LIMITATIONS OF HENDY TEST CRITERIA IN JUDGING THE PALEOCLIMATIC SUITABILITY OF SPELEOTHEMS AND THE NEED FOR REPLICATION

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Abstract: Carbon and oxygen isotopes in calcite speleothems are powerful proxies for understanding past climate change. For calcite deposited under isotopic equilibrium conditions, variations in $\delta^{18}O$ values directly reflect changes in cave temperature and the isotopic composition of meteoric water. Speleothem $\delta^{13}C$ values have bedrock, atmospheric, and soil gas sources. Soil gases can be traced to the overlying vegetation, which is related to climate. Both $\delta^{13}C$ and $\delta^{18}O$ values are therefore potentially powerful tracers of climate change. Processes that could alter speleothem $\delta^{13}C$ and/or $\delta^{18}O$ values, and thereby mask primary environmental signals, fall in the categories of 1) kinetic processes, including deposition of calcite out of isotopic equilibrium, and 2) vadose processes, including evaporation of water at or near the land surface. In truth, there is no absolute test for the absence of these kinetic/vadose-zone processes. However, the Hendy Test is widely used for assessing whether isotopic equilibrium existed during the time of calcite deposition. Criterion (1) of the Hendy Test (i.e., that $\delta^{18}O$ values remain constant along a single growth layer) may not be a valid control of equilibrium conditions because isotopic equilibrium could theoretically occur in the center of the speleothem at the same time that kinetic fractionation occurs at the flanks. Moreover, the concept of sampling along a single growth layer is flawed in both theory and practice. Criterion (2) of the Hendy Test (i.e., that there is no relationship between $\delta^{13}C$ and $\delta^{18}O$) is based on the assumption that speleothem $\delta^{13}C$ values are not linked to climate. However, speleothem $\delta^{13}C$ values may well be linked to climate because climate provides a first-order control on soil productivity and the type of vegetation. Therefore, Hendy Test criterion (2) is not a prerequisite to isotopic equilibrium in all cases. We propose instead the Replication Test (i.e., the demonstration of similar isotopic profiles among two or more speleothems) for evaluating the likelihood of calcite deposition under isotopic equilibrium conditions. Replication of isotopic profiles among two or more speleothems is possible only if kinetic/vadose-zone processes are either: 1) absent or 2) have affected spatially separated speleothems in exactly the same way. Because the second scenario is highly unlikely, we propose that the Replication Test is effectively sufficient in ruling out kinetic/vadose-zone overprinting processes. We further suggest that the Replication Test is far more robust in testing for the absence of the wide range of processes described above than is the traditional Hendy Test.

INTRODUCTION

Carbon- and oxygen-isotopic variations in speleothems have been studied for more than 40 years (Galimov and Grinenko, 1965; Hendy and Wilson, 1968; Duplessy et al., 1970), commonly with the central goal of reconstructing past environmental and/or climatic conditions. In a seminal paper, Hendy (1971) outlined the various equilibrium and nonequilibrium processes that govern $\delta^{18}O$ and $\delta^{13}C$ values during calcite speleothem formation and discussed the means of recognizing whether speleothem stable isotopic signatures might serve as appropriate paleoclimatic indicators.

Continued refinements in U/Th dating techniques (Edwards et al., 1987; Shen et al., 2002; Dorale et al., 2004; Hellstrom, 2006) and construction of high-resolution

$\delta^{18}O$ time series comparable to ice core records (Bar-Matthews et al., 1997; Dorale et al., 1998; Wang et al., 2001; Yuan et al., 2004; Spötl et al., 2006; Wang et al., 2008; Zhang et al., 2008) have generated a surge of renewed interest in using speleothems as high-resolution paleoclimatic archives. Thus, the fidelity with which $\delta^{18}O$ and $\delta^{13}C$ variations in speleothems might be interpreted as paleoclimatic indicators remains a basic and critical issue. This

