Speleothem climate records from deep time? Exploring the potential with an example from the Permian

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ABSTRACT

Speleothems are well-proven archives of terrestrial climate variation, recording mean temperature, rainfall, and surface vegetation data at subannual to millennial resolution. They also form within the generally stable environment of caves, and thus may remain remarkably well preserved for many millions of years and, most important, can be dated radiometrically to provide robust chronologies that do not rely on orbital tuning, ice-flow modeling, or estimates of sediment deposition rates. The recent adaptation of the U-Pb dating technique to speleothems has greatly extended their potential as paleoclimate recorders back into the more distant geological past, well beyond the ~500 k.y. limit previously imposed by U-series techniques, but the opportunities presented by these new methods have yet to be fully explored. As an extreme example, here we report on samples recovered from Permian cave fills, the oldest radiometrically dated speleothems so far documented. Using state of the art analytical techniques it is possible to determine not only their age and state of preservation, but also to extract apparently nearly pristine climate proxy data. Armed with these methods, it now seems reasonable to apply the lessons learned from more recent speleothems to ancient materials, wherever they can be found, and of whatever age, to generate snapshots of paleoclimate that can be used to greatly refine the records preserved within the sediments and fossils of the time.

INTRODUCTION

In recent years speleoethems have received widespread recognition as tools for paleoclimate reconstruction comparable and yet in many ways also complementary to deep-sea sediment and ice cores (e.g., Fairchild et al., 2006). Speleothem records are typically relatively short, but are terrestrial, often of very high resolution, available in all latitudes, and, most important, have the potential to furnish extremely detailed information based upon robust radiometric dating techniques. Until recently, their utility was limited to the latter part of the Quaternary by an inability to date materials older than ~500 k.y., the practical limit of U-series geochronology. The application of the U-Pb chronometer to cave calcites (e.g., Richards et al., 1998; Woodhead et al., 2006), however, now offers the prospect of extending their use deep into Earth history, wherever speleothems are discovered. Here we provide a preliminary exploration of the wealth of chronological and paleoclimate data that may be recorded in old speleothems and demonstrate some of the analytical techniques used to interpret these ancient signals.

SPELEOTHEM SAMPLES, CHRONOLOGY, AND TESTS FOR ALTERATION

Speleothems were recovered from a highly fossiliferous commercial quarry near Richards Spur, Oklahoma (United States), that has exposed a vast system of caves in Ordovician Arbuckle Limestone. These caves have yielded the most diverse fauna of exclusively terrestrial Paleozoic vertebrates known (Evans et al., 2009), documenting in great detail the initial stages of diversification in an upland environment (see the GSA Data Repository[1]). As such, this is arguably the most significant fossiliferous locality of the late Paleozoic (Maddin et al., 2006). Previous work based on the vertebrate fauna alone, however, could provide only broad estimates of the age and prevailing climatic conditions (Sullivan et al., 2000), a problem common to many other Early Permian continental strata and their terrestrial vertebrate assemblages. The intimate association of speleothems with fossil material at the Richards Spur (see the Data Repository) offers not only the potential for an absolute chronology but also a detailed climate record to assist in paleontological studies.

A U-Pb radiometric age determination, based on the method described by Woodhead et al. (2006), for a Richards Spur stalagmite provides a well-defined age of 289 ± 0.68 Ma (see the Data Repository), placing its growth in the mid-Sakmarian stage of the Early Permian Period using the time scale of Gradstein et al. (2004). $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ ratios close to secular equilibrium support this age interpretation (see the Data Repository). This is by far the oldest speleothem to be directly dated by radiometric means. Clearly, with samples of this antiquity, it is important to establish the presence and extent of any alteration phenomena. Although the postdepositional conditions to which the Richards Spur samples have been subjected over nearly 290 m.y. of Earth history are not known, petrography and high-resolution elemental mapping can help to reveal whether, despite strong fracturing, the calcite in these specimens retains compositional features that are common in modern speleothems. Optical microscope observations reveal a fabric of coarse columnar calcite radiating from a central region of mosaic calcite (see the Data Repository), comparable to features reported in young speleothems (e.g., Kendall and Broughton, 1978; Frisia, 1996). Large-scale growth banding is evident, and some regions preserve very fine laminations with a spacing of ~5–30 μm, suggestive of annual growth banding under a strongly seasonal climate (Fig. 1). This interpretation is supported by laterally reproducible trace element concentration profiles that correlate with the optical banding. Such patterns have only recently been recognized in modern speleothems (Roberts et al., 1998; Treble et al., 2003), but are now increasingly seen as a unique and valuable tool in paleoclimate reconstruction (Baker et al., 2008).

