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Biomass effects on stalagmite growth and isotope ratios: A 20th century analogue from Wiltshire, England

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Abstract

Increases in calcite deposition rates combined with decreases in $\delta^{13}C$ and $\delta^{18}O$ in three modern stalagmites from Brown's Folly Mine, Wiltshire, England, are correlative with a well-documented re-vegetation above the mine. Increased soil P_{CO_2} resulted in greater amounts of dissolved $CaCO_3$ in the drip waters, which consequently increased annual calcite deposition rates. The absence of deposition prior to 1916 (28 years after the mine was closed) indicates that vegetation had not yet sufficiently developed to allow higher P_{CO_2} values to form in the soil. Lower $\delta^{13}C$ values through time may reflect the increased input of isotopically light biogenic carbon to the total dissolved inorganic carbon (DIC). $\delta^{18}O$ decreased synchronously with $\delta^{13}C$, reflecting the increased importance of isotopically light winter recharge due to greater biomass-induced summer evapotranspiration. This is the first empirical demonstration that vegetation density can control stalagmite growth rates, $\delta^{13}C$, and $\delta^{18}O$, contributing critical insights into the interpretation of these climate proxies in ancient stalagmites.

Keywords: stalagmite; carbon isotopes; oxygen isotopes; fractionation; vegetation; growth rate

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1. Introduction

Stalagmites are widely regarded as critically important archives of terrestrial paleoclimates, but it is increasingly apparent that the mechanisms responsible for their petrographic and stable isotope signals are inadequately understood. Many stalagmites preserve visible petrographic [1,2], luminescent [3,4], and/or geochemical laminae [5,6] that not only enable the construction of highly precise chronologies, but also provide valuable paleoclimatic information. Variations in the thickness of stalagmite laminae are interpretable in terms of key climatic variables such as effective precipitation (principal control on drip rate) [7], temperature and soil P_{CO_2} [8], and when combined with precise U/Th dates and stable isotopic measurements, serve to quantify the timing and the magnitude of paleoclimatic events.

Previous studies in regions characterized by sharp ecotone transitions have suggested that stalagmite $\delta^{13}C$ fluctuations reflect climate induced shifts in vegetation

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type, primarily because plants utilizing the C3 photosynthetic pathway have significantly lower $\delta^{13}C$ values than C4 plants [9–11]. However, recent research on a stalagmite deposited during the last glaciation (MIS 3 and 4) indicates that warmer temperatures associated with Dansgaard-Oeschger events promoted the development of local vegetation resulting in more biogenic CO_2 dissolved in seepage water, obviating the need to appeal to changes in vegetation C3/C4 ratio [12]. Low $\delta^{13}C$ values (characteristic of biogenic carbon) coinciding with periods of rapid stalagmite growth were interpreted as representing increased surface vegetation density [12]. Conversely, elevated $\delta^{13}C$ values were interpreted as a representing a return to near full glacial conditions, and these increasing $\delta^{13}C$ trends were often truncated by a cessation of stalagmite growth indicative of conditions unfavorable to vegetation [12]. A need clearly exists for an improved understanding of the processes responsible for temporal changes in stalagmite $\delta^{13}C$, particularly in temperate regions where vegetation type is predominantly C3.

In this study we analyze laminae thicknesses, $\delta^{13}C$, and $\delta^{18}O$ of three modern stalagmites obtained from a site that has undergone well-documented changes in surface vegetation (Brown's Folly Mine, SW England) to establish a clear link between the extent of surface vegetation and the stalagmite record. The changes observed in the temporal distribution of calcite deposition, $\delta^{18}O$, and $\delta^{13}C$ within the Brown's Folly Mine stalagmites are similar in magnitude to variations recorded during glacial–interglacial transitions for many stalagmites [13–16], suggesting that the density of vegetation is a significant control on speleothem climate records.