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paper considers the widely used Hendy Test method for evaluating the presence or absence of isotopic equilibrium in speleothems. We reach the long overdue conclusion that the Hendy Test criteria for judging speleothems (Hendy, 1971) are not reliably effective at screening stalagmites for paleoclimatic suitability. We therefore suggest that the widespread application of Hendy Test should be discontinued. We propose instead the Replication Test (i.e., the demonstration of similar isotopic profiles among two or more speleothems) for evaluating the likelihood of calcite deposition under isotopic equilibrium conditions (e.g. Dorale et al., 1998; Wang et al., 2001; Constantin et al., 2007; Denniston et al., 2007; Wang et al., 2008). Replication of isotopic profiles among two or more speleothems is possible only if kinetic/vadose-zone processes are either: 1) absent or 2) have affected spatially separated speleothems in exactly the same way. As the second scenario is highly unlikely because of the spatial heterogeneity of the karst aquifer (Perrin et al., 2003), we propose that the Replication Test is effectively sufficient in ruling out kinetic/vadose-zone-overprinting processes.

OXYGEN AND CARBON ISOTOPES IN SPELEOTHEMS

The $\delta^{18}O$ and $\delta^{13}C$ values of speleothem $CaCO_3$ are related to the primary sources of oxygen and carbon in the cave seepage water. In the case of oxygen, this is meteoric water. In the case of carbon, this is soil CO_2, atmospheric CO_2, and carbonate bedrock. In most cases, the process of speleothem deposition can be traced back to the soil layer where biological activity produces high levels of CO_2. This soil CO_2 acidifies seepage waters, which in turn dissolve carbonate bedrock enroute to underlying caves. Upon entering a cave passage of lower CO_2 partial pressure (relative to the soil atmosphere), the seepage water releases CO_2 and $CaCO_3$ deposition takes place in accordance with the equation below (Holland et al., 1964):

$$Ca^{2+} + 2HCO_3^- \rightarrow CO_2 + CaCO_3 + H_2O \qquad (1)$$
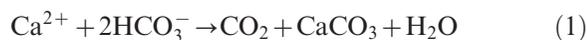
Because HCO_3^- concentrations in karst ground waters are typically in the parts per thousand range, $\delta^{18}O$ values of the water and the dissolved carbonate species are dominated by the water molecules themselves, which originated as meteoric precipitation. Therefore, the $\delta^{18}O$ values of speleothems are generally not significantly influenced by bedrock $\delta^{18}O$ values (Harmon, 1979).

Paleoclimatic interpretation of speleothem $\delta^{18}O$ variations requires knowledge and quantitative estimation of processes that may affect the isotopic composition of water during the course of the hydrologic cycle and during calcite deposition. The cave temperature effect of Williams et al. (1999) represents isotopic fractionation between water and calcite during calcite deposition. The temperature dependence of the fractionation has been experimentally determined as $\sim -0.24‰$ per $°C$ (O'Neil, 1969), meaning

that there is greater fractionation at low temperatures relative to high temperatures. The rainwater composition effect represents established empirical relationships between precipitation $\delta^{18}O$ values and certain climatic parameters such as temperature and rainfall intensity (Dansgaard, 1964). Different parts of the globe are represented by fundamentally different relationships, depending on the prevailing meteorological pattern of precipitation. In tropical regions and regions that experience a strong monsoon or a Mediterranean climate, for example, the rainwater composition effect may not have a strong link to temperature. Other factors, such as the intensity of the rainfall (Dansgaard's (1964) Amount Effect), or the partitioning of multiple moisture sources over the course of the year, may dominate variations in the $\delta^{18}O$ values of precipitation (Wang et al., 2001; Bar-Matthews et al., 2003; Wang et al., 2008). However, at many middle and high-latitude sites, the rainwater composition effect is linked to temperature. The modern day spatial slope for Greenland, for example, is 0.67‰ per $°C$ (Johnsen et al., 1989). For many mid-latitude regions, the $\delta^{18}O_{MAP(mean\ annual\ precipitation)} - MAT_{(mean\ annual\ temperature)}$ slope is generally also positive, but the slope is typically smaller than 0.67‰ per $°C$.

