PERGAMON

Quaternary International 67 (2000) 21–27

Speleothem carbon isotopic records of Holocene environments in the Ozark Highlands, USA

Rhawn F. Denniston[a,*], Luis A. González[a], Yemane Asmerom[b], Mark K. Reagan[a], Heather Recelli-Snyder[a]

[a]Department of Geology, University of Iowa, Iowa City, IA 52242, USA
[b]Department of Earth and Planetary Science, University of New Mexico, Albuquerque, NM 87131, USA

Received 15 January 2000; accepted 10 February 2000

Abstract

The carbon isotopic compositions of six stalagmites from five caves in the Ozark Highlands of central and southern Missouri and northern Arkansas provide a detailed record of early and late Holocene vegetation dynamics. A rapid decrease in speleothem $\partial^{13}C$ values between ~9500 and ~8200 yr BP indicates a period of increased C3 vegetation, suggesting cool and/or moist conditions relative to the earliest Holocene and the prairie-dominated middle Holocene. A second negative $\partial^{13}C$ excursion from ~4500 to ~3000 yr BP interrupts a predominantly C4-rich middle Holocene prairie environment that became established at ~7500 yr BP. Speleothem mineralogical indicators of cave aridity do not support previous inferences of increased regional dryness between 3800 and 3100 yr BP.

1. Introduction

The southern and central Great Plains of North America contain few high-resolution paleoenvironmental records that preserve long sequences of the Holocene or late Pleistocene. Thus, in order to expand our understanding of climate changes on the Great Plains, it is helpful to look at neighboring regions that hold alternative paleoclimatic data sets. The Ozark Highlands border the central Great Plains to the east, and while they are similarly limited in pollen sequences, the Ozarks contain thousands of caves (Bretz, 1956). The carbon isotopic chemistry of speleothems is sensitive to vegetation changes, and as speleothems can be precisely dated using U-series techniques, they have been investigated to understand changes in Holocene (Denniston et al., 1999) and Pleistocene (Dorale et al., 1998) environments in this area. Here, we report temporal trends in the carbon isotopic compositions of six calcite stalagmites from the Ozark Highlands that provide detailed records of Holocene vegetation change, clarify previous climatic interpretations, and identify significant vegetation changes throughout the Holocene.

2. Study area

The Ozark Highlands include the area east of the Great Plains, west of the Mississippi Valley Embayment, north of the Arkansas Valley, and south of the Missouri River (Fig. 1). Paleozoic carbonates and siliciclastic rocks predominate and dip gently outward off the Ozark Dome (Bretz, 1965). The topography of the Ozarks is characterized by rolling hills, the tops of which can extend several hundred feet above adjacent valley floors.

Six stalagmites were obtained from five caves: (1) Bridal Cave, Camdenton, Missouri (38° 01′N, 92° 47′W), (2) Onondaga Caverns, Leesburg, Missouri (38° 03′N, 91° 13′W), (3) Ozark Caverns, Toronto, Missouri (38° 02′N, 92° 02′W), (4) Beckham Creek Cave, Jasper, Arkansas (35° 57′N, 93° 19′W), and (5) Cosmic Caverns, Berryville, Arkansas (36° 26′N, 93° 30′W). Each cave is formed in Paleozoic carbonates including the Cambrian Eminence Dolomite (Bridal Cave), the Ordovician Powell Dolomite (Cosmic Caverns), the Ordovician Gasconade Dolomite (Onondaga Caverns and Ozark Caverns), and the Mississippian St. Joe Limestone (Beckham Creek Cave) (Bretz, 1956). Soils are typically thin and clay-rich at these localities, particularly on the upland slopes that overlie the caves (Bretz, 1965; Soil Survey Staff, 1975).

* Corresponding author.

