Quaternary Research 52, 381–387 (1999)
Article ID qres.1999.2075, available online at http://www.idealibrary.com on IDEAL®

Integrating Stalagmite, Vertebrate, and Pollen Sequences to Investigate Holocene Vegetation and Climate Change in the Southern Midwestern United States

Rhawn F. Denniston,[1] Luis A. Gonzalez, and Holmes A. Semken, Jr.

Department of Geology, University of Iowa, Iowa City, Iowa 52242

E-mail: rhawn-denniston@uiowa.edu

Yemane Asmerom

Department of Earth & Planetary Science, University of New Mexico, Albuquerque, New Mexico 87131

and

Richard G. Baker, Heather Recelli-Snyder, Mark K. Reagan, and E. Arthur Bettis III

Department of Geology, University of Iowa, Iowa City, Iowa 52242

Received December 21, 1998

Speleothem carbon and oxygen isotopic records from Onondaga Cave, south-central Missouri, and Beckham Creek Cave, north-central Arkansas, are compared with the Cupola Pond and Oldfield Swamp pollen series from southeastern Missouri and the Rodgers Shelter and Modoc Shelter vertebrate biostratigraphic sequences from central Missouri and southwestern Illinois. Similar, and roughly contemporaneous, shifts between deciduous forest and steppe indicators throughout the Holocene are revealed in each database. These independent proxies record steppe conditions between approximately 9000 and 1500 cal yr B.P. A shift toward lighter speleothem carbon may reflect a change from warm and dry to cool and dry conditions between 4500 and 3000 yr B.P. The sensitive response of speleothem δ^{13}C to changes in vegetation emphasizes their importance as paleoclimate records in an area containing few other millenial-scale climate proxies.

Key Words: **speleothem; vertebrates; pollen; paleoclimate; Holocene; Midwest.**

INTRODUCTION

Holocene vegetation/climate changes are well-recorded in the northern Midwest (Minnesota, Wisconsin, Iowa), in large measure because of pollen sequences from numerous lakes and bogs formed during the Pleistocene. Much less is known about climate shifts across the southern Midwest (southern Missouri and northern Arkansas) because of the limited number of pollen spectra. Only two Holocene pollen sequences with high temporal resolution are present in this region (King and Allen, 1977; Smith, 1984). Vertebrate fossils are also useful in reconstructing past environments, but faunal sequences exceeding a few hundred years also are scarce. Caves are abundant, however, and speleothems (e.g., stalagmites, stalactites, and flowstone) record vegetation shifts (Dorale *et al.*, 1992) which may be precisely dated using U-series techniques (Dorale *et al.*, 1992).

Each record has limitations, however. Pollen sites are sparse in this region because lakes and wetlands are rare, and interpretations of existing records are difficult because a network of modern pollen sites (which aid in interpreting fossil sites) is lacking. Vertebrate sequences from rock shelters are more common but often accumulate as the result of hunting by humans or animals, and biases inherent in prey selection can distort relative abundances of species present. Speleothems require sufficiently high precipitation/infiltration for growth, and in order for their carbon and oxygen isotopic compositions to be interpreted, speleothem calcite must crystallize under equilibrium conditions.

Examination of these climate proxies allows a critique of these biases and their value for paleoclimate interpretations. This paper integrates new speleothem data with published vertebrate and pollen records to examine biological and climate change in the region. Stalagmites from two caves provide continuous records of Holocene vegetation and climate change and help tie pollen records restricted to southeast Missouri lowlands to regional vertebrate sequences.

STUDY AREA

The study area (Fig. 1) includes southern Missouri, western Illinois, and northern Arkansas and encompasses the centrally

[1] To whom correspondence should be addressed.