Caves are excellent environments for temperature reconstructions because the ambient temperature within sufficiently deep caves is constant year-round, and reflects the mean surface temperature averaged over several years (Wigley and Brown, 1976). The $\sim -0.24‰$ per $°C$ fractionation that defines the cave temperature effect, therefore, reflects the mean annual temperature of the area. If the cave drip water can be assumed to approximate $\delta^{18}O_{MAP}$ (Yonge et al., 1985), the rainwater composition effect and the cave temperature effect may be combined to yield an $\delta^{18}O_{speleothem} - MAT$ slope that is either positive, negative, or zero, depending on the exact sign and slope of the $\delta^{18}O_{MAP} - MAT$ relationship (Hendy and Wilson, 1968; Harmon et al., 1978; Gascoyne et al., 1980; Dorale et al., 1992; Winograd et al., 1992; Dorale et al., 1998; Lauritzen and Lundberg, 1999b; Williams et al., 1999). If the $\delta^{18}O_{MAP} - MAT$ slope has a value larger than +0.24‰ per $°C$, then the $\delta^{18}O_{speleothem} - MAT$ slope will be positive (i.e. more positive $\delta^{18}O_{speleothem}$ values indicate warmer temperatures). If the $\delta^{18}O_{MAP} - MAT$ slope is less than +0.24‰ per $°C$, the $\delta^{18}O_{speleothem} - MAT$ slope will be negative, in which case more positive $\delta^{18}O_{speleothem}$ values indicate lower temperatures.

What mostly limits robust quantitative temperature reconstructions back through time is the incomplete knowledge of how the slope for $\delta^{18}O_{MAP} - MAT$ has varied through time. Possible reasons for $\delta^{18}O_{MAP} - MAT$ slope variations include fundamental changes in the seasonality or the moisture source of the precipitation (Jouzel et al., 1997). In the case of speleothems, the problems of an unknown, but presumably variable rainwater composition effect could be circumvented if

there was some way of accessing directly the water from which the calcite was precipitated. Fluid inclusions in speleothems are tiny trapped parcels of the original drip water from which the calcite was deposited. Henry Schwarcz and his students pioneered the early ideas of fluid inclusion work (Schwarcz et al., 1976; Harmon et al., 1979; Yonge, 1982), but technical difficulties in extracting an unfractionated sample of the water stymied the approach for many years. Recent work shows considerable promise in having overcome the technical challenges (Rowe et al., 1998; Matthews et al., 2000; Vonhof et al., 2006; Zhang et al., 2008).

Most recently, the clumped isotope technique has been developed as a type of quantitative paleothermometer for carbonates that requires no information or assumptions about the $\delta^{18}O$ values of waters from which carbonates grew (Eiler, 2007; Affek et al., 2008). This is an exciting development, although application of the clumped isotope paleothermometer to speleothems is in its infancy and we would think there will be significant challenges (although not insurmountable) in accurately applying the technique to speleothems because of issues with sample size and precision.

Unlike $\delta^{18}O$ values, speleothem $\delta^{13}C$ values are significantly influenced by the isotopic composition of the bedrock and the soil CO_2 (Deines et al., 1974). Vegetation is a major controlling factor of speleothem $\delta^{13}C$ values because soil CO_2 is generated largely by root respiration and the microbial oxidation of soil organic matter, which is derived from vegetation. Whereas bedrock characteristics are generally stable over the timescales of U/Th dating, vegetation can be dynamic. Most of the world's plants utilize either the C_3 photosynthetic pathway or the C_4 pathway (a minor group is the CAM pathway). The C_3 and C_4 photosynthetic pathways produce large differences in $\delta^{13}C$ values. C_3 plants have $\delta^{13}C$ values averaging ca. -26‰, whereas C_4 plants average ca. -12‰ (Deines, 1986). C_4 plants are typically warm-season grasses and a few herbs found in tropical and temperate grasslands, whereas C_3 plants include most trees, shrubs, cool-season grasses, and most herbs. Where C_3 and C_4 plant types coexist, their biomass ratio will be reflected in the soil CO_2 $\delta^{13}C$ values. Proxies capable of preserving soil $\delta^{13}C$ signatures such as speleothems (Dorale et al., 1992; 1998; Holmgren et al., 1995) are thus capable of recording the proportion of C_3 to C_4 plant biomass through time, and are indirectly linked to climate. Thus, we do not necessarily agree with the generalized assertion of Dreybrodt (2008), that "...oxygen isotope records of stalagmite are more promising for extracting paleo-climatic signals than those of carbon".