1040-6182/00/$20.00
PII: S1040-6182(00)00005-7

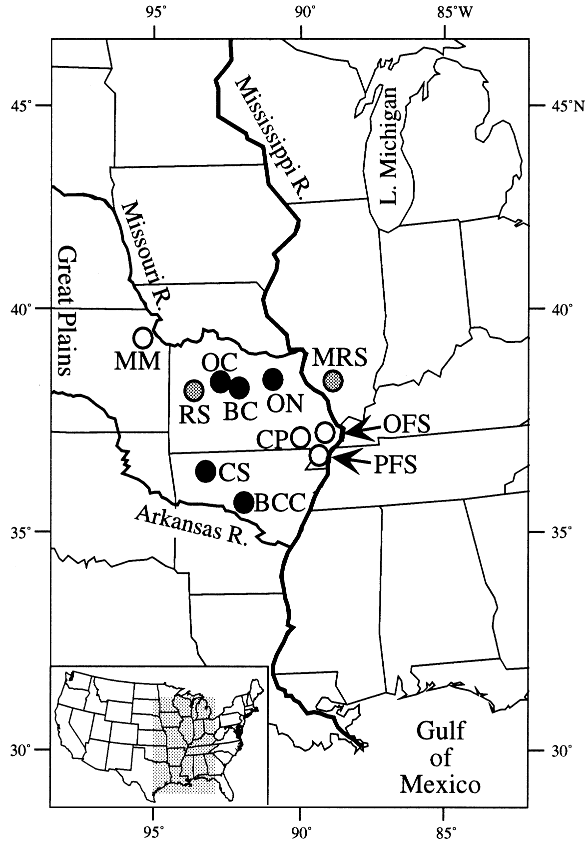

Fig. 1. Map of the study area with locations of caves (filled circles), pollen sites (open circles), and fossil vertebrate sites (shaded circles). (BC) Bridal Cave; (BCC) Beckham Creek Cavern; (CP) Cupola Pond; (CS) Cosmic Caverns; (MM) Muscotah Marsh; (MRS) Modoc Rock Shelter; (OC) Ozark Caverns; (OFS) Old Field Swamp; (ON) Onondaga Caverns; (PFS) Powers Fort Swale; (RS) Rodgers Shelter.

3. Analytical methods

Each stalagmite was sawed vertically in half, polished and visually inspected. Stalagmites from Bridal Cave, Cosmic Caverns, and Onondaga Caverns are composed of white, fibrous calcite crystals, whereas stalagmites from Beckham Creek and Ozark Caverns are characterized primarily by dense, optically clear calcite. No sign of recrystallization is apparent in any sample. Each stalagmite was sampled for $\partial^{18}O$ and $\partial^{13}C$ analysis using a modified dental drill with a 500 μm burred bit. Calcite powders were analyzed at the University of Michigan Stable Isotope Laboratory using a Finnigan MAT 251 with an on-line extraction system (Kiel device). Analytical precision is better than 0.10; $\partial^{13}C$ values are normalized to the Pee Dee Belemnite standard (PDB).

Samples were dated by $^{234}U/^{230}Th$ techniques using thermal ionization mass spectrometry at the University of New Mexico Radioisotope Laboratory (Table 1). The chemical separation was modified from Chen et al. (1986). U and Th ratios were measured on a Micromass Sector 54 thermal ionization mass spectrometer with a high-abundance sensitivity filter. All isotopes of interest (^{229}Th, ^{230}Th, ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U) were measured on an ion-counting Daly multiplier with abundance sensitivity in the range of 20 ppb at one mass distance in the mass range of U and Th, requiring very little background correction even for samples with large ^{232}Th content. Multiplier dark noise was about 0.12 counts per second. The NBL-112 U standard was measured during the course of this study and was always in the range of 1σ of the accepted $^{234}U/^{238}U$ ratio. Radiocarbon ages from previously reported studies have been converted to calendar years before present (cal yr BP) using the CALIB radiocarbon calibration program (Stuiver and Reimer, 1993).

Speleothem mineral phases were identified using optical, chemical (Feigel's solution) (Friedman, 1959), and X-ray diffraction techniques. Qualitative X-ray diffraction analyses were performed on 3–5 mg of powder using a Philips APD 3720 X-ray diffractometer.

4. Speleothem $\partial^{13}C$ as vegetation record

Paleoenvironmental interpretations based on speleothem carbon isotopic compositions require understanding the several factors that can influence $\partial^{13}C$ values. Carbon in speleothem calcite is derived primarily from two sources: (1) dissolution of carbonate bedrock, and (2) CO_2 created by plant respiration and soil organic matter decomposition (Hendy, 1971). As C3 vegetation (trees, shrubs, forbs, and cool season grasses) is characterized by lower $\partial^{13}C$ values than is C4 vegetation (many dry season grasses), changes in vegetation type affect the carbon isotopic composition of soil organic matter (Boutton, 1991). This signal is incorporated into infiltrating meteoric fluids as they pass through the soil zone and is preserved in speleothem calcite (Brook et al., 1990; Dorale et al., 1992). However, the ratio of C3–C4 vegetation growing on the land surface above the cave may be distinct from the C3/C4 ratio of soil organic matter, and as both contribute carbon to infiltrating meteoric fluids, carbon input from different sources can mask the vegetation signal recorded in speleothem $\partial^{13}C$ values. In addition, carbon isotopic signals in infiltrating meteoric fluids can be altered by several secondary processes (Hendy, 1971; Baker et al., 1997). Out-gassing of CO_2 prior to entrance of infiltrating fluids into the cave can enrich the solution, and thus calcite precipitates, in ^{13}C. Sufficiently rapid infiltration can preclude infiltrating solutions from reaching equilibrium with soil gas and/or carbonate bedrock. And, if out-gassing of CO_2 in the cave is extremely rapid, kinetic fractionation effects create disequilibrium between HCO_3^- and CO_2 (aq), thus increasing calcite $\partial^{13}C$ values. However, short-term $\partial^{13}C$ variability induced by seasonal changes in litterfall decomposition

