5.3 ± 0.7‰.

Spring Valley Cave, Minnesota

Spring Valley stalagmite SV-1 was active when collected and appears to have grown continuously since approximately 8500 years BP at an average growth rate of 75 μm/year (Figure 2). During this interval, carbon isotopic values underwent five significant shifts. First, δ^{13}C values increased from –9‰ to –5‰ between 8000 and 7600 years BP. Although marked by substantial (>2‰) variability, this period of isotopically heavy carbon continued until approximately 3000 years BP at which time δ^{13}C values began decreasing, reaching –9‰ by 1900 years BP. Carbon exhibited a less substantial and shorter-lived increase between 1900 and 1300 years BP with maximum δ^{13}C values reaching –7‰. Carbon values decreased again between 400 and 100 years BP, and then increased to –5.5‰ in the last 100 years.

Oxygen isotopes are less variable but mimic millennium-scale carbon trends. Early Holocene δ^{18}O values of –24.5‰ increased to 26.0‰ during the middle Holocene and returned to 24.5‰ during the late Holocene.

Stalagmite SV-2 grew from 7700 to 1800 years BP at an average growth rate of 115 μm/year and is characterized by average carbon and oxygen isotopic compositions similar to SV-1. The δ^{13}C values of SV-2 decreased gradually from –6‰ to –8‰ between 2800 and 1800 years BP, and δ^{18}O values decreased from 26.0‰ to 24.0‰ over the same interval.

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 (~3‰) at approximately 5900 years BP (Denniston *et al.*, 1999) (Figure 2). Maximum δ^{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 δ^{13}C values began decreasing, stabilizing at approximately –7.5‰ by 2000 years BP.

Although early and late Holocene δ^{18}O values are very similar among these three stalagmites, oxygen isotopic compositions vary significantly during the middle Holocene, with elevated δ^{18}O values in 1S, decreased δ^{18}O values in 2SS, and largely unchanged δ^{18}O values in 3L. The similarity of carbon signatures coupled with the wide variability in δ^{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 δ^{13}C values of the Cold Water Cave, Mystery Cave and Spring Valley Cave speleothems demonstrate that these

