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Episodes of late Holocene aridity recorded by stalagmites from Devil's Icebox Cave, central Missouri, USA

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Abstract

Two stalagmites from Devil's Icebox Cave, central Missouri, display similar $\delta^{13}C$ and $\delta^{18}O$ values and trends during the late Holocene. Positive $\delta^{13}C$ excursions at 3.5–2.6 ka and 1.2–0.9 ka are interpreted to reflect drier conditions. These elevated stalagmite $\delta^{13}C$ values could have plausibly been driven by increasing C_4 plant abundances over the cave or an increased contribution of bedrock carbon, both of which could reflect decreased effective moisture. A lack of corresponding oxygen isotopic anomalies during these intervals suggests that neither mean annual temperature nor the seasonality of precipitation changed concomitantly with dryness. Both of the $\delta^{13}C$ excursions identified in our stalagmite record are roughly coincident with dry intervals from a number of sites located across the Great Plains.

Keywords: Speleothem; Prairie; Late Holocene; Dryness; Carbon; Oxygen; Isotope

Introduction

Across the Great Plains of the central United States, relatively small decreases in precipitation have led to significant geomorphic consequences, including the re-activation of dunes (Madole, 1994; Stokes and Swinehart, 1997; Mason et al., 2004). Age constraints on dune mobility have revealed that the Great Plains experienced multiple episodes of decadal to centennial-scale drought during the late Holocene (Miao et al., 2007). However, how these drought intervals impacted areas east of the Great Plains is not as well understood. Here we present a continuous late Holocene stalagmite record from the northern margin of the Ozark Plateau, located in the relatively humid environment of central Missouri, that contains isotopic shifts attributable to elevated aridity. The fact that these stalagmites grew continuously and are datable by U-Th methods allows for a more precise understanding of the nature and timing of late Holocene drought in the eastern Great Plains.

Geological and ecological setting

Devil's Icebox Cave (38.9°N, 92.3°W) is located in Rock Bridge State Park, near Columbia, Missouri, on the northern margin of the Ozark Plateau (Fig. 1). The cave is developed in the Mississippian Burlington-Keokuk limestone and contains more than 5 km of passage. There is only one natural entrance, a 1 × 3 m opening out of which discharges Rock Bridge creek, which drains a 37-km^2 basin. The cave maintains a temperature of 13 °C and high humidity with minimal seasonal variability (R. Campbell, personal communication). The park contains a mixture of oak and hickory forest and restored prairie/savanna, characteristic of the presettlement vegetation of the region that lies within the diffuse prairie-forest ecotone. Soils over the cave are typically 0.5–1.0 m thick silty clay loam. The climate of the

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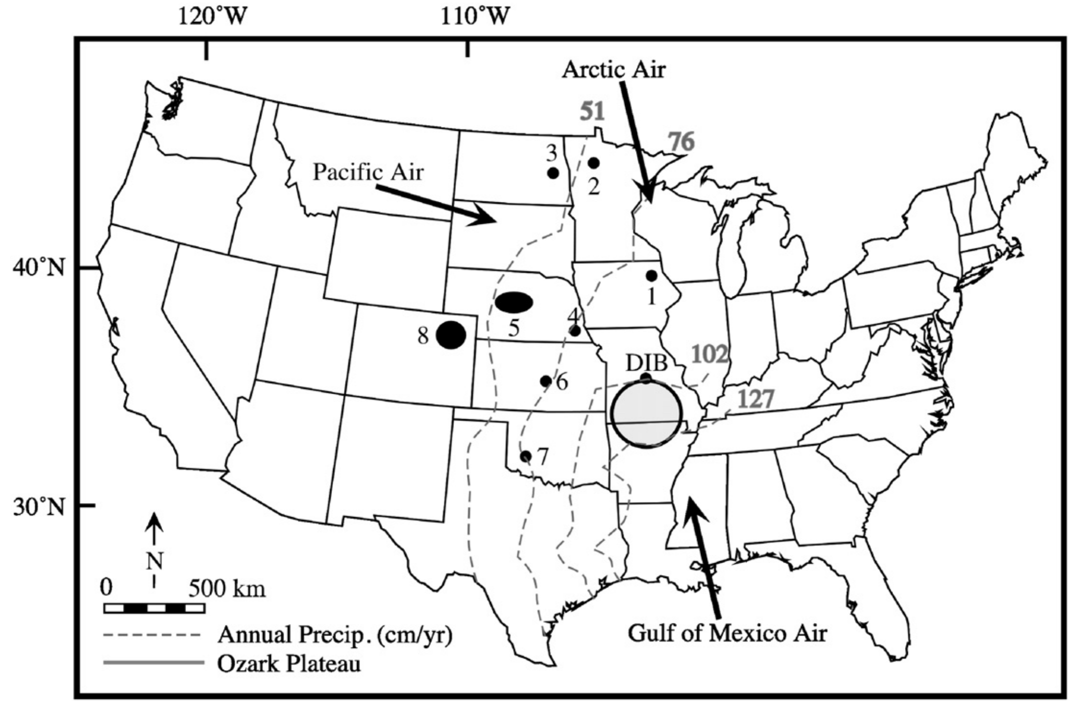