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

Sample	mm[a] from bottom	^{238}U (ng/g)	^{234}Th (pg/g)	$\delta^{234}U$[b] measured	$^{230}Th/^{238}U$ activity	$^{230}Th/^{232}Th$ atomic	Age (yr)[c]
CS-2A	18	6070	71,550	3010 (10)	3.44E-1 (26)	4.79E-4 (2)	9560 (100)
CS-2A	106	5650	31,620	2980 (11)	3.10E-1 (30)	9.10E-4 (6)	9580 (90)
BC-3	105	450	80	880 (8)	1.46E-1 (35)	1.33E-2 (38)	8890 (220)
BC-3	139	410	210	770 (7)	1.23E-1 (12)	4.05E-3 (230)	7860 (90)
BC-3	162	320	140	690 (28)	1.18E-1 (13)	4.32E-3 (50)	7790 (170)
ON-3[d]	130	370	5370	620 (7)	2.16E-6 (3)	1.44E-4 (3)	8660 (210)
ON-3[d]	265	1310	190	430 (5)	4.61E-2 (9)	5.23E-2 (30)	3590 (70)
BCC-1[d]	45	1100	310	660 (20)	1.20E-1 (1)	7.01E-3 (33)	8130 (160)
BVV-1[d]	100	690	9700	810 (4)	4.61E-3 (1)	7.01E-5 (7)	940 (130)
OC-2	12	230	470	2300(13)	9.16E-2 (19)	7.30E-4 (3)	3030 (70)
OC-2	9	710	4850	1120 (11)	7.34E-2 (85)	1.76E-4 (20)	3760 (450)
BC-2	5	90	620	1250 (6)	4.56E-2 (30)	1.72E-6 (7)	3600 (150)
BC-2	64	4900	1290	1250 (8)	4.12E-2 (2)	2.57E-3 (3)	2000 (20)

[a]The total lengths of these stalagmites are: CS-2A = 150 mm, BC-3 = 180 mm, ON-3 = 212 mm, BCC-1 = 112 mm, OC-2 = 170 mm, and BC-2 = 131 mm.
[b]$\delta^{234}U_{measured} = [(^{234}U/^{238}U)_{measured}/(^{234}U/^{238}U)_{eq} - 1] \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ is the secular equilibrium atomic ratio: $\lambda_{238}/\lambda_{234} = 5.472 \times 10^{-5}$. Values in parentheses represent 2σ errors in the last significant figure.
[c]Unsupported ^{230}Th was subtracted from the total counts using an initial $^{230}Th/^{232}Th$ ratio of $4.2 \times 10^{-6}(\pm 2.1 \times 10^{-6})$ which is representative of average crustal silicates.
[d]Data previously reported in Denniston et al. (1999).

and plant/soil respiration are averaged out by our sampling methods, which incorporate 10–20 years of speleothem growth per isotopic analysis. As hydrologic conditions differ within and among caves, it is unlikely that carbon isotopes in infiltrating fluids will be similarly fractionated at different sites. Therefore, similar trends in carbon isotopic compositions of speleothems from different caves argue strongly for regional vegetation changes to be influencing speleothem $\partial^{13}C$ values. The $\partial^{13}C$ values of speleothem calcite are dependent on the carbon isotopic composition of the carbonate bedrock as well as the C3/C4 vegetation ratio above the cave. As $\partial^{13}C$ values of Paleozoic carbonates from the Ozarks range between 0 and $+4‰$ (M. Saltzman, pers. comm.), significant offsets in carbon isotopic compositions among speleothems from separate caves may arise solely from distinct lithologies present. These differences are assumed to be temporally invariant, however, so the direction that speleothem carbon isotopic compositions shift, rather than numerical $\partial^{13}C$ values, is the most important indicator of changing vegetation types.

5. Climatic controls on speleothem mineralogy

Five of the six stalagmites are composed entirely of calcite. ON-3 is largely calcite but contains an aragonite interval between approximately 3800 and 3100 yr BP. Aragonite speleothems are observed in caves formed in dolomitic host rocks and reflect elevated cave aridity (Murray, 1954; Siegel, 1965; Thrailkill, 1971; González and Lohmann, 1988; Railsback et al., 1994) and/or decreased infiltration rates (Fairchild et al., 1997). Circumstances favoring crystallization of aragonite over calcite include rapid precipitation that occurs in an evaporative cave environment and increases in solution Mg/Ca ratios due to preferential incorporation of Ca^{2+} into early precipitates (e.g., calcite crystallized in the bedrock or along stalactites) (González and Lohmann, 1988). While increased temperatures can favor aragonite over calcite, required temperature changes are unlikely to occur in deep caves where temperatures remain close to the mean annual surface temperature (Railsback et al., 1994).

