Quaternary Science Reviews 187 (2018) 94–111

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A comparison of growth rate of late Holocene stalagmites with atmospheric precipitation and temperature, and its implications for paleoclimatology

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ARTICLE INFO

Article history:
Received 7 November 2017
Received in revised form
31 January 2018
Accepted 4 March 2018
Available online 30 March 2018

Keywords:
Holocene
Paleoclimatology
Global
Speleothems
Growth rate
Stalagmite
Rainfall
Temperature
Paleoclimate
Proxy

ABSTRACT

Growth rate of stalagmites can vary with many factors of physical environment, ecology, and karst hydrogeology, to the extent that growth rates calculated from a carefully selected set of data from 80 stalagmites from around the world vary by a factor of 400 from smallest to largest. Growth rates of those 80 stalagmites nonetheless collectively show correlations to atmospheric precipitation and temperature that are non-trivial ($r^2 = 0.12$ and 0.20, respectively) and unlikely to have arisen randomly ($p = 0.002$ and 0.00002). Those global relationships are also supported by previously published studies of individual drip sites. The general trend of growth rates is not a monotonic increase with precipitation; instead, it reaches a maximum at annual precipitation rates between 700 and 2300 mm/year, which both counters many model predictions that growth rates should increase monotonically with drip rate and complicates use of growth rate as a proxy for past precipitation. The general trend of growth rates among the 80 stalagmites is a monotonic increase with temperature. However, the low values of r^2 in both of these general trends indicate that growth rate can be at best a qualitative rather than quantitative proxy of past conditions. Growth rate shows no statistically significant relationship to effective precipitation, seemingly because of the confounding effect of temperature.

Growth rates of aragonite-bearing stalagmites are commonly greater than rates in stalagmites in which calcite is the only carbonate mineral, suggesting both the need for careful identification of mineralogy and the special applicability of aragonitic stalagmites in high-resolution studies. Aragonite has exceptionally great frequency in settings with low effective atmospheric precipitation, supporting previous linkages of that mineral to warm dry environments.

Closely-spaced sampling used in recent paleoclimatological studies suggests that unexploited long-term low-resolution records of past climate may exist in surprisingly small slow-growing stalagmites from exceptionally cold and/or dry regions.

1. Introduction

The rate of growth (specifically, the rate of vertical accretion or extension) of stalagmites has been used in paleoclimatological research as a proxy for past climate (e.g., Xia et al., 2001; Sletten et al., 2013; Muangsong et al., 2014; Nehme et al., 2015). Growth rate is commonly assumed to be positively related to rate of atmospheric precipitation or wetness, but multiple questions lurk behind this assumption. One might ask if growth rate is also related to temperature, overwhelming the precipitation signal or leading to a possible confounding effect. A second question might be if growth rate is positively correlated with precipitation across the entire range of the latter from arid to extremely wet climates, or if it decreases in very wet conditions. For example, the assumption of a positive relationship between atmospheric precipitation and growth rate in dry conditions finds unquestionable buttressing in the logic that zero precipitation on the land surface, and thus presumably zero drip rate in an underlying cave, must result in zero growth of a stalagmite, but many effects might stop or reverse that trend in much wetter conditions, as discussed herein. A third question might be if growth rate is better understood in terms of *effective* precipitation (i.e., precipitation after correction for loss of moisture to evapotranspiration). A fourth question might be if

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https://doi.org/10.1016/j.quascirev.2018.03.002
0277-3791/

growth rate is affected by mineralogy, so that growth rates might require mineralogical correction. This paper addresses these questions with a compilation of growth rates from late Holocene stalagmites that, to the extent allowed by the literature, span the globe geographically (Fig. 1 and Fig S1; Section S1) and span the observed range of temperature and atmospheric precipitation.

Despite the importance of the questions posed above, one might observe that a considerable observational literature on growth rate of stalagmites has developed since the 1980s (e.g., Baker et al., 1998; Genty et al., 2001; Banner et al., 2007; Baker et al., 2008; Baldini, 2010; Mariethoz et al., 2012) and thus might ask why a new study is needed or how it could help. The answer is three-fold. First, the literature reporting stalagmites as records of past climate, and thus reporting radiometric ages to support age models from which growth rates can be derived, has grown hugely in the last ten years (Fig. S2). Secondly, the number of radiometric ages generated per stalagmite, and thus the definition and credibility of age models, has increased greatly in the last ten to fifteen years, to as many as 47 radiometric ages from a single stalagmite (e.g., Zhao et al., 2015). Thirdly, detailed studies of varying growth rate in single stalagmites, rather than comparisons between stalagmites, have added new and well-defined results relevant to variation in growth rate. Thus much more abundant data of higher quality are available today for a compilation from which to answer questions like those posed above. Multiple results arise with regard to the overall distribution of values of growth rate (Fig. 2) and the relationship of growth rate to mineralogy (Fig. 2), atmospheric precipitation (Figs. 3–5), temperature (Figs. 6–8), effective atmospheric precipitation (Fig. 9), and ecology (Fig. 10).