0033-5894/99 $30.00

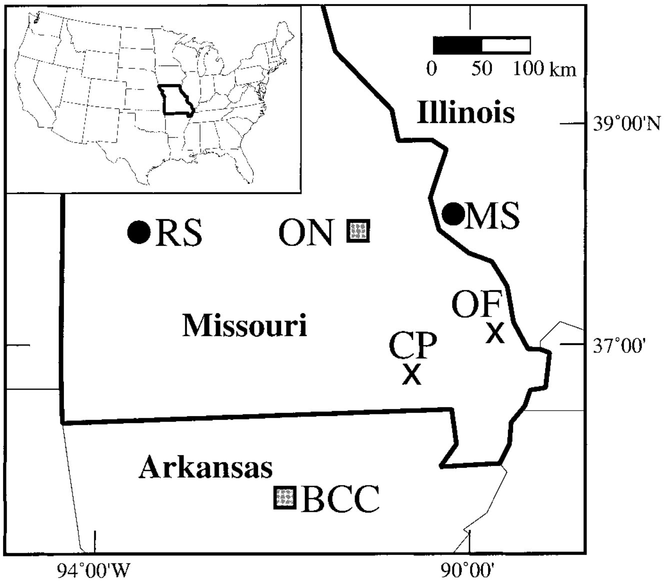

FIG. 1. Map showing the location of the study area in the southern Midwest. Filled circles represent faunal sites, shaded squares represent caves from which speleothems were obtained, and "x" represents pollen sites. MS, Modoc Rock Shelter; RS, Rodgers Shelter; CP, Cupola Pond; OF, Oldfield Swamp; BCC, Beckham Creek Cave; ON, Onondaga Caverns State Park.

located Ozark Highlands. Well-developed karst occurs throughout the Ozarks with more than 4000 caves having been described in Missouri and northern Arkansas (Bretz, 1956). Both caves in the speleothem portion of this study formed in Paleozoic carbonates, specifically the lower Mississippian St. Joe Limestone (Beckham Creek Cave, Arkansas) and the Ordovician Gasconade Dolomite (Onondaga Caverns, Missouri) (Bretz, 1956). The vertebrate samples were recovered from archeological sites, Rodgers Shelter, Missouri (McMillan, 1976; FAUNMAP Working Group, 1994) and Modoc Rockshelter, Illinois (Styles and White, unpublished data; FAUNMAP Working Group, 1994; Thorson and Styles, 1992). The pollen profiles are from Oldfield Swamp (King and Allen, 1977) and Cupola Pond (Smith, 1984), both of which are in the Mississippi River Valley of southeast Missouri.

METHODS

Stalagmites were sawed vertically in half, polished, and then sampled for $\delta^{18}O$ and $\delta^{13}C$ using a modified dental drill with a 500-μm burred bit. The resultant 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 exceeds 0.1‰; results are reported as $\delta^{18}O$ (SMOW) and $\delta^{13}C$ (PDB). Samples were dated by $^{234}U/^{230}Th$ techniques using thermal ionization mass spectrometry at the University of New Mexico Radioisotope Laboratory with a VG Sector 54 mass spectrometer (Table 1). Th (^{232}Th, ^{230}Th, ^{229}Th) and U (^{236}U, ^{235}U, ^{234}U, ^{233}U) were measured using the Daly multiplier in ion-counting mode. Fractionation during U runs was corrected using the $^{236}U/^{233}U$ atomic ratio of 1.0005 of the mixed U/Th spike. The ^{238}U was simultaneously measured in the appropriately spaced Faraday cup during each Daly cycle and was used to correct for beam growth or decay. The Faraday–Daly gain stability was better than 0.1% per hour, and multiplier dark noise was about 0.12 counts per second. The NBL-112 U standard was run with every batch of U-Th analyses, obtaining value of $\delta^{234}U = -35.2 \pm 2$ (external 2σ precision) (Table 1), which is the consensus value. Th and U blanks were in the range 5 to 10 pg, respectively. The ratios are blank and background corrected, although the corrections are negligible. Chemical separation techniques for U and Th are described in Chen *et al.* (1987). Ages of individual carbon and oxygen isotopes were interpolated between radiometric dates by assuming a constant growth rate. Temporal changes in growth rate likely occurred, however, and these appear to have slightly offset the curves (Fig. 2).

Vertebrate taxa were compiled from the FAUNMAP data base (FAUNMAP Working Group, 1994). Taxa were included only if identified to species level, with exceptions made for the jackrabbit (LS), the pocket mouse (PG), and the ground squirrel (SP), because these genera are difficult to separate specifically but still are good paleoenvironmental indicators of steppe (Table 2). Extinct taxa from the late Wisconsinan were excluded. Species were categorized by "center of distribution" (Sealander, 1979), which describes their primary habitat in terms of deciduous forest, boreal forest, steppe, or widespread. Species were plotted by normalizing the number of taxa primarily associated with each of the above biotic units to the total number of taxa from that stratum. The relative abundance of fossil vertebrates can be based on a variety of counting procedures, most commonly the presence/absence of taxa in a research unit, the number of identified specimens (NISP), i.e., bones identified representing each of the taxa in the research unit, or the minimum number of individuals (MNI) required to supply the bones identified. Each has biases in representing the community from which it was derived (Grayson, 1984). Presence/absence was chosen here because it is easily replicated, gives equal statistical weight to each taxon (as a result, rare taxa are on equal footing with common species), and is accessible from all sites in FAUNMAP. Rodgers Shelter and Modoc Shelter were examined because they contributed precise chronological control, spanned several thousand years, and contained at least 10 species in the majority of their horizons.