6. Previous speleothem-based paleoclimatic reconstructions from the Ozarks

Carbon and oxygen isotopic trends in speleothem calcite compare well with pollen spectra from Cupola Pond (Smith, 1984) and Old Field Swamp (King and Allen, 1977), southeastern Missouri and vertebrate sequences from Rodgers Shelter, west-central Missouri (McMillan, 1976; Thorson and Styles, 1992) and Modoc Rock Shelter, southwestern Illinois (Denniston et al., 1999) (Fig. 1). These records share several features, including elevated abundances of steppe indicators between ~ 7500 and 3500 yr BP. Speleothem sequences also record a pronounced decrease in $\partial^{13}C$ values between 4500 and 3000 yr BP. Low $\partial^{13}C$ values in a calcite stalagmite (BCC-1) from a limestone cave (Beckham Creek Cave, Arkansas) overlap chronologically with an aragonite

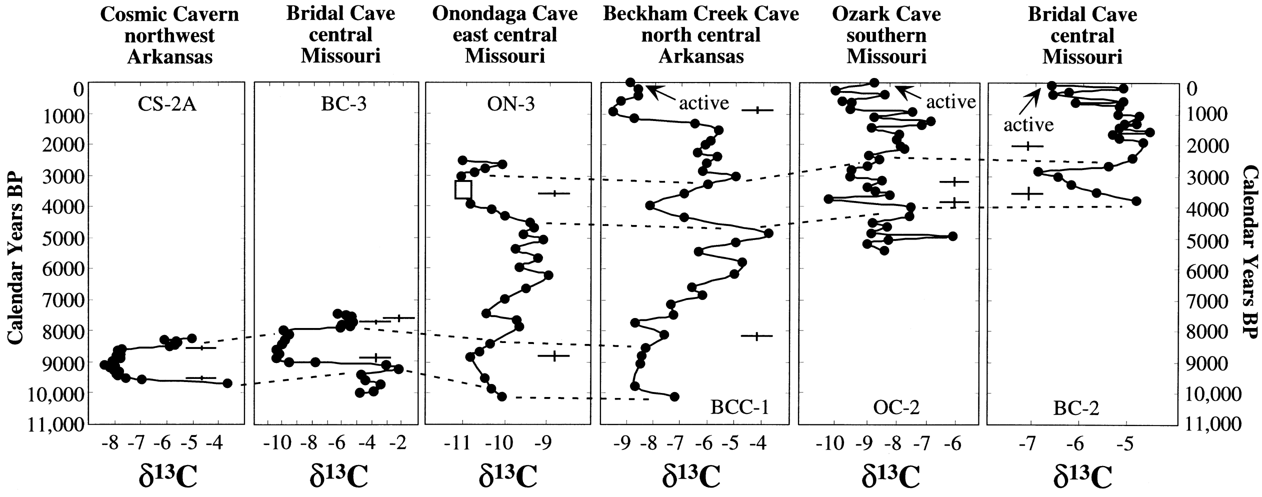

Fig. 2. Carbon isotopic composition of the stalagmites analyzed for this study. Horizontal solid lines represent dated areas and vertical solid lines denote 2σ age uncertainties. Active refers to on-going stalagmite growth at the time of collection. Dashed lines connect similar negative excursions in $\partial^{13}C$ values. Stalagmites BCC-1 and ON-3 were previously reported in Denniston et al. (1999). Unshaded box in ON-3 defines the aragonitic interval.

interval in a stalagmite (ON-3) from a dolomite cave (Onondaga Caverns, Missouri); these features were interpreted as representing regionally cool but dry conditions (Denniston et al., 1999).

7. Results

Four stalagmites from three caves were compared with the two stalagmites reported in Denniston et al. (1999). Each provides a continuous, high-resolution record spanning more than 2000 years.

7.1. Early Holocene

Two stalagmites, CS-2A from Cosmic Caverns, Arkansas and BC-3 from Bridal Cave, Missouri, record only the early Holocene, and each contains a sharp and pronounced decrease in $\partial^{13}C$ values. The timing of these changes, however, is offset by several hundred years (Fig. 2). At Cosmic Caverns, $\partial^{13}C$ values decrease sharply by approximately 4‰ at 9700 yr BP. At Bridal Cave, this shift toward lower $\partial^{13}C$ values is 8‰ and begins ~ 600 years later, at 9100 yr BP. Low $\partial^{13}C$ values persist for approximately 1000 years at both sites (9600–8500 yr BP at Cosmic Caverns and 8900–8000 yr BP at Bridal Cave), so that the timing of the subsequent increase in $\partial^{13}C$ values is similarly offset by ~ 500 years.

Stalagmites On-3 from Onondaga Cave, Missouri, and BCC-1 from Beckham Creek Cave, Arkansas, also record the early Holocene, and each contains a similar, although smaller, decrease in $\partial^{13}C$ values. In ON-3, $\partial^{13}C$ values decrease by 1‰ at 10,000 yr BP, and by ~ 2‰ at ~ 10,000 BP in BCC-1 (Fig. 2). Higher $\partial^{13}C$ values return at ~ 8700 yr BP in both stalagmites.