Figure 1. Map of the central United States including the locations of sites described in the text (black ovals): Devil's Ice Box cave (DIB); (1) Cold Water Cave; (2) Elk Lake (Bartlein and Whitlock, 1993); (3) Moon Lake (Grimm and Clark, 1998); (4) Little Nemaha River (Baker et al., 2000); (5) Nebraska Sand Hills (Stokes et al., 1999; Swinehart, 1998; Stokes and Swinehart, 1997; Miao et al., 2007); (6) Great Bend Sand Prairie (Arbogast, 1996); (7) Carnegie Canyon (Hall and Lintz, 1984); (8) various dune fields (Clarke and Rendell, 2003; Forman et al., 1995) and the Ozark Plateau (gray oval). Gray lines represent annual average precipitation (cm).

area is characterized by warm, humid summers and cool, drier winters (Fig. 2). In this area, dryness increases with distance west from the boundary between the Ozark Plateau and the Great Plains (~95°W longitude) in response to decreasing amounts of precipitation carried by Gulf of Mexico air masses (Fig. 1) and an increase in the dominance of relatively dry Pacific air masses.

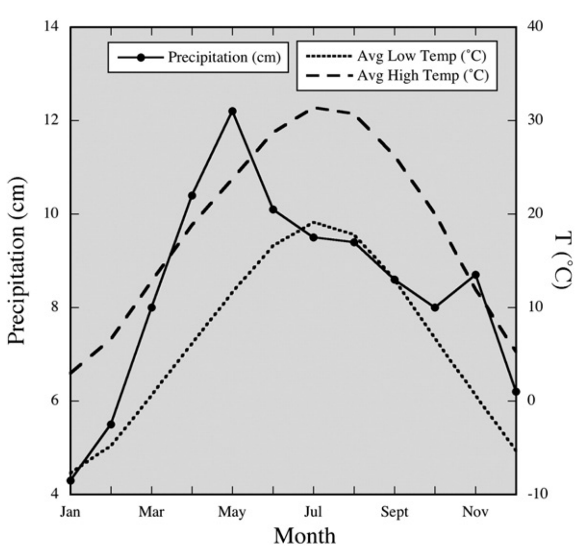

Figure 2. Monthly averages for the years 1971–2000 for Rock Bridge State Park (http://www.rssweather.com/climate/Missouri/Columbia/).

Methods

Two broken and down stalagmites, DIB-1 and DIB-2, were obtained from the Second Breakdown Room (Fig. 3), located approximately 30 m below the land surface and 1750 m from

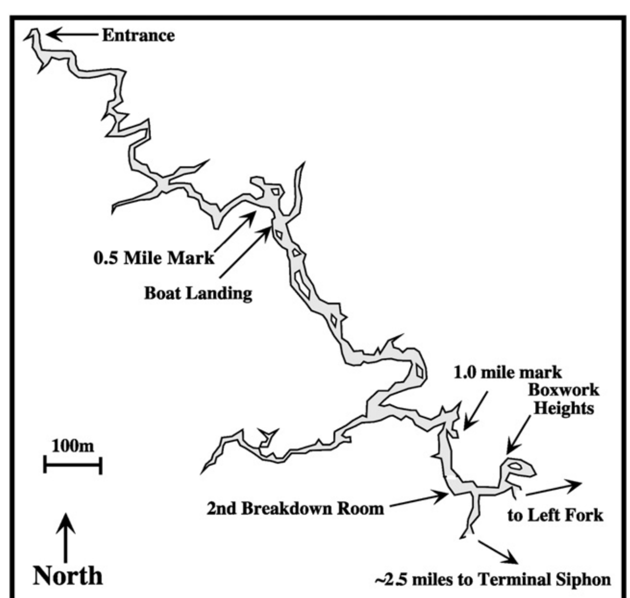

Figure 3. Map of portion of Devil's Ice Box cave including location of Second Breakdown Room and Boxworks Heights where stalagmites were collected.