2. Research setting

Brown's Folly Mine, Bathford Hill, SW England, is developed in the Bath Oolite member of the Jurassic Great Oolite Series limestone at between 5–15 m depth below the surface [17]. The mine was opened in 1836 for the extraction of building stone, thus constraining the maximum age of its stalagmites. The mine was worked until 1886, when all of its entrances were sealed. Mining continued in other mines within Bathford Hill until 1904, when the area was converted into a nature preserve and vegetation was allowed to re-establish itself. Aerial photographs of Bathford Hill indicate that large portions of the hill were still barren in 1945 (Fig. 1a) but were gradually reclaimed by the secondary deciduous forest (Fig. 1b,c). A photograph taken in 1907 (Fig. 1d) demonstrates that immediately after the cessation of mining no substantial vegetation existed on the area directly above the study site, contrasting sharply with the well-developed mixed ash, sycamore, and oak forest currently in existence (Fig. 1e). Native species of trees and shrubs were preferentially allowed to return. A thin brown rendzina soil overlies the mine [8]. The entrances to Brown's Folly Mine remained closed until cavers re-opened the entrances in the 1970s [18]. The mine is in an area of maritime temperate climate with a mean annual temperature of 10.0 °C and a mean annual precipitation of 842 mm. Precipitation is slightly more common during the winter, but rainy weather occurs throughout the year [19]. The site was chosen for this study because it affords an excellent opportunity to test the links between surface vegetation, stalagmite morphology, and stalagmite isotope geochemistry.

The three sampled stalagmites were obtained from the same chamber, within ten meters of each other, but in different years (BFM9: 1998, Boss: 1996, F2: 1998). The chamber is located approximately 300 m from the nearest entrance and is approximately ten meters wide, ten meters long, and two meters in height. The temperature in the sampling chamber was measured as 10 ± 0.4 °C, with no seasonal variation, and the humidity within the sampling chamber is close to 100% [18], effectively eliminating the possibility of evaporation. The P_{CO_2} of the sample chamber was measured as 0.0035–0.0040 atm [18]. All the entrances are at approximately the same elevation, thereby minimizing airflow through the mine. A similar thickness of bedrock exists directly over the stalagmite sampling sites, though because the overlying topography is an extremely heterogeneous karst, the hydrological routing between the surface and each of the three stalagmites could vary dramatically. The amount of vegetation directly above all three stalagmites is similar, but localized heterogeneity may still exist (e.g., more vegetation at the base of a doline).

3. Methods

Thin sections of the three stalagmites collected from the floor of the mine (BFM9, Boss, and F2) were assessed for variability in laminae structure, crystal habits, and calcite fabrics with a petrographic microscope. Growth lamina thicknesses for BFM9, Boss, and F2 were measured using high-resolution digital scans and the drafting program Canvas® (error = +/− 0.001 mm), which allowed for additional magnification where necessary and ensured that only continuous layers were measured. Three independent laminae thickness counts were conducted per stalagmite to ensure reproducibility. Couplet thicknesses are reported as percents of the total