Laser-ablation inductively coupled plasma–mass spectrometry (ICP-MS) elemental maps (Fig. 2) reveal that the spatial distribution of some elements (e.g., Mn, rare earth elements [REEs]) has undoubtedly been affected by secondary mobility along fractures; rare areas of these cracks are decorated with secondary pyrite. Concentrations of other elements, however, in particular those with paleoclimatic or geochronological significance (e.g., Mg, P, Sr, U), display patterns that correlate well with the growth banding geometry. Thus, although there is a suggestion from the

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[1]GSA Data Repository item 2010123, Table DR1, additional geological data, analytical procedures, and Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

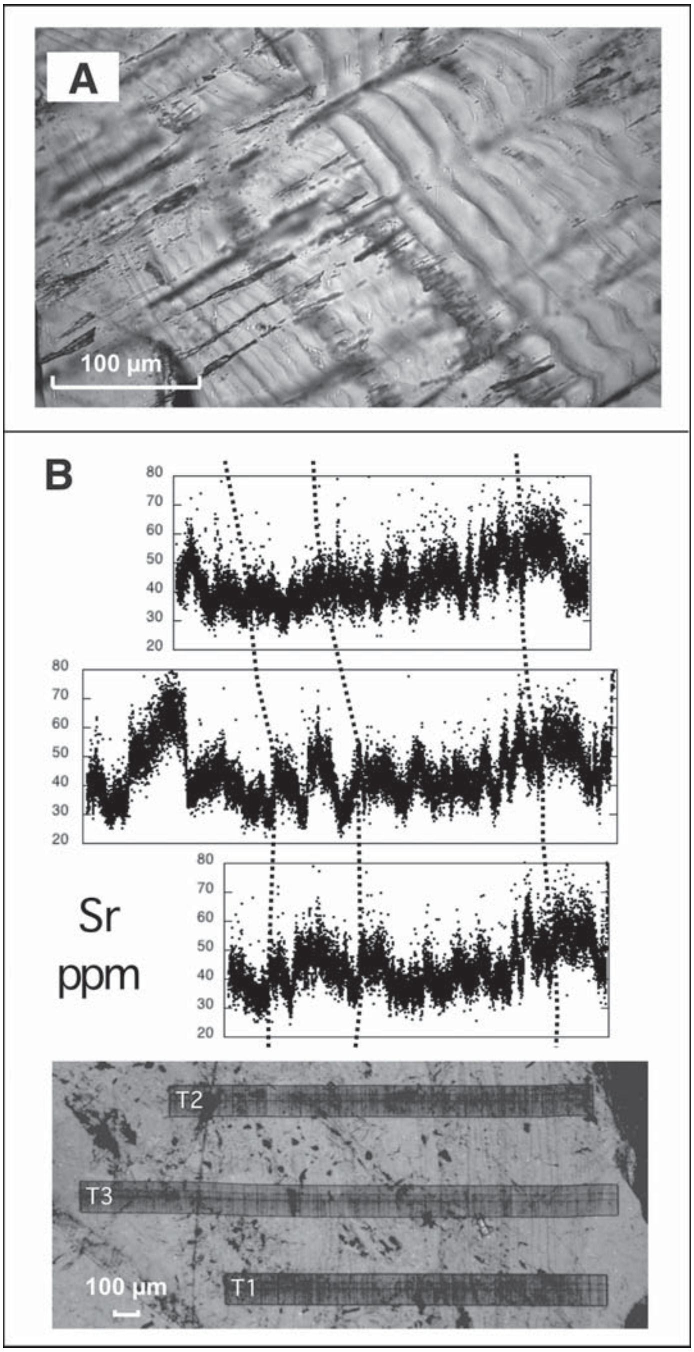

Figure 1. Possible annual banding in sample P-2 with corresponding trace element variations. A: High-resolution image showing banding on scales of 5–30 µm, with clear anastomosing structures typical of speleothem growth. B: Three laser traverses (T1–T3) were conducted using ablation slit ~100 × 3 µm wide, providing very high resolution in horizontal dimension in this figure. Three traces all show consistent elemental patterns (that of Sr shown here), suggesting that this micron-scale variation is primary feature.