the entrance to Devil's Icebox Cave. The stalagmites were cut in half, polished and inspected. DIB-1 and DIB-2 are 21 and 14 cm tall, respectively, and are composed of dense, clear, finely-crystalline calcite with distinct growth bands and without evidence of any interruptions in growth (Fig. 4). DIB-2 contains minor porosity along its central axis likely related to drip splash. A third late Holocene stalagmite, DIB-3, was collected from Boxwork Heights, a different room located tens of meters from the Second Breakdown Room (Fig. 3) and was ultimately rejected because of high porosity from the central axis to the exterior and isotopic evidence of disequilibrium crystallization (see Results).

A total of nine U-Th dates were obtained from DIB-1 and DIB-2 (Table 1) using thermal ionization mass spectrometry at the University of New Mexico Radiogenic Isotope Laboratory. Approximately 150 mg of calcite was milled from the center of the stalagmite using a computer-guided drill and processed using standard chemical separation techniques (Chen et al., 1986). U and Th were measured on a Micromass Sector 54 thermal ionization mass spectrometer with a high-abundance sensitivity filter. All isotopes of interest (^{236}U, ^{235}U, ^{234}U, ^{233}U, ^{232}Th, ^{230}Th, ^{229}Th) were measured on an ion-counting Daly multiplier, requiring very little background correction even for samples with large ^{232}Th content. Multiplier dark noise was about 0.3 counts per second. An NBL-112A U standard was measured during the course of this study and was in the range of 0.1% of the accepted ^{234}U/^{238}U ratio. Detrital (unsupported) ^{230}Th was corrected for using an initial ^{230}Th/^{232}Th ratio of 4.4 ppm (±50%). This detrital ^{230}Th correction uncertainty of ±50% when combined with the relatively low ^{230}Th/^{232}Th ratios measured in many of the DIB samples is responsible for the relatively large reported age uncertainties—uncertainties that are significantly larger than those imparted solely by analytical error.

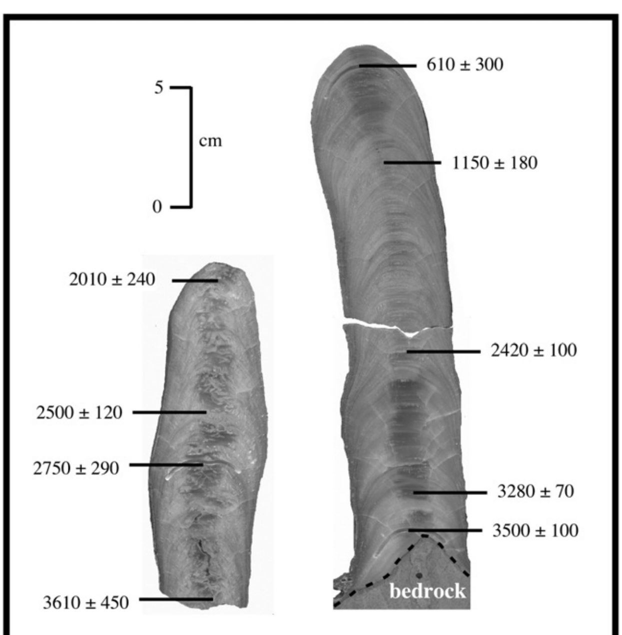

Figure 4. Cross-sections of DIB-1 and DIB-2 including dated intervals and corresponding U-Th ages (with 2σ age uncertainties).

Stalagmites were sampled for stable isotope ratios at 3-mm intervals using a 0.3-mm bur; δ^{13}C and δ^{18}O values of powdered carbonates (0.1 mg) were measured using a Finnigan MAT 252 with a Kiel III automated carbonate device at the University of Iowa's Paul H. Nelson Stable Isotope Laboratory. Daily analysis of NIST and in-house standards produced an analytical precision better than 0.1‰; stable isotope data are reported relative to the PDB standard. Oxygen and U-Th isotopic analyses integrate approximately 5 and 30 yr of growth, respectively. Ages were assigned to individual oxygen isotopic analyses via linear interpolation between consecutive U-Th dates on each stalagmite. Where necessary, radiocarbon dates from the literature were converted to calendar years BP using the Calib 5.0 program (Stuiver and Reimer, 1993).