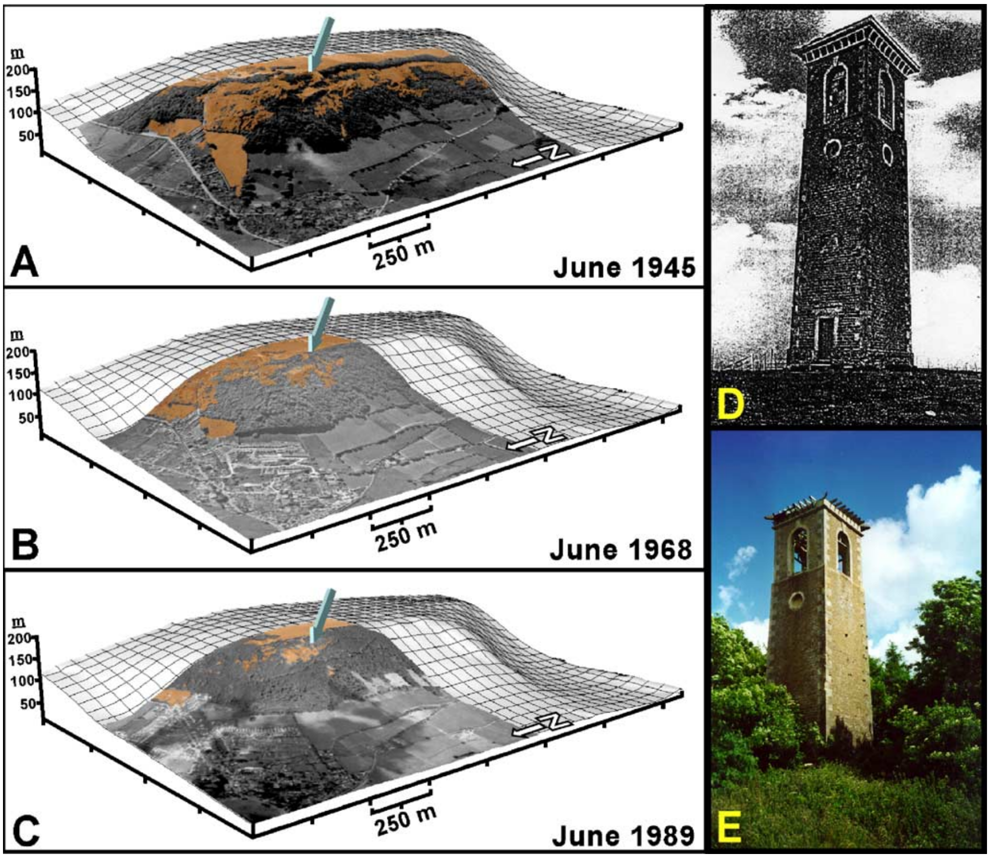

Fig. 1. A) Oldest available aerial photograph of Bathford Hill demonstrating that large portions of the hill were devoid of vegetation in 1945. Large arrow indicates location of Brown's Folly tower, which is directly above sampling area. Orange shading indicates areas with minimal vegetation and was determined by visual examination. B–C) Aerial photographs taken in 1968 and 1989, respectively, showing developing secondary forest. D) Photograph of Brown's Folly tower taken in 1907 demonstrating that the zone directly above the stalagmite sampling area was barren. E) Photograph of Brown's Folly tower taken in 1998 showing well-developed secondary vegetation now characteristic of the site.

calcite deposition (thickness of the stalagmite at the location of the laminae count) to facilitate comparison between the three stalagmites. Calcite powders (~1 mg) of were obtained using a drill equipped with a 600 μm drill bit at a mean spatial resolution of 1.2 mm and stable isotope ratios (δ^{18}O and δ^{13}C) were analyzed using a VG Prism Series 2 mass spectrometer at Royal Holloway, University of London. The analytical precision was 0.1‰ (1σ) for both δ^{18}O and δ^{13}C. The drill bit diameter results in temporal averaging (based on the growth rates presented below) of approximately 4.5 yr for the first ten years of calcite deposited and 1.5 yr for the last ten years of calcite deposited for all three stalagmites.

4. Results and discussion

All three stalagmites share the same basic petrography with varying degrees of internal layering consisting of alternating bands of laterally continuous clear calcite and dark inclusion-rich calcite (Fig. 2). The laminae within the stalagmites were most likely deposited as yearly couplets, similar to those found in previous studies [20–22]. The dark layers of the couplets probably represent the annual autumnal/winter flushing of organic compounds and debris related to leaf fall [23]. The calcite grew in large, columnar crystals oriented parallel to the growth axis apparently unaffected by the distribution of inclusion-rich and clear layers. No growth hiatuses were observed in any of the stalagmites. Clear, euhedral crystal terminations were present at the tops of BFM9, Boss, and F2, suggesting that the stalagmites were still actively growing when collected. Three radiocarbon measurements (AMS, Center for Isotope Research, University of Groningen) successfully located the radiocarbon 'bomb-spike' occurring in 1964 within BFM9, providing additional chronological control independent of that provided by the laminae