7.2. Middle Holocene

The Middle Holocene is preserved almost entirely by two stalagmites, ON-3 and BCC-1, although OC-2 records the interval from ~ 5500 yr BP. $\partial^{13}C$ values in BCC-1 and ON-3 begin rising at ~ 7500 yr BP, with respective increases of 4‰ and 1.5‰ (Denniston et al., 1999). As OC-2 does not preserve an early Holocene sequence, it is not possible to estimate relative increases or decreases in $\partial^{13}C$ values during the Middle Holocene. The highest $\partial^{13}C$ value for this sample, however, occurs at 5000 yr BP.

7.3. Late Holocene

The Late Holocene is recorded in stalagmites OC-2 from Ozark Cave, Missouri, and BC-2 from Bridal Cave, Missouri, as well as BCC-1 and ON-3 (Denniston et al., 1999). The BC-2 record extends continuously from 3900 yr BP to present, and contains $\partial^{13}C$ values that decrease by ~ 2‰ from 3000 to 2000 yr BP. Although highly variable, average carbon isotopic values generally decrease from 1500 yr BP to present. A similar trend occurs in OC-2, with a $\partial^{13}C$ minimum occurring between 4000 and 2500 yr BP. Carbon isotopic compositions return to less negative values by ~ 2000 yr BP. Subsequently, $\partial^{13}C$ values decrease to the present. Stalagmites BCC-1 and ON-3 contain increasing $\partial^{13}C$ values at ~ 4000 yr BP, and BCC-1 records continuing higher carbon isotopic values until ~ 1500 yr BP, at which point they decrease by ~ 4‰.

8. Discussion

8.1. Early and middle Holocene

Regional pollen and vertebrate sequences suggest that oak forest and savanna were well-established along much of the Mississippi embayment and across central Missouri during the early Holocene (McMillan, 1976; King and Allen, 1977; Smith, 1984; Royall et al., 1991). Thus, the negative excursion in speleothem $\partial^{13}C$ values during the early Holocene can be explained as deciduous forest displacement of oak savanna on the dry upland slopes overlying the caves. The exact nature of these environmental changes is unclear, however, because while speleothem $\partial^{13}C$ values record a rapid and pronounced shift, regional palynological evidence for an abrupt vegetation change in the early Holocene is equivocal. Old Field Swamp records a significant drop in oak (*Quercus*) pollen abundance and a concomitant increase in grass (Poaceae) pollen abundance that is coincident with this speleothem carbon isotopic anomaly (King and Allen, 1977) (Fig. 3). Some uncertainty surrounds the paleoclimatic significance of Poaceae at Old Field Swamp, however, since Old Field Swamp lies within the Morehouse Lowland, a part of the Mississippi River alluvial plain, and the abundance of canebrake at this site has complicated the interpretation of Poaceae pollen in a climatic context (King and Allen, 1977). Muscotah Marsh, northeastern Kansas, preserves Holocene pollen spectra, but only two radiocarbon dates (5100 $\pm$ 250 and 9930 $\pm$ 300 ^{14}C yr BP) were obtained from the middle and early Holocene (Gruger, 1973) (Fig. 1). As a result, it is not possible to directly compare speleothem $\partial^{13}C$ shifts to the small peaks in Cyperaceae (sedge) and *Quercus* (oak) pollen after 9930 ^{14}C yr BP (and which lie between 9000 and 8000 ^{14}C yr BP based on linear interpolation between dates) that occur in this sequence. Other regional vegetation records, including Cupola Pond (Smith, 1984) and Powers Fort Swale (Royall et al., 1991) do not reflect a systematic trend toward a more C3-rich environment during this interval, although high-resolution chronological controls on the early and middle Holocene parts of the Powers Fort Swale sequence are not available. Thus, the lack of detailed pollen spectra from the Ozarks and the southern Great Plains precludes our ability to constrain the exact nature and geographic extent of these early Holocene environmental changes.

The most prominent Holocene climatic event recorded in Greenland ice-core proxies was significant cooling that occurred between 8400 and 8000 yr BP, although some climate proxies (e.g., methane concentration, accumulation rate) suggest that this event began prior to 9000 yr BP (Alley et al., 1997). The origin of this cooling has not been identified but may be related to influx of glacial meltwater into the North Atlantic (Alley et al., 1997),

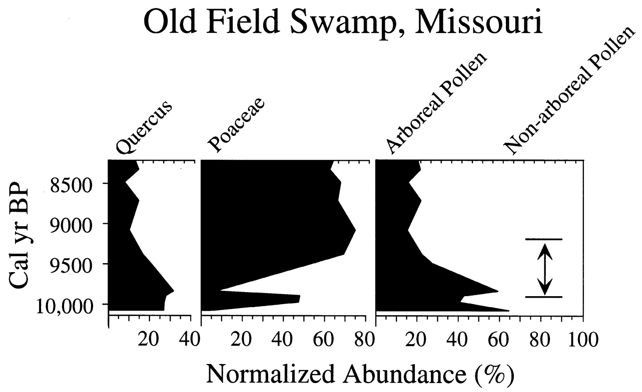

Fig. 3. Abbreviated pollen diagram from Oldfield Swamp, southeast Missouri showing *Quercus* (oak), Poaceae (grass), and arboreal and non-arboreal pollen abundances (from King and Allen, 1977). Note the pronounced and abrupt decrease in Poaceae abundance between 9900–9400 cal yr BP that coincides with the rapid decrease in $\partial^{13}C$ values of speleothem calcite. Arrow denotes interval of Poaceae decrease/*Quercus* increase.