LIMITATIONS OF THE HENDY-TEST CRITERIA

EQUILIBRIUM VERSUS NON-EQUILIBRIUM DEPOSITION OF CALCITE

Although it is clear that speleothem $\delta^{18}O$ values are controlled by temperature and the isotopic composition of meteoric water and that $\delta^{13}C$ values are controlled by the isotopic composition of bedrock and soil organic matter, the degree to which the $\delta^{18}O$ and $\delta^{13}C$ values of speleothem calcite reflect only these primary environmental variables is possibly a more complex issue. It is possible that other processes may mask these primary environmental variables (Hendy, 1971). These processes may fall into the category of kinetic processes during calcite crystallization. Hendy (1971) distinguished such kinetic effects from the more desirable isotopic-equilibrium condition. That is the condition defined by sufficiently slow degassing rates and with no evaporation, such that the fractionation of heavy and light isotopes between aqueous and solid phases is only a function of temperature. Although useful paleoenvironmental information may be recorded in speleothems deposited out of isotopic equilibrium (Talma and Vogel, 1992; Spötl and Mangini, 2002), equilibrium deposition is generally more desirable because, under such conditions, temporal variations in $\delta^{18}O$ and $\delta^{13}C$ values most likely reflect changes in the primary environmental variables of interest directly, not indirectly through complicated controls on varying degrees of non-equilibrium effects.

Recently, a number of field, experimental, and modeling studies have focused directly on the issue of isotopic equilibrium in stalagmites (e.g., Mickler et al., 2004; Mickler et al., 2006; Mühlinghaus et al., 2007; Romanov et al., 2008; Dreybrodt, 2008). All have provided valuable insight into this important issue of equilibrium versus non-equilibrium deposition, but none have seriously challenged the general applicability of the Hendy Test in screening stalagmites for paleoclimatic suitability.

THE HENDY-TEST CRITERIA AND THEIR LIMITATIONS

In many recent studies, researchers have applied Hendy Test criteria to a single stalagmite to ascertain whether the calcite was deposited under isotopic equilibrium conditions (e.g., Fleitmann et al., 2004; Dykoski et al., 2005; Vacco et al., 2005; Williams et al., 2005; Johnson et al, 2006a; Spötl et al., 2006; Mangini et al., 2007; Hu et al., 2008; Zhang et al., 2008; Zhou et al., 2008). The Hendy Test approach requires drilling subsamples along a growth layer in the stalagmite, from the center outward and down the flanks. The Hendy Test criteria are: (1) $\delta^{18}O$ values remain constant along a single growth layer; (2) there are no simultaneous enrichments of ^{13}C and ^{18}O in the speleothem calcite (i.e., there is no correlation between $\delta^{13}C$ and $\delta^{18}O$ values). The basis for ^{13}C enrichments is thought to be linked to Rayleigh distillation of the HCO_3^- (aq) reservoir during degassing of $\delta^{13}C$-depleted CO_2 (Hendy, 1971; Mickler et al., 2006; Romanov et al., 2008). In contrast, ^{18}O may not be nearly as affected by Rayleigh distillation during degassing because CO_2 hydration and hydroxylation reactions will buffer the oxygen isotopic composition of the HCO_3^- (aq) reservoir (Mickler et al., 2006). However, if the effects of Rayleigh distillation manifest themselves in the oxygen isotopic system, they will result in

$\delta^{18}O$ enrichment in the HCO_3^- (aq) reservoir and ultimately in the precipitated $CaCO_3$.