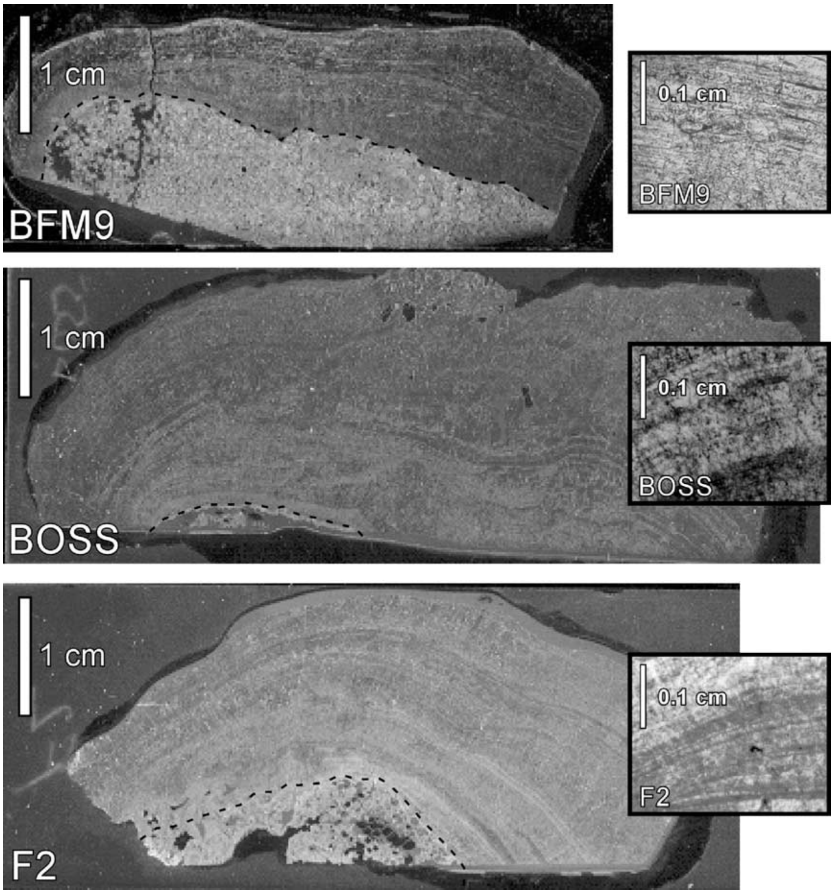

Fig. 2. Photographs of stalagmites from Brown's Folly Mine displaying characteristic layering. The windows to the right are a 5× magnification of the layering compared to the panels to the left. The dashed line separates the stalagmite from the oolitic grainstone substrate.

counts [24]. Because the couplets are deposited annually, construction of a chronology is possible.

The total thickness of stalagmite BFM9 at the central growth axis is 12 mm and it consists of approximately 67 annual couplets (67+/−3, based on three replicate counts). According to the laminae count with the greatest number of laminae, the stalagmite nucleated no earlier than 1928 (Fig. 3). Couplet thicknesses decrease until 1960 when annual calcite deposition gradually begins to increase. A dramatic increase in couplet thickness occurs in 1980, and the annual amount of calcite deposited from 1980 is approximately 4 times the annual deposition rate for the period between 1940 and 1975. The total thickness of stalagmite Boss at the central growth axis is 20 mm and it consists of 77+/−3 annual couplets, suggesting that the stalagmite nucleated no earlier than 1916 (Fig. 3). Annual calcite deposition rates increase gradually but remain low until 1975, when couplet thicknesses increase dramatically. The thickness of stalagmite F2 at the central growth axis is 18 mm and it consists of approximately 62+/−8 annual couplets, suggesting that F2 nucleated no earlier than 1931 (Fig. 3). Very little deposition occurs during the first 28 years of growth. Deposition rates double around 1960, and increase even more dramatically in 1991.