possibly in a manner similar to postulated mechanisms for the onset of the Younger Dryas (Rooth, 1982; Broecker et al., 1989). But while the onset of this Greenland climatic deterioration coincides with the shift in $\partial^{13}C$ values preserved in BC-3, it postdates the negative cartbon isotopic anomalies recorded in most of these midwestern speleothems by several hundred years. Alternatively, changes in moisture balance may have been responsible for early Holocene vegetation changes. One possible mechanism for altering precipitation in the mid-continent involves lowering surface water temperatures in the Gulf of Mexico. Modeling experiments suggest that changes in surface temperatures in the Gulf of Mexico could alter high-pressure systems over the Gulf, diverting storm tracks, and resulting in shifts in precipitation and evaporation (via increased average wind speeds) in the central US (Oglesby et al., 1989; Maasch and Oglesby, 1990).

Colman et al. (1994) identified two discrete meltwater pulses at 9900 and 9500 cal yr BP (8900 and 8600 ^{14}C yr BP) associated with Lake Agassiz that were linked to local cooling along the St. Lawrence River by Lewis and Anderson (1989). Fairbanks (1990) documented a small ($\sim$ 30% of Meltwater Pulse 1B) increase in meltwater discharge rates between 9900 and 9000 cal yr BP. While no direct evidence for heightened meltwater discharge into the Gulf of Mexico during this time interval has been identified, the timing of this early Holocene meltwater spike coincides with the negative carbon isotopic anomaly in Ozark speleothems (Fig. 4).

Without a clear understanding of the origin of this vegetation shift, it is difficult to constrain why $\partial^{13}C$ values changes several hundred years earlier at Cosmic Caverns, Arkansas, than at Bridal Cave, Missouri. This

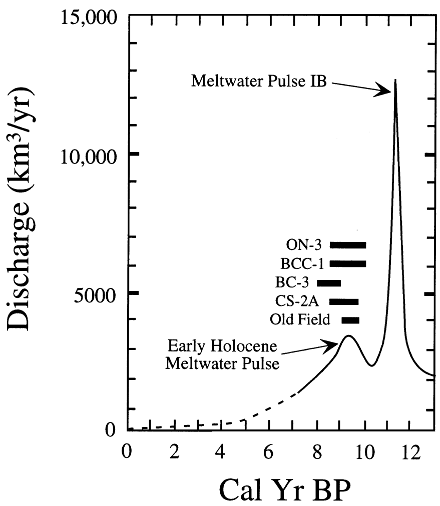

Fig. 4. Glacial meltwater discharge rates calculated from U-series dating of Barbados corals (after Fairbanks 1990), illustrating Meltwater Pulse 1B and the early Holocene meltwater pulse. Solid lines depict the timing of the carbon isotopic anomalies in Missouri and Arkansas speleothems and the decrease in Poaceae pollen at Oldfield Swamp. Dashed line represents approximate discharge rates based on extrapolated U-series chronology.

offset may reflect the complexities of responses by vegetation to changing environmental conditions. For example, the $\partial^{13}C$ decrease in stalagmites ON-3 and BCC-1 is small relative to the decrease in CS-2A and BC-3 and is likely due to more dramatic changes in C3/C4 ratios at Cosmic Caverns and Bridal Cave than at Onondaga Caverns and Beckham Creek Cave. The difference in the timing of vegetation change may also record a time-transgressive advance of a climatic boundary such as the sharp prairie-deciduous forest ecotone that migrated eastward across the northern midwestern USA during the middle Holocene and that is linked to easterly advancing dry Pacific air masses (Wright, 1971; Yu et al., 1997).

