Earth and Planetary Science Letters 392 (2014) 239–249

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Reconstructing modern stalagmite growth from cave monitoring, local meteorology, and experimental measurements of dripwater films

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ARTICLE INFO

Article history:
Received 25 June 2013
Received in revised form 11 February 2014
Accepted 15 February 2014
Available online 6 March 2014
Editor: G.M. Henderson

Keywords:
stalagmite
growth rate
analogue experiment
palaeoclimate

ABSTRACT

Interpretations of high-resolution proxy datasets from stalagmites require support from long-term cave monitoring data and quantified changes in sample growth rate. One cave site for which the modern climate signal transfer systematics are relatively well characterised by cave monitoring is New St Michael's Cave, Gibraltar. This site provides a rare opportunity to reconstruct modern calcite growth, to link growth with the cave environment and local climate, and to test the sufficiency of existing growth rate theory on monthly to inter-annual timescales. Here, we use a numerical time-series growth rate model, driven by cave monitoring and local meteorological data, and the results of an experimental investigation into variation in dripwater film thickness as a function of stalagmite apex morphology to reconstruct the modern growth (AD 1951–2004) of 'Gib04a', a stalagmite retrieved from New St Michael's Cave. Our experimental measurements demonstrate that dripwater film thickness decreases linearly with increasing stalagmite curvature and that the presence of millimetre-scale surface microtopography reduces film thickness by an order of magnitude. We identified changes in growth laminae curvature from a Gib04a cut section to determine film thickness variability through time and combined this with estimated dripwater [Ca^{2+}] and cave air $p\text{CO}_2$ seasonality to drive the model. Our reconstruction exhibits strong seasonality and tracks variability in calcite [Sr^{2+}], a trace metal whose incorporation into calcite is partially growth rate-controlled. Reconstructed growth also shows co-variation with seasonal changes in calcite fabric, with high growth corresponding to a greater density of calcite grain boundaries. We also link secular trends in karst recharge, film thickness and Gib04a growth, and assess the overall sensitivity of vertical growth rate to film thickness variability. This approach could be used to characterise the growth of other samples retrieved from well-monitored cave systems and may prove particularly useful in quantifying seasonal bias in geochemical proxy datasets, facilitating greater robustness of palaeoclimate reconstructions.

1. Introduction

High-resolution, precisely-dated, multiproxy geochemical records of late Quaternary climate change are frequently obtained from stalagmites, particularly in low- and mid-latitude regions where few alternative proxy archives exist (Fairchild et al., 2006). Cylindrical stalagmites that have undergone uniform growth are most often sampled for such research, and many stalagmite records benefit from robust chronologies based on petrographic or geochemical annual laminae (Baker et al., 2008). The acquisition of multi-annual cave monitoring datasets is a critical prerequisite for palaeoclimate reconstruction using speleothems (e.g., Mattey et al., 2008; Spötl et al., 2005).

Existing empirical relationships between cave environmental parameters, such as cave atmosphere temperature and $p\text{CO}_2$ (CO_2 partial pressure), and stalagmite growth rate appear robust (Baker et al., 1998; Baldini et al., 2008; Genty et al., 2001) and recent studies have attempted to quantify the effects of cave processes, such as ventilation, on stalagmite growth and net geochemical proxy records (Sherwin and Baldini, 2011; Wong et al., 2011). Previous speleothem growth studies include modelled spatial variability based on 'snapshot' cave atmosphere CO_2 concentration maps (Baldini et al., 2006; Whitaker et al., 2009) and comparisons of modelled and actual growth rates. Such studies have compared average values (Baker and Smart, 1995), investigated the sensitivity of growth rate to cave dripwater hydrochemistry

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http://dx.doi.org/10.1016/j.epsl.2014.02.036
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(Genty et al., 2001), and compared modelled growth with calcite grown *in situ* (Sherwin and Baldini, 2011). Collectively, this research provides first-order tests of our theoretical understanding of both instantaneous calcite growth rate and vertical stalagmite extension rate. Attempting to link stalagmite growth and morphology to climate variability, Kaufmann (2003) combined temperature estimates from ice core (GRIP and VOSTOK) and deep marine sediment core (SPECMAP) proxy data with approximations of glacial–interglacial precipitation and soil cover changes to drive a model of vertical stalagmite growth and equilibrium diameter, and Kaufmann and Dreybrodt (2004) adopted the inverse approach in attempting to derive climatic information from such stalagmite stratigraphies.