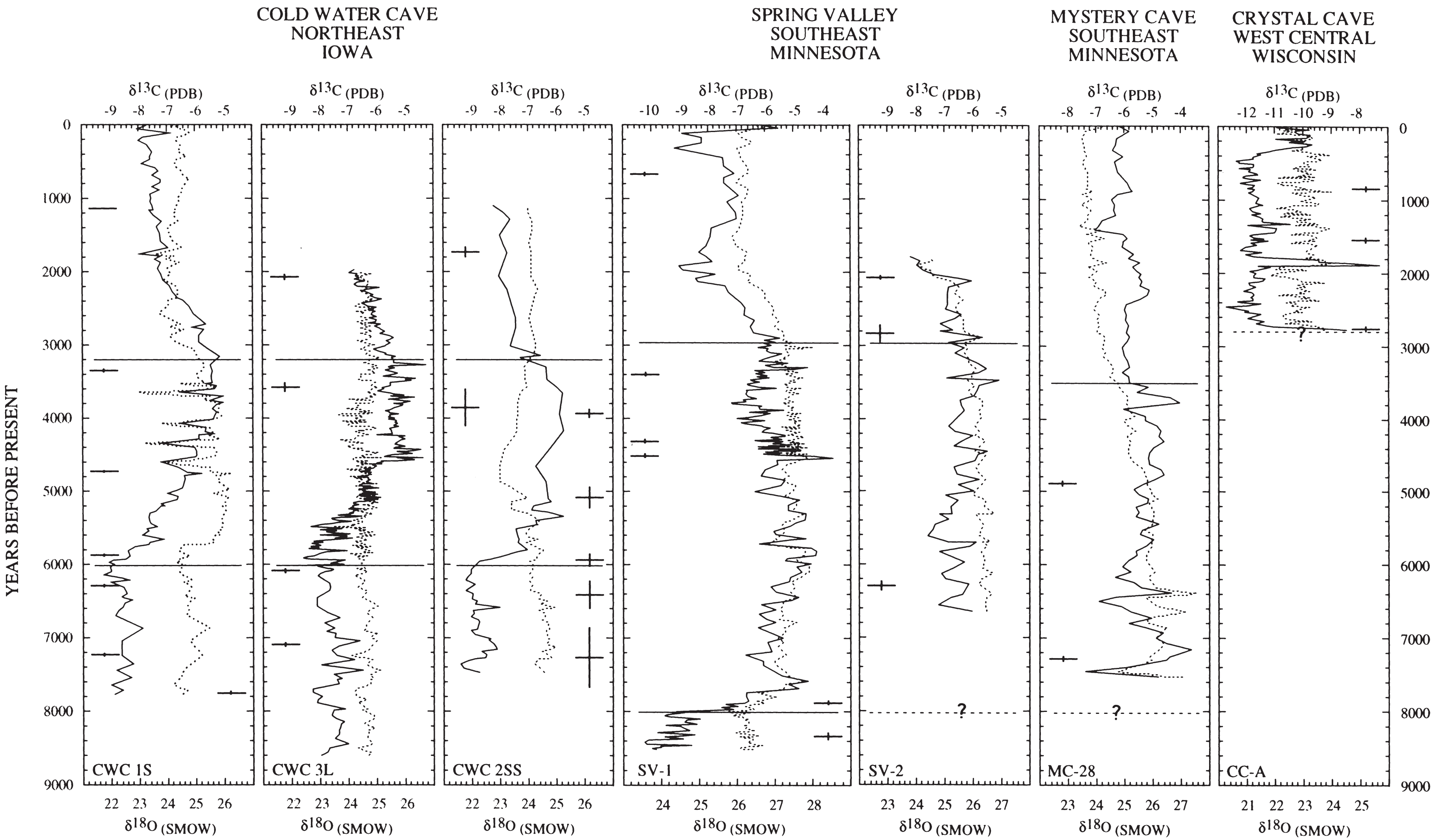

Figure 2 Carbon (solid lines) and oxygen (dotted lines) isotopic trends for each stalagmite discussed in this study. The scales for both carbon and oxygen have ranges of 6‰ for all speleothems except for SV-1. The scale for SV-1 has a range of 8‰ for both isotope ratios. The absolute distance representative 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 δ^{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 δ^{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 11 000 and 10 000 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 Ehhalt, 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 δ^{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 δ^{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 δ^{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

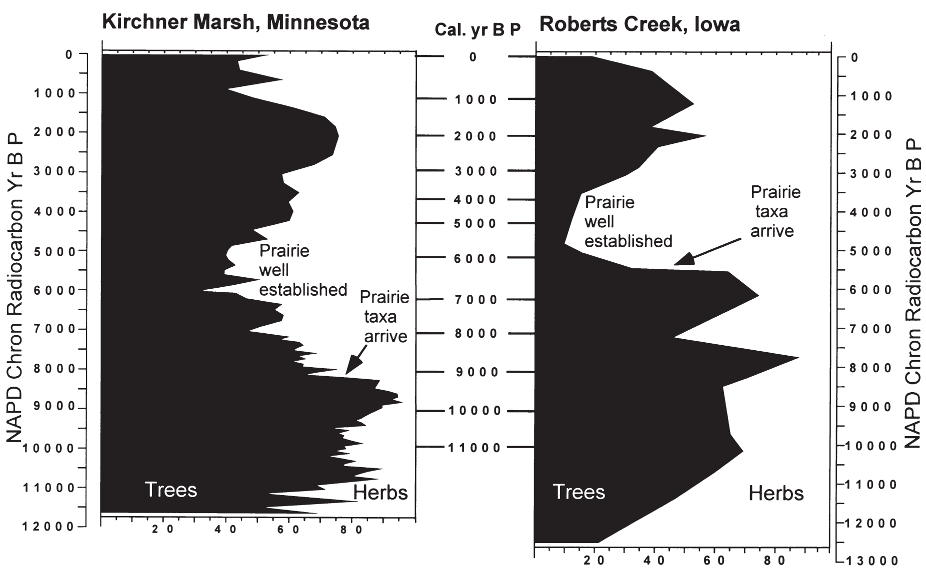

Figure 3 Pollen sequences from two sites on opposing sides of the middle-Holocene prairie-forest border illustrating the >2000 year offset in the arrival of prairie. Pollen data and chronologies were compiled from the North American Pollen Database (National Geophysical Data Center, NOAA Paleoclimatology 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 (–12‰) between 2700 and 500 years BP suggest that local vegetation was C_3-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 synchroneity 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 (~1°C/15 km) between Cold Water Cave and Spring Valley Cave.

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