Pollen data and chronologies were compiled from the North American Pollen Database (National Geophysical Data Center, NOAA Paleoclimatology Program). Diagrams were plotted using the TILIA program. Radiocarbon ages for both vertebrate and pollen sequences were converted to calibrated years before present (cal yr B.P.) using the Calib radiocarbon calibration program (Stuiver and Reimer, 1993). For the purposes of this discussion, the terms cal yr B.P. (used with vertebrate, pollen, and other sequences dated using ^{14}C techniques) and yr

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)	$\delta^{234}U^{a,b}$ measured	$^{230}Th/^{238}U$ activity	$^{230}Th/^{232}Th$ atomic	Age (yr)[c]
BCC-1	45.0	1100	310	660 (20)	1.20E-1 (1)	7.01E-3 (33)	8130 (160)
BCC-1	100.0	690	9700	810 (4)	4.61E-3 (1)	7.01E-5 (7)	940 (140)
BCC-1	111.0	n/a	n/a	n/a	n/a	n/a	0 (active)
ON-3	130.0	370	5370	620 (7)	2.16E-6 (3)	1.44E-4 (3)	8660 (210)
ON-3	265.0	13,110	190	430 (5)	4.61E-2 (9)	5.23E-2 (30)	3590 (70)

[a] Here, $\delta^{234}U_{measured} = [(^{234}U/^{238}U)_{measured}/(^{234}U/^{238}U)_{eq} - 1] \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ is the secular equilibrium atomic ratio: $\lambda_{238}/\lambda_{234} = 5.472 \times 10^{-5}$.
[b] 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 4.4×10^{-6} ($\pm 2.2 \times 10^{-6}$) which is representative of average crustal silicates.

B.P. (used with stalagmite sequences dated by U/Th techniques) may be directly compared.

SPELEOTHEMS AS PALEOCLIMATIC RECORDS

Speleothem $\delta^{18}O$

The oxygen isotopic composition of speleothem calcite is primarily a function of the isotopic composition of infiltrating meteoric fluids and the temperature at which the calcite crystallizes (Hendy and Wilson, 1968). Because the ambient air temperature of deep, poorly ventilated caves approximates mean annual temperature, the oxygen isotopic composition of speleothem calcite can be linked to mean annual temperature through the temperature dependence of water–calcite fractionation effects (Hendy and Wilson, 1968). Deriving temperatures from speleothem calcite is complicated, however, because other factors such as the seasonality of precipitation and seasonal biases in infiltration related to increased evapotranspiration during the growing season are difficult to evaluate.

Speleothem $\delta^{13}C$

Speleothem carbon is derived from dissolution of carbonate bedrock and from organic carbon liberated during plant respiration and decomposition (Dorale *et al.,* 1992). Changes in the carbon isotopic signatures of speleothem calcite can therefore result from changes in the types of vegetation over the cave. During photosynthesis, nearly all trees, shrubs, forbs, and cool-season grasses discriminate against ^{13}C in favor of the lighter ^{12}C. C_3 vegetation is isotopically lighter than plants utilizing the C_4 (less discriminatory) photosynthetic pathway. The isotopic composition of C_3 vegetation ranges from −32‰ to −22‰ (PDB) while C_4 vegetation falls between −18‰ and −12‰ (Boutton, 1991). North American prairies are rich in C_4 vegetation with C_4 abundance reaching 70% on the Texas plains, although the C_4/C_3 plant ratio generally decreases from south to north (Teeri and Stowe, 1976). Therefore, when prairie grasses displace a conifer or deciduous forest, $\delta^{13}C$ values of soil organic matter, and hence of soil CO_2, increase (become enriched in ^{13}C); this signal can then be recorded by speleothems in underlying caves (Dorale *et al.,* 1992).

