# Quantifying the value of laminated stalagmites for paleoclimate reconstructions

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[1] From the Permian through to the modern day, stalagmites are an important archive of environmental change. Annually laminated stalagmites provide both a precise chronology and a paleoclimate proxy. The rate of annual vertical growth of stalagmites is recorded in changes of calcite fabric, annual fluxes of fluorescent organic matter or annual variations in trace element composition. The processes governing stalagmite growth are the flux of water, the $CO_2$ saturation of drip water relative to the cave atmosphere, and the temperature. Although these processes are well understood, they depend on the specific hydrogeological flow routing of individual stalagmites. Therefore, although past climates are recorded in the vertical growth lamina thickness, the climatic signal is perturbed by noise related to local hydrologic factors. To separate local from global factors, we used geostatistical tools to analyze annual growth rate data from eleven stalagmites located on four continents. Variogram analyses permit the quantification of the signal content contained within the growth rate records. The information content ranges from 23 to 87%. Analysis of the growth derivative shows a negative correlation at a 1 year lag, meaning that acceleration in growth rate tends to be systematically followed by deceleration in growth rate and vice versa. We call this behavior "flickering" growth, and argue that it is related to the size of the store feeding the stalagmite. Variogram analysis and flickering are used to screen which types of signals can potentially be recorded in a given speleothem. **Citation:** Mariethoz, G., B. F. J. Kelly, and A. Baker (2012), Quantifying the value of laminated stalagmites for paleoclimate reconstructions, *Geophys. Res. Lett.*, *39*, L05407, doi:10.1029/2012GL050986.

## 1. Introduction

[2] Stalagmites are an important archive of paleoenvironmental change at periods ranging from the Late Holocene [*Trouet et al.*, 2009] to the Permian [*Woodhead et al.*, 2010], with arguably the most significant contribution to date being Late Quaternary records of climate variability from the $\delta^{18}O$ record of stalagmite calcite from multiple Chinese stalagmites [*Cheng et al.*, 2009]. Annual stalagmite vertical growth is typically in the range of 10–300 micrometers per year [*Baker et al.*, 1998], although it has been shown that theses rates can be exceeded [*Cai et al.*, 2010]. The determining processes and theoretical models of stalagmite growth are increasingly well understood and modeled [*Dreybrodt*, 1999; *Kaufmann and Dreybrodt*, 2004; *Romanov et al.*, 2008]. In summary, the main controls of stalagmite growth are the flux of water, the $CO_2$ saturation of drip water relative to the cave atmosphere, and temperature. The processes determining all three are both complex and inter-related [*Dreybrodt*, 1999; *Sherwin and Baldini*, 2011]. The drip water rate for optimum growth is of the order of 1–5 minutes per drip [*Dreybrodt*, 1999]. Faster water supply leads to incomplete degassing and slower drip rates lead to a water supply limitation. Drip water $CO_2$ saturation is a complex function of soil $CO_2$ transport and production (which depends on temperature and soil moisture), and subsequent geochemical evolution of the groundwater, which typically includes degassing and calcite precipitation in fractures and voids above any particular stalagmite. The rate of degassing of $CO_2$ during stalagmite formation is also dependent on the $CO_2$ concentration in the cave atmosphere, which may be greater than atmospheric values and may vary both spatially and temporally depending on cave morphology. Despite the multiple processes determining stalagmite growth rate, cave monitoring and sampling programs have demonstrated a first-order global relationship between vertical growth rate and mean annual temperature [*Genty et al.*, 2001].

[3] The rate of annual growth accumulation of stalagmites permits geochemical and petrographic analyses at annual resolution or better when required. Over the last two decades, the analysis of annually laminated stalagmites has led to the investigation of annual growth increments preserved in changes in calcite fabric [*Genty et al.*, 1997], annual fluxes of fluorescent organic matter [*Baker et al.*, 1993] and annual variations in trace element composition [*Fairchild et al.*, 2001]. Annual laminae have provided a new chronological tool to the stalagmite paleoclimate research community, and in many cases variations in growth rate (annual lamina thickness) have been shown to correlate with climatic parameters such as temperature and precipitation [*Proctor et al.*, 2002; *Tan et al.*, 2003] and have been used in multiproxy reconstructions of climate of the last millennia [*Mann et al.*, 2008; *Moberg et al.*, 2005; *Smith et al.*, 2006].