Understanding stalagmite growth variability is important for palaeoclimate research for various reasons. (i) Several studies (e.g., Polyak and Asmerom, 2001; Proctor et al., 2000) employed stalagmite growth rate itself as a palaeoclimate proxy and others have described seasonally variable stable isotope ratios (e.g., Johnson et al., 2006; Mattey et al., 2008) and trace element concentrations (e.g., Huang et al., 2001) in stalagmites that potentially result from cave ventilation dynamics and/or karst hydrological processes, both of which also affect stalagmite growth. (ii) High vertical extension rates are conducive to generating high-resolution geochemical proxy datasets from stalagmites, yet to-date few studies have characterised stalagmite growth on intra-annual to decadal timescales and its implications for geochemical climate signal capture. (iii) Seasonal growth rate fluctuations potentially bias net proxy signals towards the season favourable to deposition (Baldini et al., 2008; Banner et al., 2007; Fairchild et al., 2006; Frisia et al., 2000; Mattey et al., 2008; Spötl et al., 2005). (iv) Growth rate variability may be related to climate signal modification by other processes, such as biomass change above the cave (e.g., Baldini et al., 2005) and surface and epikarst hydrology (Baker and Bradley, 2010; Bradley et al., 2010; Darling, 2004). Moreover, stalagmite growth rate may provide a proxy for surface or soil temperature (Genty et al., 2001), rainfall amount (Genty and Quinif, 1996), or vegetation changes (Baldini et al., 2005). The work of Kaufmann (2003) and Kaufmann and Dreybrodt (2004) represents an important advance in linking stalagmite growth with climate variability, but the model resolutions used (1000 and 200 years, respectively) are too low to be directly applicable to many high-resolution palaeoclimate studies using stalagmites.

The principal non-biological controls on calcareous speleothem deposition (temperature, drip rate, dripwater $[Ca^{2+}]$, and soil and cave air pCO_2) are relatively well understood (Dreybrodt, 1999; Genty et al., 2001). Recent research has characterised their spatio-temporal variability at certain sites (Banner et al., 2007; Whitaker et al., 2009) and, in particular, highlighted the importance of cave atmosphere pCO_2 dynamics for speleothem palaeoclimatology (Baldini et al., 2008; Fairchild et al., 2006). Although interpreting climatic variability from stalagmite morphology alone is challenging (Dreybrodt, 1988), understanding the physical controls on stalagmite growth, such as drop volume and dripwater film thickness, is necessary for proper linkage of local climate variability, cave environment systematics, and stalagmite growth behaviour.

The following equation describes *vertical* stalagmite extension rate (R_0) fed by a punctiform drip source theoretically (Baker et al., 1998; Baldini et al., 2008; Buhmann and Dreybrodt, 1985; Dreybrodt 1980, 1999):

$$R_0 = 1174\left(\left[Ca^{2+}\right] - \left[Ca^{2+}\right]_{app}\right)\left(\delta t^{-1}\right)\left(1 - e^{-\alpha t \delta^{-1}}\right) \tag{1}$$