RESULTS

Speleothem $\delta^{18}O$

Temperatures calculated using $\delta^{18}O$ values of calcite collected from the active top of the Beckham Creek Cave stalag-

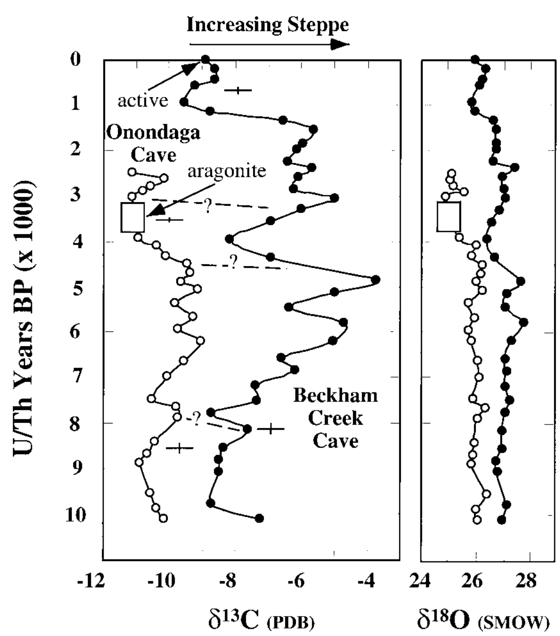

FIG. 2. Temporal oxygen and carbon isotopic trends of the speleothems analyzed for this study. Open circles, Beckham Creek Cave, Arkansas; filled circles, Onondaga Caverns, Missouri. Horizontal bars define dated areas and vertical bars represent 2σ uncertainty. Dashed lines connecting carbon trends from Beckham Creek Cave and Onondaga Cave denote possibly synchronous shifts; apparent offset may be a function of fluctuating growth rates not accounted for by age interpolations. The open box represents the aragonite interval in the Onondaga Cave speleothem and is used to define its position stratigraphically in the sample; it does not represent carbon and oxygen isotopic compositions.

TABLE 2
List of All Animal Taxa Included in this Study and Their Habitats

Habitat	Common name	Scientific name	FAUNMAP code
B	southern bog lemming	*Synaptomys cooperi*	SNco
D	short-tailed shrew	*Blarina brevicauda*	BLba
D	least shrew	*Cryptotis parva*	CSpa
D	opossum	*Didelphis virginianus*	DEva
D	southern flying squirrel	*Glaucomys volans*	GLvo
D	woodland vole	*Microtus pinetorum*	MIpi
D	woodchuck	*Marmota monax*	MTmx
D	eastern woodrat	*Neotoma floridana*	NEfl
D	rice rat	*Oryzomys palustris*	ORpa
D	eastern mole	*Scalopus aquaticus*	SAaq
D	gray squirrel	*Sciurus carolinensis*	SCca
D	fox squirrel	*Sciurus niger*	SCni
D	cotton rat	*Sigmodon hispidus*	SIhi
D	Franklin's ground squirrel	*Spermophilus franklinii*	SPfr
D	eastern cottontail	*Sylvilagus floridanus*	SYfl
D	eastern chipmunk	*Tamias striatus*	TAst
D	gray fox	*Urocyon cinereoargenteus*	UYci
S	pronghorn	*Antilocapra americana*	ACam
S	bison	*Bison bison*	BIbi
S	coyote	*Canis latrans*	CAla
S	plains pocket gopher	*Geomys bursarius*	GEbu
S	jack rabbit	*Lepus* sp.	LS
S	prairie vole	*Microtus ochrogaster*	MIoc
S	pocket mouse	*Perognathus* sp.	PG
S	spotted skunk	*Spilogale putorius*	SLpu
S	ground squirrel	*Spermophilus* sp.	SP
S	13-lined ground squirrel	*Spermophilus tridecemlineatus*	SPtr
S	badger	*Taxidea taxus*	TXta
W	beaver	*Castor canadensis*	CRca
W	American elk	*Cervus canadensis*	CVca
W	bobcat	*Felis rufus*	FSru
W	river otter	*Lutra canadensis*	LUca
W	striped skunk	*Mephitis mephitis*	MEme
W	long-tailed weasel	*Mustela frenata*	MUfr
W	mink	*Mustela vison*	MUvi
W	white-tailed deer	*Odocoileus virginianus*	ODva
W	muskrat	*Ondatra zibethicus*	OTzi
W	racoon	*Procyon lotor*	PRlr
W	black bear	*Ursus americanus*	URam
W	red fox	*Vulpes vulpes*	VUvu