Carbon isotopes in speleothem calcite as indicators of vegetation

Dorale et al. (1992) and Baker et al. (1998) linked stalagmite δ^{13}C values to the advance and retreat of prairie grasses in northeastern Iowa. Since then, a great deal of research has been focused on understanding the mechanisms that determine δ^{13}C values and variability in speleothem calcite (for a detailed overview, see review papers by Dorale et al., 2002; Quade, 2004). In general, the four mechanisms capable of producing elevated δ^{13}C values at Devil's Icebox Cave are

(1) an increase in the proportion of C_4 to C_3 plants;
(2) a decrease in soil respiration rates leading to an increased contribution of atmospheric CO_2 to soil gas;
(3) fractionation of carbon isotopes during infiltration and/or the drip step; and
(4) an increased limestone carbon component.

The δ^{13}C value of soil CO_2 reflects the type (C_4 vs. C_3) of soil organic matter and surficial vegetation. The δ^{13}C values of C_3 (e.g., trees and some grasses) and C_4 (e.g., many prairie grasses) plants average −27‰ and −12‰, respectively (Tieszen and Boutton, 1989). The δ^{13}C value of CO_2 respired by vegetation is nearly identical to that of the vegetation itself, and thus changes in vegetation type should result in concomitant shifts in the δ^{13}C values of soil CO_2. The isotopic composition of soil CO_2 is also impacted by differential molecular diffusion of $^{13}CO_2$ and $^{12}CO_2$ at rates proportional to their relative concentrations in the soil atmosphere. For example, at soil CO_2 concentrations of $10^{-2.0}$, the δ^{13}C values of CO_2 respired by C_3 and C_4 vegetation (−27‰ and −12‰, respectively) is elevated by diffusion by ~4‰ to −22‰ and −8‰, respectively (Cerling, 1984), although this may not apply to all cave systems. This diffusion gradient also reflects contributions from atmospheric CO_2, and as pre-industrial atmospheric CO_2 δ^{13}C values average −6‰ (Broecker and Peng, 1982), increases in atmospheric CO_2 should result in elevated soil CO_2 δ^{13}C values. Atmospheric components become negligible outside deserts at depths exceeding ~10 cm (Cerling,

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

Sample	Distance from bottom (mm)	^{238}U (ng/g)	^{232}Th (ng/g)	$\delta^{234}U$ [a] (measured)	$^{230}Th/^{234}U$ (activity)	$^{230}Th/^{232}Th$ (atomic)	Uncorrected age (ka)	Corrected [b, c] Age (ka)
DIB-01-1	220	1260	40.83	633 (9)	0.0110 (3)	9.0e−6 (0.1)	1.21 (0.03)	0.61 (0.30)
DIB-01-1	181	1380	27.32	731 (5)	0.0136 (6)	1.9e−5 (0.1)	1.49 (0.06)	1.15 (0.18)
DIB-01-1	85	1830	18.80	880 (7)	0.0234 (5)	7.1e−5 (0.1)	2.59 (0.05)	2.42 (0.10)
DIB-01-1	26	2450	4.43	1056 (6)	0.0298 (5)	5.6e−4 (0.1)	3.30 (0.07)	3.28 (0.07)
DIB-01-1	13	2550	27.07	1023 (8)	0.0330 (5)	1.0e−4 (0.02)	3.66 (0.07)	3.50 (0.10)
DIB-01-2	140	2510	42.74	653 (4)	0.0225 (3)	3.6e−5 (0.1)	2.48 (0.03)	2.01 (0.24)
DIB-01-2	84	2200	28.30	707 (4)	0.0247 (4)	5.4e−6 (1)	2.72 (0.03)	2.50 (0.12)
DIB-01-2	64	1120	39.16	758 (11)	0.0299 (9)	2.6e−5 (0.1)	3.30 (0.10)	2.75 (0.29)
DIB-01-2	7	1900	95.61	702 (5)	0.0404 (6)	2.2e−5 (0.1)	4.49 (0.07)	3.61 (0.45)

[a] $\delta^{234}U_{measured} = [(^{234}U/^{238}U)_{measured}/(^{234}U/^{238}U)_{eq} - 1] \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ is the secular equilibrium atomic ratio: $\lambda_{238}/\lambda_{234} = 5.472 \times 10^{-5}$.
[b] The initial $^{230}Th/^{232}Th$ ratio of $4.5 \times 10^{-6} \pm 2.25 \times 10^{-6}$ was subtracted from measured $^{230}Th/^{232}Th$ ratios (see text).
[c] Values in parentheses represent 2σ errors in the last significant figure.