2. Growth rate, atmospheric precipitation, and the complexity of karst hydrology

The variation in the data (Figs. 2–4 and 6 and 7 and 9 and 10) and the small values of r^2 (Figs. 4 and 6) are not surprising in light of the extreme complexity of karst hydrology (Milanovic, 1981; White, 1988; Ford and Williams, 1989, 2007; Klimchuk, 2000; Fairchild and Baker, 2012; Gilli, 2015). Many factors not considered in this study could contribute to variation in growth rates of stalagmites.

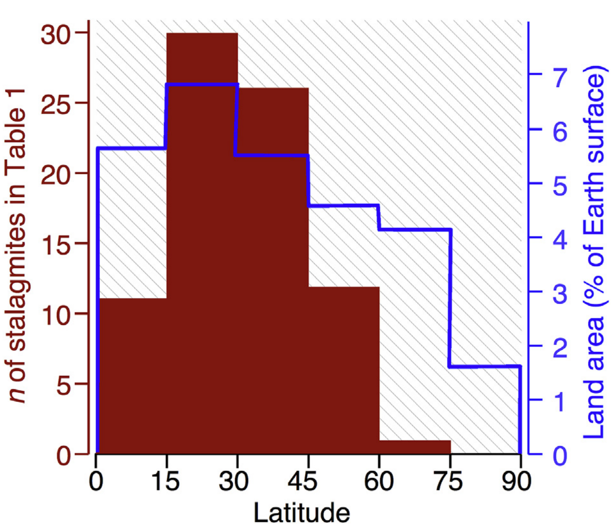

Fig. 1. Red bars: histogram of latitude of stalagmites used in this study and listed in Table 1. Blue lines: histogram of land area as a proportion of the surface area of the Earth. The relationship of the red bars and blue lines is discussed in Section 3.3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Factors differing from cave to cave, or even from drip site to drip site in one cave, can include (but are not limited to) seasonality of precipitation (as in Fig. 1 of Railsback, 2017), density and type of vegetation, extent of evapotranspiration (which is considered further in Section 4.4), slope of the land surface and resultant differences in infiltration, permeability of the land surface, surface temperature (which is considered further in Section 4.3) and its effects on biological productivity, thickness of soil, thickness and lithology of bedrock, areal size of the catchment for the drip, reservoirs in the catchment, cave temperature and the extent of its annual variation, pathway of water in the cave to the drip site, extent of cave ventilation controlling P_{CO2} (in turn dependent on cave entrances and passages), presence or absence of a stalactite at the drip site, kinetic effects exerted by trace elements dissolved in the drip water, vertical distance of the drip, and extent of microbial activity on the growing stalagmite. Factors relevant through time at one drip site can additionally include (but are not limited to) how antecedent moisture or vegetation conditions affect infiltration, whether dual-porosity systems allow by-pass flow behavior during extremely wet periods, and development and evolution of a stalactite at the drip site.

The resultant variation from all these factors is why this article reaches inferences about “the general trend of growth rates”. It is not because there is a single precise mathematical relationship or transfer function between growth rate and factors like atmospheric precipitation or temperature, about which the article is making imprecise statements. It is instead because the combined variation of the many controlling factors dictates that there can be at most a general trend to the growth rates reported here. Furthermore, the combination and interaction of all of these factors dictate that growth rate will at best be a qualitative, rather than quantitative, proxy for past environmental parameters.

3. Methods

3.1. Sources, materials, and calculations

Articles used as sources of data for Figs. 2–4 and 6 and 7 and 9 and 10 were found by searching the Web of Science index using the terms “stalagmite”, “climate” and “Holocene”. “Climate” was used as a search term to target articles reporting radiometrically dated stalagmites. As the search moved to progressively earlier articles, increasing rate of failure of those earlier articles to supply sufficient age data discouraged searching of papers published before 2006 (eliminating only 19% of all articles returned with the search terms). However, three earlier articles were used to fill specific geographic gaps. Each age model was examined to assure sufficient ages and continuity of deposition to yield a meaningful growth rate. Further details of the search are provided in Section S2.

To minimize the possibility of an excessively uniformitarian approach, articles were selected for use only if they allowed estimation of growth rates within the last 3000 years. Exceptions were made to fill geographic gaps, but none of the data represented by filled symbols in Figs. 2–4 and 6 and 7 and 9 and 10 represent deposition earlier than 5000 years ago. One open symbol in Fig. 4 represents deposition from 5500 to 9500 years ago; it is included there (but in no other part of this work) because it is from a region of uncommon rainfall.

In cases where growth rate during the stalagmite's entire history was not uniform, the growth rate during the last century was calculated, reported in Table 1, and used in the figures in this article. This is because the goal of the article is to compare growth rate with instrumental measurements of atmospheric precipitation and temperature, and those climatological measurements typically extend backward only a few decades. Thus some stalagmites from