8.2. Middle and late Holocene

A shift toward higher $\partial^{13}C$ values at 7500 yr BP is interpreted as marking the arrival of C4-rich prairie vegetation in the southern Midwest (Denniston et al., 1999). This shift is corroborated by increases in abundance of both vertebrate (McMillan, 1976; FAUNMAP, 1994) and vegetative (King and Allen, 1977; Smith, 1984) indicators of prairie. Prairie was prevalent at each cave until $\sim$ 1000 yr BP except for the period between $\sim$ 4500 and 3000 yr BP when prairie was replaced by a more C3-rich environment, as marked by a negative $\partial^{13}C$ anomaly at each cave. In ON-3, the presence of aragonite in dolomitic caves and lower $\partial^{13}C$ values in calcite speleothems from limestone caves was interpreted to represent increased aridity and cooler temperatures (Denniston et al., 1999), which stabilized dry season C3 grasses. However, the absence of aragonite in OC-2 and BC-2 (both of which formed in caves hosted by dolomitic rocks) suggests that the aridity responsible for stabilizing aragonite at Onondaga Cave may not likely have been regionally significant (BCC-1 formed in a limestone cave and thus would not have contained aragonite). Therefore, the $\sim 2‰$ decrease in $\partial^{13}C$ values from $\sim$ 4500 to $\sim$ 2500 yr BP at Ozark Cvaverns, Missouri (OC-2), Bridal Cave, Missouri (BC-2), and Beckham Creek Caverns (BCC-1) demonstrates that C3 vegetation (most likely deciduous forest) interrupted the prairie period across the Ozark Highlands in the late Holocene. At Bridal Cave, Ozark Caverns, and Beckham Creek Caverns, the overall trend toward lower $\partial^{13}C$ values that began between 2000 and 1000 yr BP and continued to the present marks the return of deciduous forest to the region.

9. Conclusions

Speleothems from northern Arkansas and central and southern Missouri record a rapid increase in the abundance of C3 vegetation during the early Holocene. These changes coincide with elevated meltwater rates, although specific causal mechanisms remain speculative. The arrival of prairie in the Ozark region began shortly afterward at $\sim$ 7500 yr BP, as noted by elevated speleothem $\partial^{13}C$ values. A C3-rich (probably deciduous forest) interval from 4500 to 3000 yr BP interrupts this prairie period, and the absence of aragonite in speleothems from dolomite caves (BCC-1, OC-2, BC-2) argues against previous inferences of regional aridity from 3800 to 3100 yr BP. C4 vegetation returned to prominence between $\sim$ 3000 and 1500 yr BP. At $\sim$ 1500 yr BP, declining $\partial^{13}C$ values mark the establishment of deciduous forests that are present today.

Acknowledgements

This research was supported by grants from the Geological Society of America, the Cave Research Foundation, the Richmond Area Speleological Society, the Cave Conservancy of the Virginias, the National Speleological Society, Sigma Xi, and the University of Iowa Department of Geology (to Denniston) and National Science Foundation grant EAR93-16875 (to González and Reagan). We thank Randy Langover with Cosmic Caverns, the Missouri Department of Natural Resources at Onondaga Caverns State Park and Ozark Caverns, Steve Thompson at Bridal Cave, and Walt Manger, John Hay, and Angela Braden for generous assistance at Beckham Creek Cave.

References

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. Geology 25, 483–486.

Baker, A., Ito, E., Smart, P.L., McEwan, R.F., 1997. Elevated and variable values of ^{13}C in speleothems in a British cave system. Chemical Geology 136, 263–270.

Boutton, T.W., 1991. Stable carbon isotope ratios of natural materials. II. Atmospheric, terrestrial, marine, and freshwater environments. In: Coleman, D.C., Fry, B. (Eds.), Carbon Isotope Techniques. Academic Press, San Diego, pp. 173–185.

Bretz, J.H., 1956. Caves of Missouri, Vol. 39 (2nd Series). State of Missouri Department of Business and Administration.

Bretz, J.H., 1965. Geomorphic History of the Ozarks of Missouri. Vol. 41 (2nd Series). State of Missouri Department of Business and Administration.

Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., Wolfli, W., 1989. Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. Nature 341, 318–321.

Brook, G.A., Burney, D.A., Cowart, J.B., 1990. Desert palaeonvironmental data from cave speleothems with examples from the Chihuahuan. Somali-Chalabi, and Kalahari deserts. Palaeogeography, Palaeoclimatology, Palaeoecology 76, 239–311.

Chen, J., Edwards, L., Wasserburg, W., 1986. ^{238}U, ^{234}U, and ^{232}Th in seawater. Earth and Planetary Science Letters 80, 241–251.

Colman, S.M., Keigwin, L.D., Forester, R.M., 1994. Two episodes of meltwater influx from glacial Lake Agassiz into the Lake Michigan basin and their climatic contrasts. Geology 22, 547–550.

Denniston, R.F., González, L.A., Semken Jr., H.A., Asmerom, Y., Baker, R.G., Recelli-Snyder, H., Reagan, M.K., Bettis III, E.A., 1999. Integrating stalagmite, vertebrate, and pollen sequences to investigate Holocene vegetation and climate change in the Southern Midwest. Quaternary Research, 52, 381–387.

Dorale, J.A., Edwards, R.L., Ito, E., González, L.A., 1998. Climate and vegetation history of the midcontinent from 75 to 25 ka: a speleothem record from Crevice Cave. Missouri, USA. Science 282, 1871–1874.

Dorale, J.A., González, L.A., Reagan, M.K., Pickett, D.A., Murrell, M.T., Baker, R.G., 1992. A high-resolution record of Holocene climate change in speleothem calcite from Cold Water Cave, northeast Iowa. Science 258, 1626–1630.