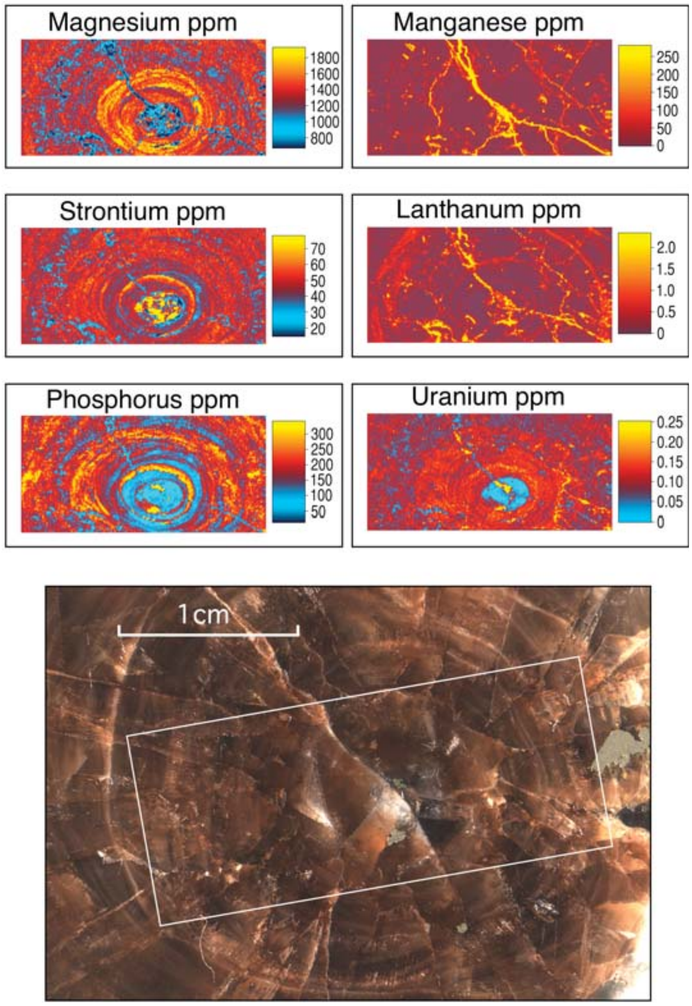

Figure 2. Elemental maps for sample P-2. These were obtained by laser-ablation inductively coupled plasma–mass spectrometry from central region of sample, and show some element mobility both in core and along cracks, but evidence of strong compositional variation following primary growth fabric. Note minor pyrite growth in bottom figure, representing ingress of mineralizing fluids along cracks.

crystal fabric of some diagenetic changes affecting in particular the core of the specimen, if any diagenesis has occurred in the outer layers, it appears to have preserved most of the original features and trace element distribution. As a consequence, we now investigate whether such calcite may also preserve primary stable isotope signatures that could be used in paleoclimatic interpretation.

EXPLORING THE POTENTIAL CLIMATE PROXY RECORD

During the Early Permian, the Richards Spur region was in the tropical lowlands of western equatorial Pangea, at very low northern latitudes and drifting north (Blakey, 2007). The late Pennsylvanian–Early Permian climate of Pangea is thought to have been characterized by a large-scale monsoonal circulation system over the western (i.e., Laurentian) tropics, and a massive continental ice sheet at high southern latitudes that covered a large area of the Gondwanan portion of Pangea (Isbell et al., 2003; Tabor et al., 2009). The ice sheet is thought to have varied in extent through several protracted glacial intervals during the Pennsylvanian and Early Permian. Based largely on paleosol studies, the Sakmarian climate of the Texas-Oklahoma region is inferred to have been strongly seasonal, with significant variation between arid, semiarid, and semihumid over short time scales. The strong seasonality may have been the result of warm-season cyclonic circulation around a low-pressure center situated farther north over Laurentian Pangea (Tabor et al., 2009).

In an attempt to investigate what new information these ancient speleothems could contribute to this picture, stable isotope profiles were measured on two specimens: a short (4 cm) reconnaissance low-resolution