Based on the above argument, criterion (1) may at face value appear to have a sound theoretical basis, but it may not be a perfect test for the presence of equilibrium conditions because isotopic equilibrium fractionation could occur in the center of a stalagmite at the same time that kinetic fractionation occurs at the flanks (Talma and Vogel, 1992; Spötl and Mangini, 2002; Dreybodt, 2008). In this particular case, criterion (1) of the Hendy Test could fail to indicate that isotopic equilibrium was maintained in any sector of the studied stalagmite. An additional, and largely underappreciated, problem with criterion (1) revolves around the issues of sampling resolution and sampling errors. In practice, criterion (1) is difficult (if not impossible) to apply, in part, because even small sampling errors could invalidate the within growth layer comparison, and in part, because the geometry of a typical stalagmite is not well-suited for the task. A typical growth layer is commonly thickest along the top surface of the stalagmite and becomes progressively thinner along the sides. If growth layers were of uniform thickness, stalagmites would be twice as wide as they are tall, which is seldom, if ever, the case. Therefore, when a constant diameter drill bit is used, drillings from the sides of the stalagmite (where the targeted layer is thinner) will likely include calcite that is younger and/or older relative to drillings from the top surface. This errantly sampled young and old calcite (possibly even including small growth hiatuses not present in the stalagmite center) may have a significantly different isotopic composition than that of targeted growth layer. Thus, a comparison of coeval sub-samples from the top and the sides is not truly valid, and a negative result of the Hendy Test does not, therefore, necessarily indicate kinetic fractionation during deposition (Lauritzen and Lundberg, 1999a). A truly valid attempt at executing criterion (1) would by necessity use multiple drill bits of variable diameter. This approach has never, to our knowledge, been reported in the literature.

Another, possibly more critical issue with regard to sampling resolution, involves the large temporal mismatch between drilled subsamples and the actual timescale of calcite-formation processes. Subsamples drilled using modern techniques are time integrations typically on the order of months to centuries, depending on calcite deposition rates. Even the short end of this timescale is clearly incompatible with the seconds to hours timescale of drip rate, CO_2 degassing, calcite precipitation, and other reaction processes being evaluated as equilibrium versus non-equilibrium by Hendy Test criterion (1). In other words, since drilled sub-samples often incorporate years to centuries of material into a single isotopic value, criterion (1) implicitly assumes that any level of apparent isotopic disequilibrium detected by criterion (1) was maintained at some constant level for the entire time of integration. This is highly unlikely, as numerous studies of cave drip waters have shown high variability in seasonal drip and related isotopic phenomena (e.g. Bar-Matthews et al., 1996; Treble et al., 2005; Johnson et al., 2006b; Cobb et al., 2007).

The same temporal mismatch is problematic for the same reason to studies of modern drip waters and associated speleothems, which has been claimed by some to offer the most convincing case for assessing whether isotopic equilibrium exists in a given cave setting (e.g., Bar-Matthews et al., 1996; Mickler et al., 2006; Harmon et al., 2004). The problem again is that drip waters collected in modern settings represent isotopic snapshots of seconds-to-minutes while calcite collected for comparison (due to sample size constraints) may represent much longer time integrations. Furthermore, this mismatch in water volume versus calcite volume (normalized to time) to enable measurements on both probably results in significant bias in modern drip/calcite studies toward fast-growing calcites. Unfortunately, this may well be the type of calcite most likely to have been deposited out of isotopic equilibrium.