Fairbanks, R.G., 1990. The age and origin of the 'Younger Dryas Climate Event' in Greenland ice cores. Paleoceanography 5, 937–948.

Fairchild, I.J., Huang, Y., Tooth, A.F., McDermott, F., Heaton, T.J., Sprio, B., Borsato, A., Frisia, S., Keppens, E., Verheyden, S., Longinelli, A., van der Borg, K., Hawkesworth, C.J., 1997. Combining isotopic and trace element data to interpret paleoclimates from speleothems. Geological Society of America Abstracts with Programs 29, 171.

FAUNMAP Working Group, 1994. FAUNMAP: A database documenting late Quaternary distributions of mammalian species in the United States. In: Graham, R.W., Lundelins, E.L. (Eds.), Illinois State Museum Scientific Paper No. 25, 690pp. (2 vol.), Springfield.

Friedman, G.M., 1959. Identification of carbonate minerals by staining methods. Journal of Sedimentary Petrology 29, 87–97.

González, L.A., Lohmann, K.C., 1988. Controls on mineralogy and composition of spelean carbonates; Carlsbad Caverns, New Mexico. In: James, N.P., Choquette, P.W. (Eds.), Paleokarst. Queen's University, Kingston, Ontario, Canada, pp. 81–101.

Gruger, J., 1973. Studies on the late Quaternary vegetation history of northeastern Kansas. Geological Society of America Bulletin 84, 239–250.

Hendy, C., 1971. The isotopic geochemistry of speleothems — I. The calculation of the effects of different modes of formation on the isotopic composition of speleothems and their applicability as palaeoclimatic indicators. Geochimica et Cosmochimica Acta 35, 801–824.

King, J.E., Allen Jr., W.H., 1977. A Holocene vegetation record from the Mississippi River valley, southeastern Missouri. Quaternary Research 8, 307–323.

Lewis, C.F.M., Anderson, T.W., 1989. Oscillations of levels and cools phases of the Laurentian Great Lakes caused by inflows from glacial lake Agassiz and Barlow-Ojibway. Journal of Paleolimnology 2, 99–146.

Maasch, K.A., Oglesby, R.J., 1990. Meltwater cooling of the Gulf of Mexico: a GCM simulation of climatic conditions at 12 ka. Paleoceanography 5, 977–996.

McMillan, R.B., 1976. The dynamics of cultural and environmental change at Rodgers Shelter, Missouri. In: Wood, W.R., McMillan, R.B. (Eds.), Prehistoric Man and His Environments: A Case Study in the Ozark Highlands. Academic Press, New York, pp. 211–231.

Murray, J.W., 1954. The deposition of calcite and aragonite in caves. Journal of Geology 62, 481–492.

Oglesby, R.J., Maasch, K.A., Saltzman, B., 1989. Glacial meltwater cooling of the Gulf of Mexico: GCM implications for Holocene and present-day climates. Climate Dynamics 3, 115–133.

Railsback, L.B., Brook, G.A., Chen, J., Kalin, R., Fleisher, C.J., 1994. Environmental controls on the petrology of a late Holocene speleothem from Botswana with annual layers of aragonite and calcite. Journal of Sedimentary Research A64, 147–155.

Rooth, C., 1982. Hydrology and ocean circulation. Progress in Oceanography 11, 131–149.

Royall, P.D., Delcourt, P.A., Delcourt, H.R., 1991. Late Quaternary paleoecology and paleoenvironments of the Central Mississippi Alluvial Valley. Geological Society of America Bulletin 103, 157–170.

Siegel, F.R., 1965. Aspects of calcium carbonate deposition in Great Onyx Cave. Kentucky. Sedimentology 4, 285–299.

Smith Jr., E.N., J 1984. Late-Quaternary vegetation history at Cupola Pond, Ozark National Scenic Riverways, southeastern Missouri. M.Sc. Thesis, The University of Tennessee, Knoxville, Tennessee, USA.

Soil Survey Staff, 1975. Soils of the United States. In: Soil Taxonomy, USDA Soil Conservation Service Agriculture Handbook No. 436, United States Government Printing Office, pp. 754.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Thorson, P.J., Styles, B.W., 1992. Analysis of faunal remains. In: Ahler, S.R., Bade, M.J., King, F.B., Styles, B.W., Thorson, P.J. (Eds.), Late Archaic component at Modoc Rock Shelter, Randolf County, Illinois. Illinois State Museum Reports of Investigations 48, 52–80.

Thrailkill, J., 1971. Carbonate deposition in Carlsbad Caverns. Journal of Geology 79, 683–695.

Wright Jr., H.E., 1971. Late Quaternary vegetational history of North America. In: Turekian, K.K. (Ed.), Late Cenozoic Glacial Ages. Yale University Press, New Haven, pp. 425–464.

Yu, Z., McAndrews, J.H., Eicher, U., 1997. Middle Holocene dry climate caused by changes in atmospheric circulation patterns: Evidence from lake levels and stable isotopes. Geology 25, 251–254.