The temporal trends in calcite deposition rates are broadly similar in all three stalagmites. Differences in the second-order variability between the records probably result from heterogeneities in the hydrological routing of the drips feeding the stalagmites. Although the mine entrances were closed in 1886, no deposition occurred in any of the three stalagmites prior to 1916. The re-opening of the entrances to the mine in the 1970s theoretically could have increased the growth rates of the stalagmites, but because the growth rate increases occurred at different times, the sampling site was not located close to an entrance, and because the observed isotopic shifts (discussed later) are not consistent with increased ventilation, the re-opening of the mine entrances is not believed to have affected the growth rate of the stalagmites. Photographic evidence

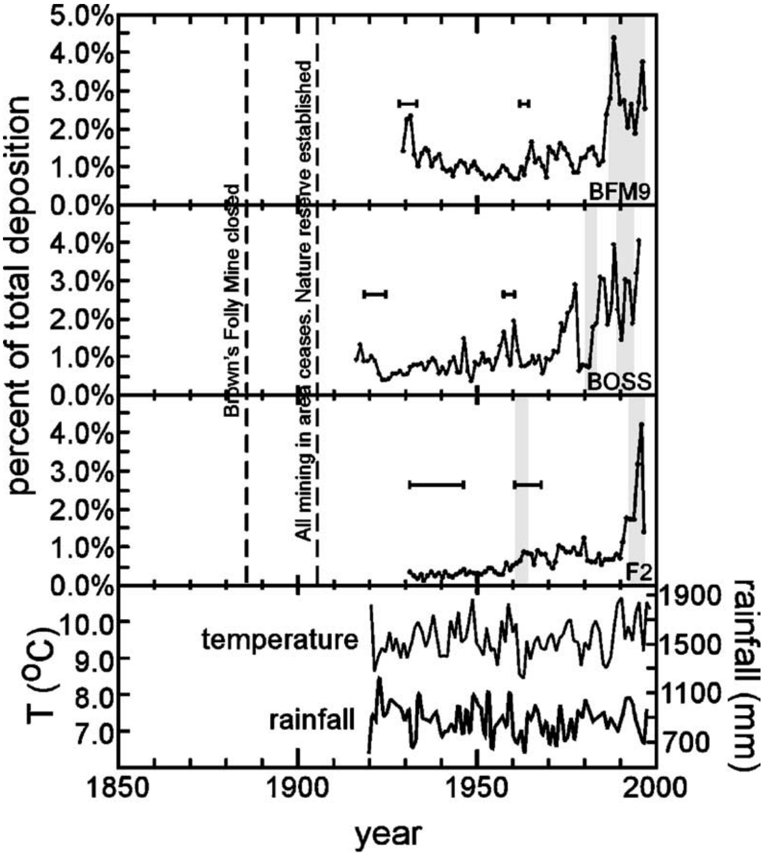

Fig. 3. Couplet thickness records for BFM9, Boss, and F2. Each individual record averages couplet thicknesses for each year obtained in three independent layer counts. Error bars indicate error in the chronology and are based on the difference between the total numbers of layers counted in the three independent counts per stalagmite. Chronological uncertainty is therefore smaller near the tops of the stalagmites and increases toward the bases. Shaded bars represent areas of where calcite petrography complicated layer counting, generally due to less well developed dark laminae. Also marked are the dates when the mine was closed (1886) and when the area was turned into a nature preserve (1904). Lowermost panel shows annual rainfall (Long Ashton Meteorological Station, 40 km from site) and temperature (Central England Temperature Record, [30]). Three samples were drilled from BFM9 for radiocarbon analysis. Two samples corresponding to calcite deposited during the years 1944–1958 and 1985–1991 were enriched in ^{14}C, indicating that deposition occurred during or after the period of abundant nuclear weapons testing (1945–1964). The remaining sample (corresponding to calcite deposited during the years 1929–1931) was not enriched in ^{14}C, indicating that deposition occurred before the initiation of nuclear weapons testing. These points were selected to verify the chronology derived from the counting of couplet thicknesses, but were not directly applied towards the development of the chronology. Absolute ^{14}C concentrations were unimportant; only their enrichment relative to the 'bomb spike' was interpreted.