Hendy Test criterion (2) is based on the assumption that there is no systematic change in the $\delta^{13}C$ value of soil CO_2 with a change in climate as reflected by $\delta^{18}O$ values (Hendy, 1971). While this scenario is theoretically possible, it would appear to be unlikely in the majority of cases. In fact, the concentration and $\delta^{13}C$ values of soil CO_2 are tied to climate, which controls the soil bio-productivity (Cerling and Quade, 1993; Hellstrom et al., 1998; Hellstrom et al, 2000; Genty et al., 2006) and the type of vegetation (Cerling, 1984; Deines, 1986). As one example, vegetation could change with a change in climate (Cerling, 1984; Dorale et al., 1992; 1998). Clearly in this case, simultaneous changes in speleothem $\delta^{13}C$ and $\delta^{18}O$ values could be expected (Dorale et al., 1992; Baker et al., 1998; Holmgren et al., 1995; Bar-Matthews et al., 1997; Dorale et al., 1998; Denniston et al., 2000; Frumkin et al., 2000; Denniston et al., 2001; Xia et al., 2001; Burns et al., 2002; Vaks et al., 2003, McDermott et al., 2004; Zhang et al., 2004, 2006; Frisia et al., 2005; Vacco et al., 2005; Cruz Jr. et al., 2006; Vaks et al., 2006; Mangini et al., 2007). Thus, in some cases, such a coupling of $\delta^{13}C$ and $\delta^{18}O$ values is not related to the kinetic isotope effects, but is instead an indication of climatic change. Several examples follow below.

The work of Dorale et al. (1998) provides a highly illustrative example of this type of coupling in their study of several stalagmites from Crevice Cave, Missouri, USA. They found that multiple stalagmites yielded highly replicating $\delta^{13}C$ and $\delta^{18}O$ profiles throughout part of the last glacial period (Fig. 1). Temperatures interpreted from $\delta^{18}O$ values and C_4 plant biomass interpreted from $\delta^{13}C$ values were both relatively high from 59–55 ka (Fig. 1). Declining $\delta^{13}C$ and $\delta^{18}O$ values were interpreted as a cooling climate with forest replacing grassland around 55 ka. The key element in interpreting the coupled changes in $\delta^{13}C$ and $\delta^{18}O$ values as climate-driven versus kinetic-driven (as might be concluded from a Hendy Test
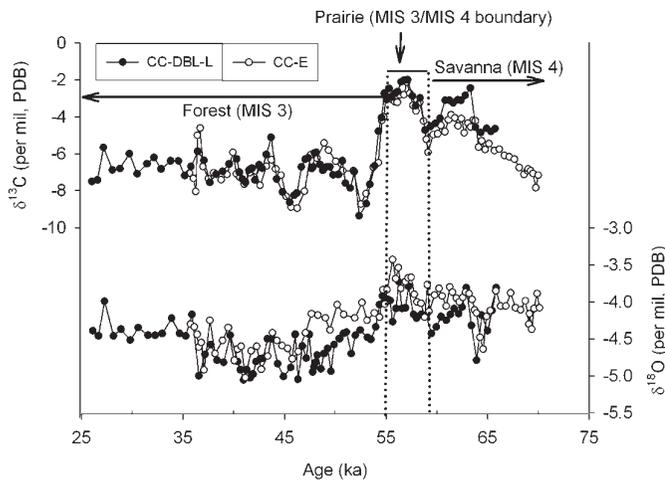
Figure 1. The $\delta^{13}C$ and $\delta^{18}O$ values vs. time, for stalagmites CC94-DBL-L and CC94-E (after Dorale et al., 1998), showing that the simultaneous enrichment of ^{13}C and ^{18}O (or a negative result of the Hendy Test) is the indication of change in both climate and vegetation type, but not the result of nonequilibrium isotopic fractionation. That means a negative result of the Hendy Test does not necessarily indicate kinetic fractionation.