1984); but in thin soils decreases in soil respiration (root respiration + microbial oxidation of organic material) can lead to an increase in atmospheric CO_2 in the soil and thus elevated speleothem $\delta^{13}C$ values (Frumkin et al., 2000).

Increases in speleothem $\delta^{13}C$ values unrelated to vegetation change may occur by rapid infiltration of water through the soil zone that precludes it from reaching isotopic equilibrium with soil CO_2 and degassing of drip water in voids above the cave or in the cave itself (Baker et al., 1997). Thus, tests for equilibrium calcite precipitation in a single stalagmite (e.g., the Hendy Test) are insufficient for detecting all modified $\delta^{13}C$ signals. The most reliable method for ensuring that speleothem calcite accurately reflects paleovegetation is the documentation of multiple speleothems with similar $\delta^{13}C$ values and trends from the same cave (Dorale et al., 1998; Denniston et al., 1999).

Temporal variations in the influence of bedrock carbon on speleothem $\delta^{13}C$ values may also occur due to changes in infiltration hydrology. Pedogenic carbonates form in soils with an essentially unlimited pool of CO_2 and do not derive appreciable carbon from the dissolution of associated carbonate rocks (Quade et al., 1989). Speleothems, on the other hand, form from waters that have passed through the soil into the more closed system of the underlying karst. In this case, approximately half of the carbon in the solution is derived from dissolution of carbonate bedrock (average $\delta^{13}C = \sim 0 \pm 4‰$) (Hendy, 1971). However, the rate of infiltration can impact the nature of this closed system behavior. When the transit time through the bedrock is short (possibly due to conduit flow or a shallow cave), the solution may not reach equilibrium with bedrock carbonate. A slowing of infiltration rate could therefore increase the contribution of bedrock carbon in the infiltrating solution, thereby increasing stalagmite $\delta^{13}C$ values.

Oxygen isotopes in speleothem calcite as indicators of climate

The oxygen isotopic composition of speleothem calcite reflects the $\delta^{18}O$ value of infiltrating meteoric waters, crystallization temperature, kinetic effects and/or post-crystallization alteration. As previously discussed, screening for kinetic effects, alteration and even pre-infiltration evaporative enrichment of ^{18}O in meteoric waters is accomplished by the existence of identical values and trends in multiple coeval stalagmites. Unless drip water evolves significantly (for example, via multiple steps of calcite crystallization and subsequent dissolution) during its pathway into the cave (Baker et al., 1997), oxygen isotopes of cave drip water should reflect the oxygen isotopic composition of effective infiltration and the temperature at which the calcite precipitates from the dripwater. For middle latitude regions, the global average relationship between the oxygen isotopic composition of mean annual precipitation (MAP) and mean annual temperature (MAT) is +0.6‰/°C (Dansgaard, 1964; Gat, 1980), and the temperature dependence of oxygen isotopic fractionation in the calcite–water system is −0.23‰/°C. Coupling these two relationships yields a speleothem $\delta^{18}O$ vs. mean annual temperature relationship of ~0.35‰/°C (Dorale et al., 1992). The overall functionality of this relationship has been demonstrated for other speleothems from this region (Dorale et al., 1998), and we apply it here.

Results

The chronologies of DIB-1 and DIB-2 are derived from linear interpolation between the U-Th mass spectrometry dates obtained from each stalagmite. In both speleothems, growth rates remain largely unchanged from the base to the top of each stalagmite (69 ± 9 μm/yr; $n = 4$ (1σ) and 86 ± 24 μm/yr; $n = 3$, for DIB-1 and DIB-2, respectively) (Fig. 5). Although analytical precision was better than 1% for both U and Th isotopic ratios, errors on U-Th ages range from 2% to as high as 50% due to the variable concentration of ^{232}Th at each dated interval and the quoted uncertainty in the initial $^{230}Th/^{232}Th$ ratio. The ^{232}Th concentration may change significantly from one point in a stalagmite to another and is, in the case of DIB-1 and DIB-2, tied to the amount of detritus, particularly clays, incorporated into the speleothem (Dorale et al., 2004). The measured $^{230}Th/^{232}Th$ ratio is adjusted by subtracting an assumed $^{230}Th/^{232}Th$ ratio equal to that of crustal silicates, which has an average value 4.4 ppm, as follows:

$$^{230}Th_{corrected} = {}^{230}Th_{measured} - \left[{}^{232}Th_{measured} \times \left(\frac{^{230}Th}{^{232}Th} \right)_{crustal} \right]$$