(Fig. 1) indicates that no substantial surface vegetation existed prior to the conversion of the area to a nature preserve in 1904, strongly suggesting that the absence of vegetation resulted in a groundwater with low levels of dissolved CO_2, minimizing bedrock dissolution and subsequent calcite deposition in the mine. Thus, increasing annual calcite deposition rates through time may reflect the gradual re-establishment of the forest above the mine, unaccompanied by any systematic long-term change in either temperature or precipitation (Fig. 3). The difference in the timing of the onset of rapid calcite deposition at the three sites probably results from differences in the local hydrological routing and local heterogeneities in the distribution of surface vegetation. The strong similarity between the temporal calcite depositional patterns observed in the modern stalagmites discussed here and those characteristic of glacial–interglacial transitions [13,25,26] demonstrates that calcite deposition is dependent on surface biomass and respiration. Previous studies focusing on stalagmite deposition through time in Europe demonstrated that stalagmite growth rates decrease during glaciations [13,25,26]. Because the anthropogenic changes in surface vegetation that occurred above Brown's Folly Mine approximate those in mid and high latitude regions caused by natural climatic shifts, we suggest that changes in temperature and meteoric precipitation accompanying climatic transitions affect the rate of calcite deposition primarily by inducing changes in the biomass/bioproductivity overlying the cave.

All three stalagmites have similar $\delta^{13}C$ values (means: BFM9 = −9.3 ± 0.6‰, Boss = −9.6 ± 0.5‰, F2 = −8.8 ± 0.5‰, PDB) that decrease through time (Fig. 4), broadly correlating with increasing laminae thickness. This is consistent with the signal expected from the re-establishment of vegetation (i.e., reduced $\delta^{13}C$ values in response to a greater contribution of isotopically light biogenic carbon). The absolute $\delta^{13}C$ values are similar to those found in ancient stalagmites in other studies, but the change in values (BFM9 = −1.86‰, Boss = −1.23‰, F2 = −2.12‰) marking the transition from low-biomass to high-biomass conditions is slightly less than that found in ancient stalagmites. For example, Genty et al. [12] found that $\delta^{13}C$ values decreased by approximately 4‰ over the two thousand years immediately following a cold event (coincident with Heinrich event 6) which was manifested in the stalagmite record as a growth hiatus. This difference in magnitude of the $\delta^{13}C$ shift is probably attributable to the lack of sufficient soil development overlying Brown's Folly Mine. Whereas in a natural situation soil development would parallel transitions through successive biomes controlled by gradual climate change, vegetation growth over Brown's Folly Mine was not constrained by any climatic parameters resulting in soil development that lags vegetation development. Additionally, calcite deposition would not have occurred until the soil was sufficiently developed to produce a soil gas P_{CO_2} greater than the P_{CO_2} of the poorly ventilated mine atmosphere. Therefore, the earliest calcite deposition in the mine may have low $\delta^{13}C$ values because deposition only occurred after some soil development, consequently reducing the range of observed $\delta^{13}C$ values in the three stalagmites. The presence of some soil organic carbon developed before the mining related disturbance to the site may have also reduced $\delta^{13}C$ values. The $\delta^{13}C$ data presented here demonstrate that stalagmites are able to successfully record vegetation shifts, and suggest that the $\delta^{13}C$ variations observed in previous studies may partly result from changing amounts of biomass as well as shifts in the distribution of C3/C4 plant species.