Note. B, boreal forest; D, deciduous forest; S, steppe; W, widespread.

mite are similar but slightly cooler than present conditions. We attribute this shift to a bias toward cool-season (spring and fall) infiltration, which has been observed at two caves in the northern Midwest (Crystal Cave, Wisconsin, and Cold Water Cave, Iowa) (A. Suzuki, personal communication, 1998). In addition, relationships between latitude and the isotopic composition of precipitation are not well-established for the central United States, and thus small-scale deviation from Dansgaard's relationships may be responsible for additional error. On the coarse scale, isotopic evolution of moist maritime air masses results in higher precipitation $\delta^{18}O$ values in Arkansas than in central Missouri, and stalagmites from Arkansas (Beckham Creek Cave) contain consistently higher $\delta^{18}O$ values than those from Missouri (Onondaga Cave) for the entire Holocene record (Fig. 2). In addition pre-infiltration evaporative enrichment of water ^{18}O has been documented for the middle Holocene and thus may account for some oxygen isotopic variability (Denniston *et al.*, 1998).

Speleothem $\delta^{13}C$

Both Beckham Creek and Onondaga Cavern stalagmites record large carbon isotopic excursions during the Holocene (Fig. 2). The early Holocene was characterized by isotopically light speleothem carbon between ~10,000 and 9000 cal yr B.P., suggesting a C_3-rich environment, possibly a forest/parkland setting. Beginning at 9000 cal yr B.P., $\delta^{13}C$ values began increasing, and elevated $\delta^{13}C$ values lasted until 4500 cal yr B.P. with peak values at 5000 cal yr B.P. A shift to lower carbon isotopic values occurred between approximately 4500 and 3000 cal yr B.P. At Onondaga Cave, this interval is composed of aragonite. Carbon isotopic compositions increased again between 3000 and 1500 cal yr B.P. (the Onondaga speleothem stopped growing at 2500 cal yr B.P.). Modern $\delta^{13}C$ values were established at Beckham Creek Cave by 1000 cal yr B.P. Evaporation can affect both speleothem carbon and oxygen isotopic compositions, but it cannot account for the similarity of the timing and magnitude of the trends observed in these speleothems from Beckham Creek Cave and Onondaga Cave, which are located over 100 km apart. Changes in vegetation, therefore, must be driving these shifts in speleothem $\delta^{13}C$.

Vertebrate Succession Record

In the Holocene vertebrate sample from Modoc and Rodgers shelters, deciduous forest species are typically the most common, followed by widespread species, steppe, and finally boreal species (Fig. 3). Steppe taxa are higher at Rodgers Shelter, the westernmost faunal site, than at Modoc to the east. The relative abundances of each changed sharply at times, and these shifts, while of varying magnitude, are generally synchronous.

Deciduous forest elements were dominant during the early Holocene. Boreal species (represented by the southern bog lemming) were rare in the early Holocene and are only recorded sporadically thereafter. During most of the middle Holocene, the number of steppe taxa grew at the expense of deciduous species. Elevated abundances of steppe indicators began at approximately 9000 cal yr B.P. and lasted until 3000 cal yr B.P. at Rodgers Shelter (the Modoc record ended at ~5000 cal yr B.P.). Shifts toward higher relative abundances of deciduous taxa are recorded at the finely stratified and