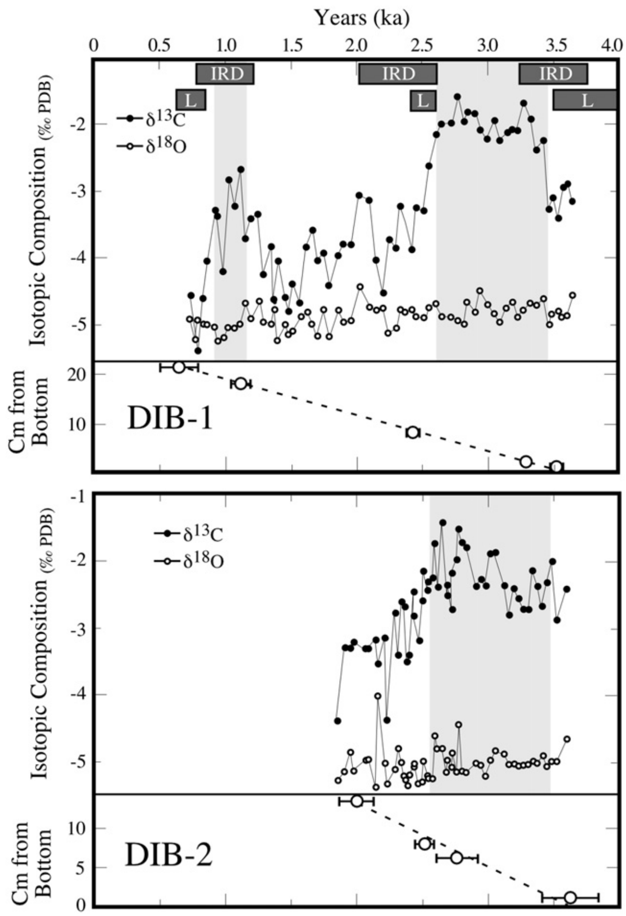

Figure 5. Carbon (filled circles) and oxygen (open circles) isotopic profiles for DIB-1 and DIB-2 with dated intervals (large circles) and two-sigma age uncertainties (horizontal bars). Gray boxes denote intervals of elevated carbon isotopic values corresponding to high C_4/C_3 ratios or low infiltration rates at Devil's Icebox. Dark boxes near top denote ice-rafted debris (IRD) minima as presented in Miao et al. (2007) after data in Bond et al. (2001).

Since this ratio is not well constrained in DIB stalagmites, however, it is included with an uncertainty of ±50%. It is unfortunate that the upper date on DIB-1 has an unusually large ^{232}Th abundance, and thus a large age correction, but the corrected age falls in line with the expected age based on dates from older sections of the same stalagmite, all of which have considerably smaller initial ^{232}Th corrections.

Carbon and oxygen isotopic ratios and trends in DIB-1 and DIB-2 are similar (Fig. 5). Oxygen isotopic ratios exhibit little overall variability for DIB-1 (average = −4.9 ± 0.2‰; n = 66) and DIB-2 (average = −5.0 ± 0.2‰; n = 53), and both define similar trends of decreasing δ^{18}O values with time (approximately 0.1‰/1 kyr). DIB-3, the stalagmite that was rejected, contains δ^{18}O values similar to those of DIB-1 and DIB-2 but with significantly higher variability (average = −4.9 ± 0.6‰; n = 64). In addition, δ^{13}C values were extremely noisy, with a ∼2‰ offset between numerous adjacent stable isotope samples.

The δ^{13}C trends in DIB-1 and DIB-2, however, are considerably less noisy and instead shift smoothly over several hundred years across a range of 2–3‰. The general trend is of a prominent positive δ^{13}C excursion from ∼3.5 to 2.6 ka although δ^{13}C values begin increasing at 3.6 ka and decline until 2.4 ka. A second, less pronounced positive δ^{13}C anomaly occurs from 1.2 to 0.9 ka with δ^{13}C values beginning to rise at 1.5 ka and falling until 0.8 ka.

Discussion

Origins of DIB stalagmite δ^{13}C values and variability

According to the model presented above, the periods of elevated δ^{13}C values in DIB speleothems could result from non-equilibrium fractionation of carbon isotopes during infiltration or the drip step (Mickler et al., 2006). However, the likelihood of these effects producing such similar carbon and oxygen trends in multiple stalagmites is unlikely (Denniston et al., 1999). Alternatively, these intervals could reflect an increased contribution of atmospheric carbon, perhaps through a decrease in soil respiration rates. Given the thickness of the soils above DIB, this too seems unlikely. Or, changes in infiltration hydrology may have resulted in a greater bedrock carbon contribution. Finally, increases in C_4 biomass could have increased soil gas δ^{13}C values. A study by Hsieh (1993) near Devil's Icebox Cave found soil organic turnover rates on labile fractions to be on the order of decades, supportive of the contention that DIB speleothems should record the timing of vegetation change, if that is indeed the mechanism changing δ^{13}C values, with the minor lag due to soil carbon reservoir effects.