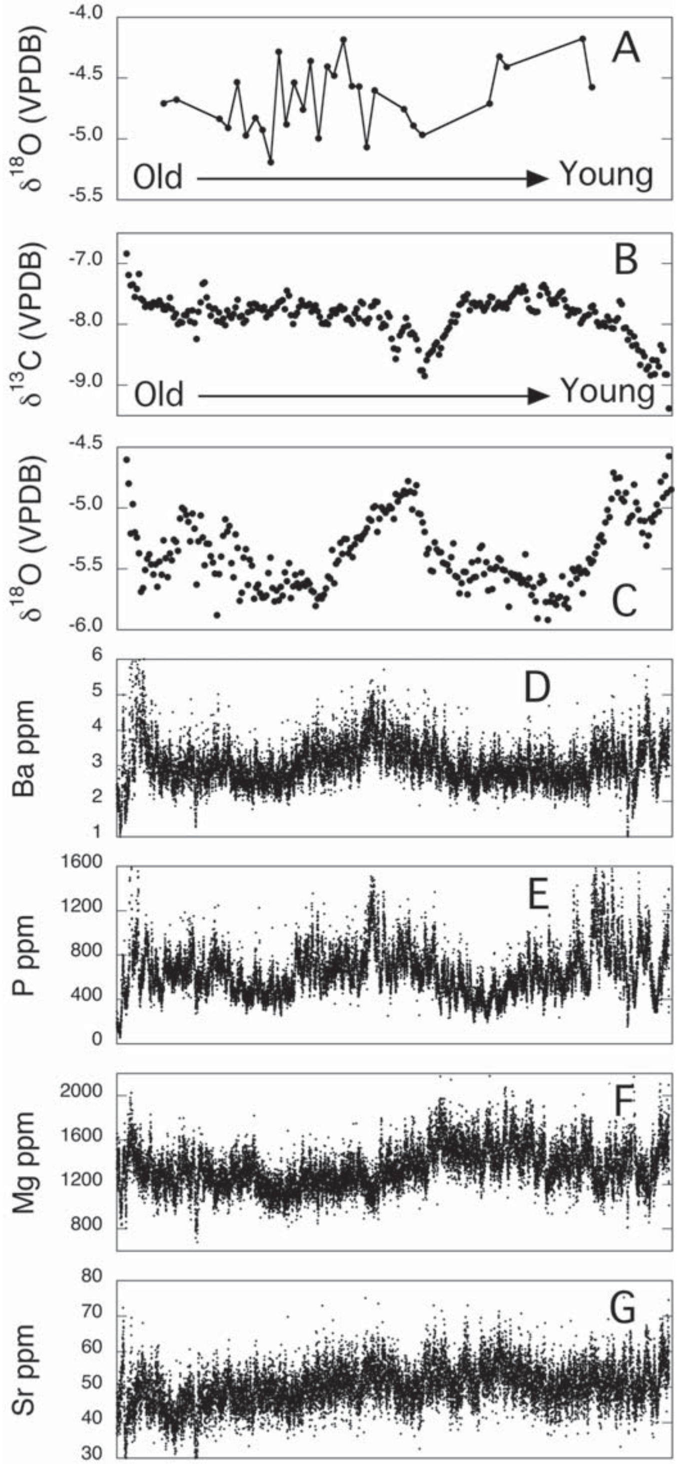

Figure 3. Stable isotope and trace element variations. A: Low-resolution stable isotope profile of sample P-1 spanning ~0.4–8.0 k.y. (VPDB—Vienna Peedee belemnite). B–G: High-resolution stable isotope and trace element profiles of sample P-2 spanning ~0.6–12.0 k.y. These are all characterized by cyclic variations identical to those observed in Quaternary speleothems. Lower $\delta^{18}O$ is likely to represent higher rainfall periods.

traverse on the stalagmite dated to 289 ± 0.68 Ma (P-1; Fig. 3A), and a longer (~6 cm), much higher resolution traverse parallel to a high-resolution trace element profile on another larger sample (P-2; Fig. 3C). Unfortunately we do not have sufficient age resolution with such small samples to develop an internal chronology for either specimen (one current limitation of the U-Pb method for older speleothems). Therefore growth rates were estimated by analogy to modern specimens from monsoonal, semiarid climates thought to resemble conditions inferred for the tropical western lowlands of Early Permian Pangea. There are of course many uncertainties in such an approach, but, based on growth rates in these modern analogues (5–100 mm/k.y.; e.g., Burns et al., 1998; Wang et al., 2006), we infer that each of the Richards Spur data series represents between 1 and 20 k.y. of speleothem growth.