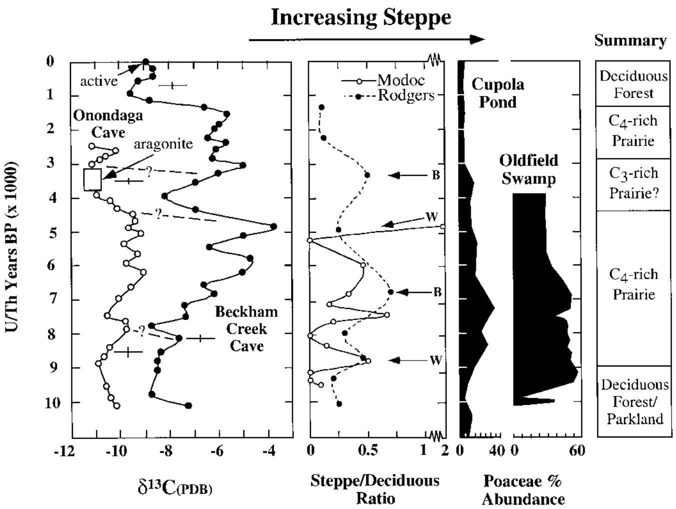

FIG. 3. Summary diagrams showing speleothem carbon, vertebrate, and pollen sequences discussed in the text. For vertebrate sequences, the plot shows relative abundances of the types of animal taxa in this study. Arrows point to peaks in boreal (B) or widespread (W) habitats. Grass pollen spectra for Cupola Pond and Oldfield Swamp are plotted as percentages of total pollen. Uncertainties associated with both pollen sequences are discussed in the text. The summary diagram is based on combined speleothem, vertebrate, and pollen data sets.

well-dated Modoc sequence at approximately 8000, 7200, and 5300 cal yr B.P. The 8000 and 5000 cal yr B.P. events are also recorded at Rodgers. The upper part of the Modoc section was removed during road construction prior to excavation, but the Rodgers section extends into the late Holocene and indicates a mesic period shortly after 5000 cal yr B.P. Modern, relatively mesic conditions returned to Rodgers at 3000 cal yr B.P. and are recorded until the end of deposition at approximately 1500 cal yr B.P.

Pollen Record

Only two sites with a fossil pollen record are available in the region, Cupola Pond (Smith, 1984) and Oldfield Swamp (King and Allen, 1977). The Holocene record at Cupola Pond is confined to a 1.5-m core with only two ^{14}C dates (590 ± 80 yr B.P. at 18 cm and 8830 ± 130 yr B.P. at 115 cm) for chronological control. Thus, undetected hiatuses may be present. The Oldfield Swamp locality lies in the middle of a canebreak and much of the Poaceae (grass) pollen recovered probably was derived from this source. However, fluctuations in the relative abundance of Poaceae are marked, appear coeval with the Cupola Pond and stalagmite records, and thus are included for comparison (Fig. 3).

Pollen recovered from Oldfield Swamp documents increases in Poaceae and corresponding decreases of *Quercus* (oak) pollen from 9500 to 6000 cal yr B.P. (King and Allen, 1977). These changes are interpreted to represent replacement of lowland swamp forests by grasslands as the water table dropped. After 6000 cal yr B.P., grass pollen decreased and tree pollen increased, suggesting the return of lowland swamp forest. The upper part of the Oldfield record may be compressed or missing.

At Cupola Pond, grass and oak pollen percentages rose beginning about 10,000 cal yr B.P., grass stayed relatively high until about 3000 cal yr B.P., and oak percentages dropped about 5000 cal yr B.P., suggesting that a relatively dry forest with openings was present for most of the Holocene. Modern forests seem to have been established for the last 3000 years.

DISCUSSION

Early Holocene environmental conditions between ~10,000 and 9000 cal yr B.P. across southern Missouri and northern Arkansas were cool and moist enough to support oak savanna in both moist lowland areas such as those around Cupola Pond and relatively arid upland slopes such as those overlying Onondaga Cave and Beckham Creek Cave. Deciduous forest vertebrates dominate the faunal samples at both Modoc and Rogers Shelter at this time (Fig. 2). An early Holocene environment rich in C_3 vegetation at this time is supported by Humphrey and Ferring (1994), based on isotopically light carbon in pedogenic carbonates from north central Texas, and by Nordt *et al.* (1994), based on the carbon isotopic composition of soil organic matter from central Texas. In addition, a pollen sequence from Ferndale Bog, eastern Oklahoma, also records increased abundances of *Acer* (walnut) and *Quercus* between approximately 11,000 and 9600 cal yr B.P. (Holloway, 1993).