Oxygen isotopic variations decrease through time and correlate well with $\delta^{13}C$ for all three stalagmites. Increases in cave air temperature can decrease $\delta^{18}O$ values of a stalagmite (−0.24‰ per °C at 10 °C) because of changes in the fractionation factor between water and calcite [27,28]. The temperature change cal-

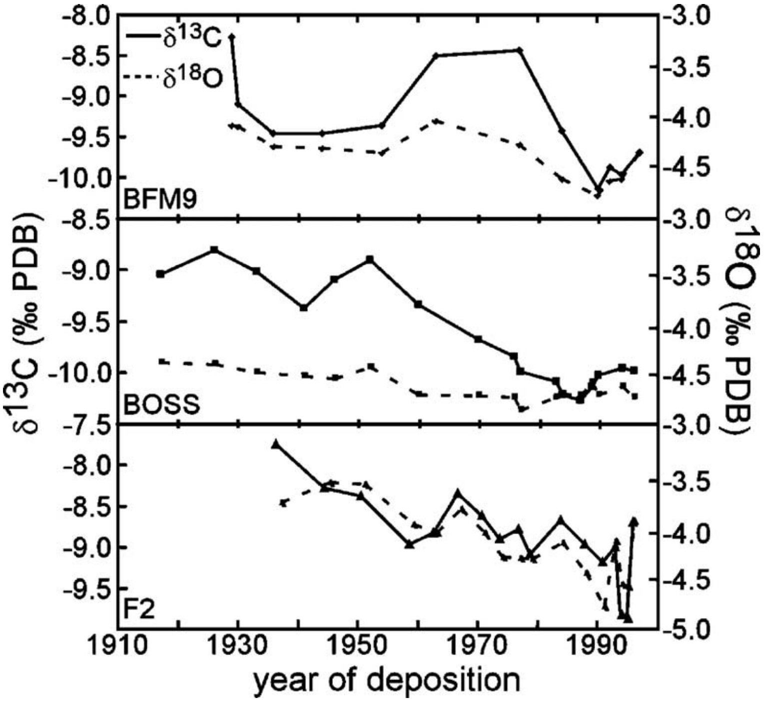

Fig. 4. Carbon and oxygen isotope changes through time for stalagmites BFM9, Boss, and F2 ($\delta^{13}C$ = solid line; $\delta^{18}O$ = dashed line). Overall decreases in both $\delta^{13}C$ and $\delta^{18}O$ are apparent. Modeled $\delta^{18}O$ values of calcite precipitated through time based solely on changes in the seasonality of rainfall do not reproduce the decreasing trend in values apparent for the three stalagmites.

culated by using the difference between the mean $\delta^{18}O$ values for the first 20 years of deposition for each stalagmite and the last 20 years (BFM9 = 1.5 °C, Boss = 1.2 °C, F2 = 3.0 °C) significantly overestimates the actual warming (0.34 °C, Central England Temperature record [29,30]) for the same periods. Besides being affected by temperature variations, stalagmite $\delta^{18}O$ values are also influenced by fluctuations in rainfall $\delta^{18}O$. This explanation is also improbable because available data (1982–2001, GNIP, Wallingford, UK) suggest that systematic long-term changes in mean annual rainfall $\delta^{18}O$ have not occurred recently. A possible explanation for the covariance observed in $\delta^{13}C$ and $\delta^{18}O$ is that it is controlled by kinetic fractionation. The entrances to the mine were re-opened in the 1970s [18], potentially resulting in ventilation leading to a sudden reduction in the P_{CO_2} in the mine and disequilibrium fractionation (e.g., [31]). A test for isotopic equilibrium conducted on a layer within F2 deposited circa 1984 displays a positive correlation between $\delta^{13}C$ and $\delta^{18}O$ ($r^2 = 0.74$), indicating the possibility of kinetic fractionation [32–34]. Oxygen isotope ratios decrease 0.56‰ towards the flanks of the stalagmite and $\delta^{13}C$ values decrease by 1‰. However, kinetic fractionation would result in both $\delta^{13}C$ and $\delta^{18}O$ *enrichment* [31,35], which is the opposite of what is observed in the three stalagmites during the 20th century and precludes kinetic fractionation as a possible explanation for these long-term trends. Because the progressive isotopic depletion observed in all three stalagmites cannot result from kinetic fractionation, additional Hendy tests were not conducted. Additionally, any sudden changes in ventilation should affect isotopic values and growth rates for the three stalagmites simultaneously, which is not observed.