where the constant 1174 converts molecular accumulation rate of calcite ($\mathrm{mmol\,mm^{-1}\,s^{-1}}$) to vertical extension rate ($\mathrm{mm\,a^{-1}}$); $[Ca^{2+}]$ is the initial calcium cation concentration of the dripwater ($\mathrm{mmol\,L^{-1}}$); $[Ca^{2+}]_{app}$ is the apparent dripwater $[Ca^{2+}]$ ($\mathrm{mmol\,L^{-1}}$) after equilibration with a given cave atmospheric pCO_2; δ is the dripwater film thickness (mm) from which calcite precipitates according to $Ca^{2+}_{(aq)} + 2HCO^{-}_{3\,(aq)} \leftrightarrow CaCO_{3(s)} + CO_{2(g)} + H_2O_{(l)}$; t is the drip interval (s); and α is a 'kinetic constant' ($\mathrm{mm\,s^{-1}}$) that is sensitive to change in δ and ambient cave temperature. Note that R_0 may also be denoted 'W_0' (e.g., by Kaufmann, 2003). This equation was tested by Sherwin and Baldini (2011), who found close agreement between measured *in situ* calcite deposition and a model estimate. However, the main source of uncertainty encountered in this study was in estimating δ, highlighting the need to constrain this parameter before any time-series reconstruction of stalagmite growth may be attempted. Of particular interest is whether δ tends to remain constant or varies significantly with time, according to relationships with other variables.

In this paper, the 51-year growth of a modern stalagmite ('Gib04a') retrieved from New St Michael's (NSM) Cave, Gibraltar (Mattey et al., 2008), is reconstructed in an *a priori* forward model driven by cave monitoring (cave atmosphere pCO_2 and temperature and drip discharge) and local meteorological (surface temperature, rainfall, and water excess) time series datasets. Additionally, this model is refined with experimental measurements of dripwater films, which provide basic constraints on the role of film thickness on growth rate. Our rationale for selecting Gib04a as a target specimen is as follows. (i) Cave monitoring data (continuous logging and spot measurements) are available since 2004 (Mattey et al., 2008) and modern climate signal transfer systematics have been relatively well constrained at NSM Cave by Mattey et al. (2010). (ii) Continuous monthly meteorological time series datasets (surface air temperature and precipitation) are available from the nearby Royal Air Force Meteorological Office (RAFMO) station, which is also the site of Global Network for Isotopes in Precipitation (GNIP) sampling since 1962 (Fig. 1), with a temporal coverage appropriate to drive the time series growth model. (iii) Gib04a underwent relatively fast vertical extension (~0.9 $\mathrm{mm\,a^{-1}}$) and exhibits annual petrographic laminae, providing a robust age model, which is substantiated by annual carbon isotope cyclicity and correct identification of the atmospheric ^{14}C activity 'bomb spike' (Mattey et al., 2008). Altogether, these factors provide a rare opportunity to (i) develop, to our knowledge, the first time-series growth reconstruction for a modern speleothem and (ii) test the sufficiency of existing growth rate theory (as a natural system description) in capturing seasonal and interannual variation. To conclude, the implications for linking stalagmite growth and local climate are considered.

2. Site description

NSM Cave developed within the dolomitised Gibraltar Limestone Formation of the Rock of Gibraltar (Gibraltar peninsula, southern Iberia; 36°9′ N, 5°21′ W), whose maximum elevation is 426 m above mean sea level (Fig. 1). Pervasive fracturing provides extensive macroporosity, and drips sites within NSM Cave are fed by down-dip and sub-vertical fracture systems. NSM Cave is at least Pleistocene in age (Rodríguez-Vidal et al., 2004), phreatic in origin, has experienced uplift of ~275 m, and preserves evidence for multiple phases of drainage and secondary speleothem decoration (Tratman, 1971). NSM Cave has no known natural entrances; however, a 1 m^2 trap door, constructed in 1942 and the only link with Old St Michael's Cave, does not significantly disturb the natural chimney-effect ventilation (Mattey et al., 2010, 2008 and references therein).

Mattey et al. (2010) identified links between ventilation dynamics, calcite fabrics, stable isotope ratio and trace element seasonality, and dripwater trace element variability. Seasonal ventilation of NSM Cave is characterised by rapid summer-to-winter increases and winter-to-summer decreases in cave atmosphere pCO_2,