Enrichment in ^{13}C of ∼10‰ occurs as CO_2(g) dissolves in infiltrating meteoric waters and moves through the chemical steps that lead to speleothem calcite (Hendy, 1971). Thus, given a bedrock δ^{13}C value of +3‰ for the Burlington-Keokuk limestone in central Missouri (Banner and Kaufman, 1994; Cramer et al., in press) and assuming applicability of the Cerling diffusion model to this system, a C_3-dominated deciduous forest vegetation with an average δ^{13}C value of −27‰ would theoretically produce stalagmite δ^{13}C values of approximately −4‰ via Eq. (1).

$$(0.5)(-27‰ + 4‰ + 10‰) + (0.5)(3‰) = -4‰ \quad (1)$$

Prairie vegetation, with an average C_4 value of −12‰, would theoretically result in stalagmite δ^{13}C values of approximately +2.5‰ (Eq. (2)).

$$(0.5)(-12‰ + 4‰ + 10‰) + (0.5)(3‰) = 2.5‰ \quad (2)$$

Thus, the observed shift in stalagmite δ^{13}C values between −2‰ and −4‰ are consistent with a C_4 plant increase in an overall savanna-type vegetation community, either more forest-like or prairie-like depending on the extent that the Cerling diffusion applies at Devil's Icebox.

Origins of DIB stalagmite δ^{18}O trends

If interpreted solely in terms of mean annual temperature, the 0.3‰ decrease in stalagmite δ^{18}O values between 3.6 and 0.8 ka represents ∼1 °C of cooling. Such a decrease is not recorded in stalagmites from Cold Water Cave, northeastern

Iowa (Dorale et al., 1992; Denniston et al., 1999); in fact, these stalagmites exhibit a small *increase* in speleothem $\delta^{18}O$ values from 3.0 ka to the present. The origin of this difference in $\delta^{18}O$ values between Devil's Icebox and Cold Water Cave is unclear. Several variables such as moisture source impact stalagmite $\delta^{18}O$ values (Denniston et al., 1999). The climate of northeastern Iowa is controlled by the interaction of Arctic, Pacific and Gulf of Mexico air masses, while central Missouri is dominated by Gulf of Mexico air. Gulf of Mexico air moisture, which is predominant at both sites, has the highest $\delta^{18}O$ values (Simpkins, 1995). Thus, an increase in Gulf of Mexico moisture during the late Holocene at Cold Water Cave could have increased stalagmite $\delta^{18}O$ values, but given its position farther north, it would likely have had a similar impact at Devil's Icebox. Alternatively, pre-infiltration evaporative controls on the ^{18}O values of drip water have been suggested during the middle Holocene prairie period (Denniston et al., 1999), but these effects do not appear to have played a role in the late Holocene (post-prairie period) at Cold Water Cave. Changes in precipitation seasonality or mean annual temperature would have plausibly altered the abundance of C_4 biomass at DIB because the relation of C_4 vegetation to climate in North American prairies is largely a function of maximum summer temperature and the timing and amount of rainfall (Teeri and Stowe, 1976). But no $\delta^{18}O$ shift occurs contemporaneously with the periods of elevated $\delta^{13}C$ values. Therefore, the monotonic decrease in speleothem $\delta^{18}O$ values throughout both DIB-1 and DIB-2, without any departures during the dry intervals at 3.5–2.6 ka and 1.2–0.9 ka, remains unexplained but supports the notion that neither changes in mean annual temperature nor the seasonality of precipitation were responsible for the periods of elevated $\delta^{13}C$ values.