Higher stalagmite δ^{13}C values and increases in the abundances of steppe vertebrate indicators and grass pollen percentages indicate that the middle Holocene climate of the Ozark region was considerably drier than at present. Prairie-steppe was better developed in southern Missouri and northern Arkansas during the middle Holocene than at present, arriving at approximately 9000 cal yr B.P. Maximum steppe expansion occurred between 6000 and 5000 cal yr B.P. (Fig. 2). This picture of middle Holocene climate is similar to interpretations of environmental conditions from the Great Plains. Increases in grass pollen abundance occurred from 6600 to 3400 cal yr B.P. in Iowa (Van Zant, 1979) when prairie forb values were increased in the northern Midwest (Webb *et al.*, 1983). In northeastern Kansas, the Muscotah Marsh pollen record documents a prairie environment from 11,000 to 5900 cal yr B.P. (Gruger, 1973). Sediment and pollen sequences from Cheyenne Bottoms, central Kansas, suggest increased C_4 activity from 9500 to 4100 cal yr B.P. (Fredlund, 1995). Detrital organic matter from inactive sand dunes in south central Kansas indicate a dominance of C_4 vegetation from approximately 5000 cal yr B.P. to present (Arbogast and Johnson, 1998). Nordt *et al.* (1994) interpreted isotopically heavy soil organic carbon as reflecting a shift toward a more C_4-rich plant community in central Texas between approximately 7000 and 5700 cal yr B.P., and Humphrey and Ferring (1994) noted an increase in $\delta^{13}C$ values of pedogenic carbonate between approximately 8000 and 4500 cal yr B.P. in north Texas.

Given the dominance of C_4 vegetation during the middle Holocene, the decrease in $\delta^{13}C$ recorded in these two stalagmites about 3500 yr B.P. is puzzling. Several studies have documented a period of increased aridity during the late Holocene. Hall and Lintz (1984) inferred lowered water tables between 3400 and 2700 cal yr B.P. in central Oklahoma from analysis of buried trees and molluscan fauna. Nordt *et al.* (1994) reported that modern conditions were established at approximately 4500 cal yr B.P., but that these conditions were interrupted by a return to drier and/or warmer conditions between 2600 and 2000 cal yr B.P. Similarly, phytoliths from southeast Nebraska record a pronounced increase in C_4/C_3 ratios between 3500 and 3000 yr B.P. (Baker and Fredlund, 1998). The aragonite interval in the Onondaga Cave stalagmite between 3800 and 3100 cal yr B.P. coincides with a similar decrease in $\delta^{13}C$ values in the Beckham Creek Cave stalagmite. Aragonite is a mineralogical indicator of increased cave aridity (Railsback *et al.*, 1994), which may represent a drier regional environment. A shift toward a more C_3-rich environment (as suggested by lower carbon isotopic compositions in both stalagmites) typically occurs during more moist and/or cooler conditions. If aridity did in fact increase during this interval, then these data may be explained by cooler conditions which stabilized dry-season C_3 grasses. Cooler conditions at this time are also supported by a peak in the numbers of boreal taxa in the Rodgers and Modoc sequences (Fig. 2).

Finally, peaks in widespread vertebrate taxa abundance coincide with the arrival and departure of prairie. Thorson and Styles (1992) demonstrated that distinct environments existed within short geographic domains in the middle Holocene and were probably linked to topographic controls on moisture availability (e.g., dry upland slopes and moist, sheltered lowlands). Thus, the shift from forest/savanna to prairie at 8500 cal yr B.P. and the return of deciduous forest about 4500 cal yr B.P. allowed intermingling of vertebrate ecotypes and indicate that these were periods of significant ecological change.

CONCLUSIONS

Comparison of speleothem carbon, faunal assemblages, and pollen sequences clarifies regional vegetational/climatic trends across the southern Midwest. Oak parkland was replaced by prairie-steppe about 9000 cal yr B.P. The middle Holocene advance of prairie extended across the Ozarks and as far south as northern Arkansas. Elevated abundances of steppe indicators in southern Missouri and northern Arkansas are linked with late Holocene increases in C_4 vegetation observed in central and north-central Texas and southern Oklahoma. The late Holocene experienced a pronounced change in vegetation between approximately 4500 and 3000 cal yr B.P., which appears to reflect drier and possibly also cooler conditions. This preliminary study suggests that speleothems may be useful in constructing a detailed chronogeographic map of vegetation change across the southern Midwest.

ACKNOWLEDGMENTS

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 (all to R.D.), and NSF grant EAR93-16875 (to L.G.). We thank the Missouri DNR (Onondaga Caverns State Park), John Hay, and Dr. Walt Manger for their generous assistance with Beckham Creek Cave. This manuscript benefitted from reviews by E. Grimm and T. Webb III.