Figure 2. The $\delta^{13}C$ and $\delta^{18}O$ values vs. time, for adjacent increments of cores MD3 and ED1 (after Hellstrom et al., 1998), showing that the simultaneous enrichment of ^{13}C and ^{18}O (or a negative result of the Hendy Test) is not related to the kinetic isotope effects in this case, but rather an indication of changes in both climate and forest productivity.

approach) was the replication. The stalagmites differed in growth rates, diameters, and a number of other characteristics that could be considered reflective of drip rates, CO_2 degassing rates, and calcite precipitation rates (all thought to influence equilibrium versus non-equilibrium deposition), yet $\delta^{13}C$ and $\delta^{18}O$ values replicated. The replication implies that the differences in hydrologic characteristics between specific drip pathways cannot account for the long-term changes in speleothem $\delta^{13}C$ and $\delta^{18}O$ values. Instead, these $\delta^{13}C$ and $\delta^{18}O$ trends likely reflect a more pervasive influence, such as the climate driven changes in $\delta^{13}C$ values of the overlying soil and vegetation.

Hellstrom et al. (1998) produced a detailed record of climate and vegetation change from the $\delta^{13}C$ and $\delta^{18}O$ profiles of two New Zealand speleothems (Fig. 2). The $\delta^{13}C$ record (Fig. 2) is interpreted in terms of inorganic processes acting on carbon derived purely from C_3 plants (as C_4 plants do not exist in New Zealand), and appears to be closely related to changes in soil CO_2 concentration above the cave. As such, it is considered a proxy for forest productivity above the cave, a conclusion strongly supported by its similarity to pollen-based records of forest extent in the region. Notably, an extremely rapid increase in forest cover (indicated by steep decrease in $\delta^{13}C$ values (Fig. 2)) coincident with a significant increase in speleothem growth rate, was centered on 15 ka and marking the end of glacial maximum conditions (indicated by the highest speleothem $\delta^{18}O$ values and highest speleothem $\delta^{13}C$ values at ~19 ka (Fig. 2)) in the region. Close examination of Figure 2 reveals a short delay in the decline of $\delta^{13}C$ values relative to $\delta^{18}O$ values, which may capture a
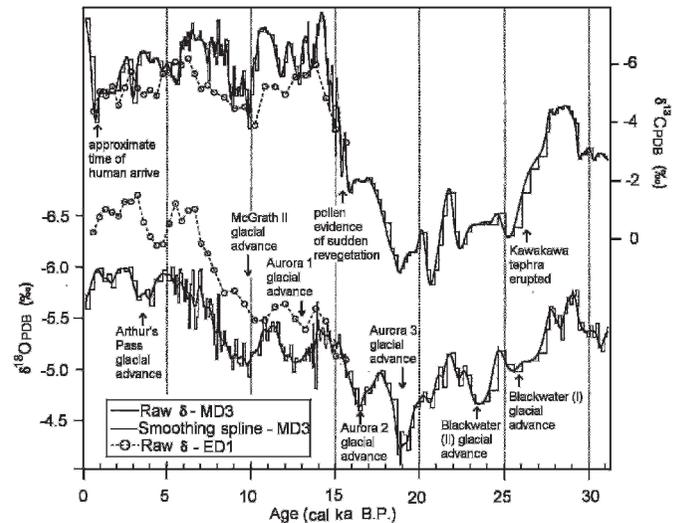
small lag between the time of climate change and soil microbe re-activation induced by the climate change. Similar to the example from Crevice Cave, the systematic co-variation between $\delta^{13}C$ and $\delta^{18}O$ values is again not necessarily related to kinetic isotopic fractionation, but instead, is likely forced by climate change.

In our last example, Baldini et al (2005) found that increases in calcite deposition rates, combined with decreases in $\delta^{13}C$ and $\delta^{18}O$ values in three modern stalagmites from Brown's Folly Mine, Wiltshire, England, are correlative with a well-documented re-vegetation above the mine. Increased soil pCO_2 resulted in greater amounts of dissolved $CaCO_3$ in the drip waters, which consequently increased annual calcite deposition rates. Lower $\delta^{13}C$ values through time may reflect the increased input of isotopically light biogenic carbon to the total dissolved inorganic carbon (DIC). In this case, $\delta^{18}O$ values decreased synchronously with $\delta^{13}C$ values, reflecting the increased importance of isotopically light winter recharge due to greater biomass-induced summer evaportranspiration.