Comparison with regional records of elevated aridity

Varied lines of evidence point to increased aridity across the Great Plains between ~3.5 and 2.5 ka (Fig. 1). Studies reporting dryness during this interval include Stokes and Swinehart (1997) and Stokes et al. (1999), who interpreted luminescence ages for a parabolic dune in the Sand Hills of Nebraska as indicating discrete dune mobilization events, one of which was 3.5–2.8 ka. Other study areas showing late Holocene dune mobility include south-central Kansas (Arbogast, 1996). By analyzing prairie macrofossils and $\delta^{13}C$ values of soil organic matter, Baker et al. (2000) noted a strong C_4 plant pulse from 3520 to 3030 cal yr BP in southeastern Nebraska. Similarly, Grimm and Clark (1998) identified an increase in Ambrosia pollen from 3800 to 2800 cal yr BP from lakes in the Sand Hills of Nebraska and eastern North Dakota. Analyses of buried soils, buried trees and mollusks from west-central Oklahoma suggest drier-than-present conditions from approximately 3400 to 2800 cal yr BP (Hall and Lintz, 1984). Miao et al. (2007) report an extensive and well-dated (via OSL and ^{14}C) stratigraphic record of dune fields and loess deposits from the Great Plains that preserves evidence of dune and loess mobilization at 4.5–2.3 ka with peaks centered around 3.8 and 2.5 ka and again from 1.0 to 0.7 ka. This latter dry interval at approximately 1.0 ka has also been reported by several authors (Forman et al., 1995; Stokes and Swinehart, 1997; Swinehart, 1998; Stokes et al., 1999; Swinehart et al., 2000; Cook et al., 2004; Mason et al., 2004; Daniels and Knox, 2005), but a clear picture of regional drought is not always evident. For example, multi-proxy evidence from varved lake sediments at Elk Lake, Minnesota, and other areas suggest a warm and moist late Holocene (3.5 ka to present) uninterrupted by significant drought (Bartlein and Whitlock, 1993; Fritz et al., 2001).

The OSL- and radiocarbon-dated record of Miao et al. (2007) offers perhaps the most robust chronology for any late Holocene sequence of aridity changes and thus offers a solid basis for comparison with the Devil's Icebox speleothem record. Within the time frame marked by DIB speleothems, loess mobilization in the Sand Hills clustered at 0.67 ± 0.1 ka, 2.5 ± 0.1 ka and 3.8 ± 0.3 ka (2σ). In contrast, the DIB record suggests a more sustained dry interval between 3.5 and 2.5 ka in central Missouri. Similarly, increases in aridity may have occurred earlier at Devil's Icebox between 1.3 and 0.8 ka (Fig. 5). However, dates on eolian sand contain more scatter than dates on loess, with eolian sand ages ranging back to approximately 1.1 ka, more in agreement with the onset of aridity at Devil's Icebox.

Mid-continent aridity has been linked to cool eastern tropical Pacific sea surface temperatures and a warm north Atlantic (Schubert et al., 2004). Miao et al. (2007) tied increased aridity in central Nebraska at 3.8, 2.5 and 0.7 ka to periods of reduced ice-rafted debris (IRD), but noted that dating errors coupled with lags in the eolian response system make their correlation tenuous. The DIB speleothem record supports a correlation between an IRD minimum and elevated speleothem $\delta^{13}C$ values from ~1.2 to 0.8 ka but does not support this correlation from ~2.6 to 2.0 ka (Fig. 5). In fact, the latter period falls nicely *between* IRD minima. Miao et al. (2007) also investigated the link between ENSO and mid-continent aridity but their interpolation is partly limited by uncertainties in their chronology. The fact that episodes of aridity documented from the Great Plains appear to extend eastward into the more humid areas of the Ozark Plateau suggest that longer, high-resolution speleothem records spread across the Eastern Plains may offer unique insight into the timing and causes of regional aridity.

Conclusions

Two intervals of elevated stalagmite $\delta^{13}C$ values occur at 3.4–2.6 and 1.2–1.0 ka at Devil's Icebox Cave. The exact mechanism driving these changes in stalagmite $\delta^{13}C$ values is unclear, but it appears likely associated with increased aridity, either through increases in C_4 abundance or the proportion of bedrock carbon in infiltrating solutions. The limited impact of temperature change during these elevated $\delta^{13}C$ episodes is supported by the absence of concomitant increases in stalagmite $\delta^{18}O$ values. The observation that the timing of these more arid periods at Devil's Icebox Cave are similar but not identical to the timing of more arid intervals across the eastern Great Plains may be explained by (1) different response rates to climate change among caves, dunes and pollen/macrofossil records; (2) errors and uncertainties among the distinct chronologies (Useries for stalagmites vs. OSL or ^{14}C dunes vs. ^{14}C for pollen/macrofossils); and/or (3) temporal and/or geographic heterogeneity during periods of enhanced aridity. Across the Eastern Plains, karst is abundant and the high temporal resolution inherent to the speleothem record points to its utility in reconstructing episodes of heightened aridity.

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