Another possible control on the $\delta^{18}O$ of the stalagmites involves changes in the seasonal distribution of rainfall. Existing monthly rainfall data demonstrates that seasonal rainfall patterns changed abruptly in 1974: summer rainfall decreased and winter precipitation increased [36,37]. This may have skewed groundwater recharge towards isotopically light winter precipitation [mean $\delta^{18}O_{JULY} = -4.46$, mean $\delta^{18}O_{JANUARY} = -8.01$ (1982–2001, GNIP, Wallingford, UK)], resulting in reduced $\delta^{18}O$ values in the stalagmites. However, stalagmite $\delta^{18}O$ values resulting exclusively from variations in rainfall seasonality were modeled and demonstrate no decreasing trend for the period 1921–1991. Therefore, if the only variables affecting the $\delta^{18}O$ of the stalagmites were the $\delta^{18}O$ of the rainfall combined with changes in rainfall seasonality, no decreasing trend in stalagmite $\delta^{18}O$ would exist. Additionally, the observed decreases in $\delta^{18}O$ occur gradually, do not occur simultaneously in the three stalagmites, and are correlated to $\delta^{13}C$ changes. For these reasons, the slight shift in the seasonal distribution of precipitation cannot result in the observed $\delta^{18}O$ trend in the stalagmites.

The data therefore suggest that the decrease observed in oxygen isotopes reflects the gradual development of vegetation on the surface through the 20th century. A soil moisture deficit often exists at the study site during the summer [mean water excess$_{JULY} = 4.5$ mm, mean water excess$_{JANUARY} = 64.8$ mm (1921–1991, Bath Meteorological Station)], but this was probably lower before the establishment of vegetation. It is proposed here that increased evapotranspiration during the summer months associated with increased vegetation density may skew groundwater recharge towards isotopically light winter precipitation, resulting in reduced $\delta^{18}O$ values in the stalagmites. This would also explain the observed correlation between $\delta^{18}O$ and $\delta^{13}C$ throughout the record; increased biological activity would increase the importance of winter precipitation (lowering $\delta^{18}O$) while simultaneously increasing soil P_{CO_2} (lowering $\delta^{13}C$).

5. Conclusions

The growth rate and $\delta^{13}C$ variations of the three modern stalagmites observed in this study test the ability of stalagmites to record changes in the density of surface vegetation, analogous to those that occurred during glacial/interglacial transitions. Annual calcite deposition rates increase through time, reflecting an increasing difference between soil and mine atmosphere P_{CO_2} due to the re-establishment of vegetation on a previously barren mining site. $\delta^{13}C$ values decrease through time due to increased input of isotopically light biogenic carbon to the total dissolved inorganic carbon (DIC). Increased summer evapotranspiration may increase the importance of isotopically light winter recharge to the aquifer relative to summer precipitation, resulting in decreases in $\delta^{18}O$. This illustrates another potentially critical mechanism capable of altering $\delta^{18}O$ in stalagmites and needs to be researched further. The research presented here strongly corroborates previous studies suggesting that periods of reduced calcite deposition and increased $\delta^{13}C$ values are associated with colder/drier climatic perturbations. Our conclusions demonstrate that stalagmite growth rates, $\delta^{13}C$, and $\delta^{18}O$ are at least partially controlled by vegetation, which in glacial periods is dependent on climatic conditions.

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