Finally, in view of his recent modeling results Dreybrodt (2008) concluded that stalagmites collected for paleoclimatic studies should have grown with drip intervals of less than 50 seconds, which results in diameters of at least 10 cm and predicts oxygen isotopic equilibrium in the calcite. We find this result intriguing and perhaps reflective of the situation in several recently published Chinese cave $\delta^{18}O$ records, which are derived from fast-growing, large diameter, replicating stalagmites (e.g., Wang et al., 2001; Yuan et al., 2004). On the other hand, the replicating fossil stalagmites from Crevice Cave are characteristically slow-

growing (typical range: 1–10 µm yr^{-1}) and with diameters typically in the range of 4–7 cm. Therefore, our field evidence from Crevice Cave would not appear to support the predictions of Dreybrodt's (2008) model. We suspect instead that slow degassing and calcite precipitation rates, as reflected in the slow growth rates of these particular speleothems, likely contributed to their replicating profiles, which we interpret as equilibrium deposition.

CONCLUSIONS

The argument for replication is simple, straightforward, and powerful. Imagine the scenario where two coeval stalagmites from a given cave contain disparate $\delta^{13}C$ and $\delta^{18}O$ profiles. Which stalagmite contains the correct climatic signal, stalagmite A, stalagmite B, or neither? Traditionally the Hendy Test would be employed to sort out this mystery, but we have shown here that the Hendy Test is prone to producing invalid comparisons and false negative results; and therefore, cannot be considered accurate in its approach. In truth and in practice, the Hendy Test is an easily executed exercise widely used in the review and editorial process to validate speleothem climate records, but, unfortunately, it is not a reliable exercise.

To help resolve the conundrum of our stalagmite A versus B scenario, should we instead adopt the advice from modeling studies such as Dreybrodt (2008) and choose the larger diameter stalagmite over the smaller diameter one? Should we choose the stalagmite with the less porous fabric, or the one less colored? Should we choose the stalagmite with flat layering or the one with arced layering? In truth, we cannot know from these types of basic observations which one, if either, reflects equilibrium deposition. Had a single stalagmite been used in the study, the entire issue of disparity would have been avoided, but we would be no closer to the truth in deciphering the status of equilibrium deposition.

We would argue that only in the case where two or more stalagmites replicate $\delta^{18}O$ and $\delta^{13}C$ values can we have any significant measure of confidence that isotopic equilibrium was maintained. Others have argued that the only real test of equilibrium deposition is to directly measure and monitor the isotopic composition of drip waters and calcites, along with the environmental conditions the calcite is precipitated under, in modern systems, and then use this information to help interpret the ancient speleothem record (e.g., Bar-Matthews et al., 1996; Mickler et al., 2004; 2006; Harmon et al., 2004). While we do not necessarily disagree with the wisdom of this approach, it may not be feasible in many cases, and also, there is no guarantee that modern conditions mimic ancient ones. In fact, with large differences in climate and the whole range of carbonate chemistry and water flow parameters linked to climate, it may even be likely that modern systems are poor analogs for ancient ones. We would argue, again, that replication is a key, as is a high level of agreement with

independent indicators of paleoclimatic conditions, such as paleovegetation or ice cores.

Finally, our advocacy for replication has implications for cave conservation. Speleothem collection should always be carried out with the very highest standards of conservation. In some cases, the collection of multiple speleothems simply may not be justifiable. Instead, we should focus our efforts on those systems that have an adequate resource to allow for sampling with minimal impact. In the case of Crevice Cave, for example, literally hundreds of speleothems, naturally broken, exist in the cave. We might also consider increasing our depth of understanding of those systems that have already displayed promise of faithfully capturing paleoclimatic conditions, versus racing around the globe attempting to collect samples from pristine settings.

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