REFERENCES

Arbogast, A. F., and Johnson, W. C. (1998). Late-Quaternary landscape response to environmental change in south-central Kansas. *Annals of the Association of American Geographers* **88,** 126–145.

Baker, R. G., and Fredlund, G. G. (1998). Holocene environments of the central Great Plains. *Geological Society of America Abstracts with Programs, Toronto,* **30,** 249–250.

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

Bretz, J. H. (1956). "Caves of Missouri." State of Missouri Department of Business and Administration, Vol. XXXIX (2nd Series), 490 pp.

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

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus* **16,** 436–468.

Denniston, R. F., Gonzalez, L. A., Asmerom, Y., Baker, R. G., Reagan, M. K., and Bettis, E. A. III (1999). Evidence for increased cool season moisture during the middle Holocene. *Geology* **27,** 815–818.

Dorale, J. A., Gonzalez, L. A., Reagan, M. K., Pickett, D. A., Murrell, M. T., and 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.

Ferring, C. R. (1995). Middle Holocene environments, geology, and archaeology in the Southern Plains (E. A. Bettis, III, Ed.). *In* "Archaeological Geology of the Archaic Period in North America," Geological Society of America Special Paper, 297.

FAUNMAP Working Group (1994). "FAUNMAP: A Database Documenting Late Quaternary Distributions of Mammalian Species in the United State (R. W. Graham and E. L. Lundelins, Eds.). Illinois State Museum Scientific Paper No. 25, 690 pp. (2 vol.), Springfield.

Fredlund, G. G. (1995). Late Quaternary pollen record from Cheyenne Bottoms, Kansas. *Quaternary Research* **43,** 67–79.

Grayson, D. K. (1984). "Quantitative Zooarchaeology: Topics in the Analysis of Archaeological Faunas." Academic Press, New York, 202 pp.

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

Hall, S. A., and Lintz, C. (1984). Buried trees, water table fluctuations, and 3000 years of changing climate in west-central Oklahoma. *Quaternary Research* **22,** 129–133.

Hendy, C. H., and Wilson, A. T. (1968). Palaeoclimatic data from speleothems. *Nature* **216,** 48–51.

Holloway, R. (1993). "Pollen Analysis of Ferndale Bog, Oklahoma." University of North Texas, Report to the Institute of Applied Sciences, 49 p.

Humphrey, J. D., and Ferring, C. R. (1994). Stable isotopic evidence for late Pleistocene to Holocene climate change, north-central Texas. *Quaternary Research* **41,** 200–213.

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

McMillan, R. B. (1976). The dynamics of cultural and environmental change at Rodgers Shelter, Missouri. *In* "Prehistoric Man and His Environments: A Case Study in the Ozark Highlands" (W. R. Wood and R. B. McMillan, Eds.). Academic Press, New York, 271 pp.

Nordt, L. C., Boutton, T. W., Hallmark, C. T., and Waters, M. R. (1994). Late Quaternary vegetation and climate changes in central Texas based on the isotopic composition of organic carbon. *Quaternary Research* **41,** 109–120.

Railsback, B. L., Brook, G. A., Chen, J., Kalin, R., and 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, Section A* **64,** 147–155.

Sealander, J. A. (1979). "A guide to Arkansas Mammals." River Road Press, Conway, 313 pp.

Smith, E. N., Jr. (1984). "Late-Quaternary Vegetation History at Cupola Pond, Ozark National Scenic Riverways, southeastern Missouri." Thesis, The University of Tennessee, Knoxville, Tennessee.

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

Teeri, J. A., and Stowe, L. G. (1976). Climatic patterns and the distribution of C_4 grasses in North America. *Oecologia* **23,** 1–12.

Thorson, P. J., and Styles, B. W. (1992). Analysis of faunal remains. *In* "Late Archaic component at Modoc Rock Shelter, Randollf County, Illinois" (S. R. Ahler, Ed.), pp. 52–80.

Van Zant, K. (1979). Late glacial and postglacial pollen and plant macrofossils from Lake West Okoboji, Northwestern Iowa. *Quaternary Research* **12,** 358–380.

Webb, T., III, Cushing, E. J., and Wright, W. E., Jr. (1983). Holocene changes in the vegetation of the Midwest. *In* "Late Quaternary Environments of the United States" (H. E. Wright, Jr., Ed.), pp. 142–165. University of Minnesota Press, Minneapolis.