Oxygen isotope variations in speleothems are a complex response to multiple, largely hydrological, influences (Lachniet, 2008). In Holocene examples from tropical and subtropical settings, $\delta^{18}O$ clearly reflects isotopic variations in local precipitation. These are controlled largely by changes in major atmospheric circulation patterns, which in turn are ultimately driven by changes in summer insolation (e.g., Asmerom et al., 2007). Our $\delta^{18}O$ records from the two speleothems are very similar. The $\delta^{18}O$ profile for P-1, covering a range of –4‰–5‰, displays considerable structure where sample density is high, but there are no clear long-term patterns. The $\delta^{18}O$ values in the longer, higher-resolution record from P-2 show a similar total range, but the pattern appears to be shifted to slightly lower (~0.5‰) $\delta^{18}O$. It is significant that P-2 shows several regular oscillations between higher and lower $\delta^{18}O$ values that are not resolved in the P-1 record. Based on comparison with speleothems from modern tropical, subtropical, and semiarid settings with monsoonal climates (e.g., Kaufman et al., 1998; Wang et al., 2005), we interpret the low ^{18}O intervals in the Richards Spur speleothem to represent periods of increased precipitation associated with more intense convective circulation at low latitude (the amount effect of Rozanski et al., 1993). In P-2, two wetter intervals are punctuated by drier intervals. At growth rates in the range of 5–100 mm/k.y., these wet periods would describe variation on centennial to millennial time scales. The apparently periodic structure in the $\delta^{18}O$ record coupled with the results of elemental mapping suggest that such samples may provide new avenues for exploring Sakmarian climate that are unobtainable by other means. The climate was clearly wet enough to maintain persistent speleothem growth, but was not punctuated by extreme drying events or shifts in state on time scales of decades to millennia. Such information is important in determining the links between climate change, paleoecology, and evolution.

The high-resolution trace element profiles of P-2 (Figs. 3D–3G) were obtained parallel to the $\delta^{18}O$ profile. Trace element variations in speleothems are now recognized as useful proxies for temperature, paleohydrology, or eolian input, although the responses of different elements may vary from site to site and should be considered on a case by case basis (e.g., Fairchild and Treble, 2009). Profiles of Ba and P in P-2 are correlated with $\delta^{18}O$, i.e., higher Ba and P concentrations during the higher $\delta^{18}O$ intervals interpreted as drier intervals. Similar correlations in speleothems representing dry intervals over the past 60 k.y. at Soreq Cave, Israel, were interpreted as a result of greater contributions from sea spray and eolian dust during dry conditions (Ayalon et al., 1999). However, in contrast to their counterparts in the Soreq Cave record, Mg and Sr variations in P-2 are complex and only correlate with variations in Ba, P, and $\delta^{18}O$ values in some parts of the profiles. Nonetheless, the coherent and regular isotopic and trace element variations appear to be consistent with preservation of original geochemical compositions and highlight the wealth of unexplored scientific data afforded by ancient cave deposits.

CONCLUSIONS AND PROSPECTS FOR FUTURE STUDY

Although much remains to be learned about ancient speleothems, we now have the analytical tools to determine accurate and precise U-Pb ages for materials well beyond the range of U-series methods, and to ascertain if they preserve primary climate-related stable isotope, trace element, and other information. When coupled with the rapid growth in our understanding of modern and late Quaternary speleothem-climate relationships, the extremely old samples from Richards Spur clearly demonstrate the enormous potential of these materials, especially if more extensive records from longer speleothems can be found. Such samples will always require detailed petrographic and geochemical studies to assess the potential effects of recrystallization and alteration; in addition, it will often be difficult to establish internal chronologies given the resolution of the U-Pb method. Nevertheless, this is an area of immense potential. Two nascent technologies, fluid inclusions (Vonhof, 2006; van Breukelen et al., 2008) and clumped isotopes (Affek et al., 2008), will further revolutionize the information that can be extracted from such samples. Once fully calibrated and developed, these techniques have the potential to produce precise cave paleotemperature estimates independent of knowledge of local groundwater $\delta^{18}O$ composition. Coupled with existing techniques, it should then become possible to derive high-resolution paleotemperature and rainfall histories from speleothems which have occurred throughout a large portion of the Phanerozoic.

The samples we have started to study here will allow us to reexamine the terrestrial vertebrate fauna at Richards Spur within the context of the first absolute age and direct paleoclimate data for the Early Permian, one of the most significant chapters of vertebrate history. Because this age is significantly older than traditional stratigraphic correlations would suggest, it may be necessary to reconsider currently accepted biostratigraphic ages for most Early Permian fossil sites in Pangea. Our current views on the timing and tempo of early reptilian and synapsid diversification are likely to change significantly as we tie together for the first time precise age and climate determinations with the initial stages of higher vertebrate evolution on land.

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