[4] In this paper, we analyze temporal characteristics at various timescales of annual growth rate data from eleven laminated stalagmites, which were growing during the Late Holocene in seven different regions on four continents (Table 1). All stalagmites have provided proxy paleoclimate information, and we use additional statistical approaches to better understand the growth of annually laminated stalagmites and the processes that drive their behavior over short timescales (of the order of a decade). Despite the increasing use of stalagmite lamina thickness to reconstruct past climatic conditions, statistical analysis has been limited, with previous research focused on growth rate trends and spectral analysis [*Tan et al.*, 2006]. Little attention, however,

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**Table 1.** Statistical Properties of the Eleven Stalagmites Studied[a]

| Stalagmite Description | *MG* | *IQR* | *SK* | *r* | *c* | *n* | *IC* | *f* | References |
|---|---|---|---|---|---|---|---|---|---|
| NW Scotland SU967 | 0.024 | 0.023 | 1.26 | 60 | 0.42 | 0.18 | 70 | −0.28 | *Proctor et al.* [2002] |
| NW Scotland SU961 | 0.028 | 0.026 | 1.65 | 250 | 0.60 | 0.20 | 75 | −0.36 | *Proctor et al.* [2002] |
| NW Scotland SU962 | 0.023 | 0.024 | 1.78 | 200 | 1.00 | 0.15 | 87 | −0.34 | *Proctor et al.* [2002] |
| New Mexico BC2 | 0.095 | 0.042 | 0.85 | 90 | 0.20 | 0.66 | 23 | −0.37 | *Rasmussen et al.* [2006] |
| New Mexico HC1 | 0.106 | 0.048 | 0.65 | 180 | 0.35 | 0.50 | 41 | −0.39 | *Rasmussen et al.* [2006] |
| Italian Alps ER76 | 0.047 | 0.042 | 0.78 | 120 | 0.90 | 0.15 | 86 | −0.26 | *Frisia et al.* [2003] |
| Italian Alps ER77 | 0.019 | 0.018 | 1.95 | 150 | 0.28 | 0.05 | 85 | −0.24 | *Frisia et al.* [2003] |
| China TS9501 | 0.043 | 0.033 | 0.81 | 290 | 0.60 | 0.50 | 55 | −0.37 | *Tan et al.* [2003] |
| Ethiopia ACH-1 | 0.530 | 0.213 | 1.07 | 80 | 0.30 | 0.68 | 31 | −0.36 | *Asrat et al.* [2007] |
| Norway L-03 | 0.041 | 0.025 | 0.16 | 100 | 0.30 | 0.35 | 46 | −0.33 | *Linge et al.* [2009] |
| Oman S03 | 0.329 | 0.094 | 0.73 | 62 | 0.22 | 0.70 | 24 | −0.31 | *Fleitmann et al.* [2004] |

[a]*MG*: median growth rate (mm), *IQR*: interquartile range (mm), *SK*: skewness, *r*: variogram range (years), *c*: sill contribution, *n*: nugget effect, *IC*: information content (%), *f*: flickering intensity.

has been paid to variations on short time scales. At annual time scales, temporal analysis of the first derivative of annual growth thickness allows us to identify a specific behavior of stalagmite growth for all eleven samples that we call "flickering". Flickering indicates a regular yearly oscillation around a stable median value. Although flickering is a high frequency process (yearly), our analyses show that it is a condition for systemic stability, which is necessary to obtain long term laminae growth. For longer time scales, we characterize the information content of each stalagmite based on a variographic analysis [*Chilès and Delfiner*, 1999; *Goovaerts*, 1997]. This method can distinguish the purely random component of laminae thickness, related to local hydrologic processes, from long range phenomena that may contain paleoclimatic information. The variographic analysis also provides information on the temporal correlation of laminae thickness. This temporal correlation potentially gives insights into the volume of the water store that feeds the stalagmite.

## 2. The Data Set

[5] We analyzed annual growth rate data from eleven stalagmites; three stalagmites from NW Scotland [*Proctor et al.*, 2002]; two stalagmites from New Mexico [*Polyak and Asmerom*, 2001; *Rasmussen et al.*, 2006]; two from Italy [*Frisia et al.*, 2003]; one from China [*Tan et al.*, 2003], one from Ethiopia [*Asrat et al.*, 2007], one from Norway [*Linge et al.*, 2009] and one from Oman [*Fleitmann et al.*, 2004]. All stalagmites have continuous annual lamina sequences of between 200–2500 years before present, with the annual growth rate of the Scotland, China and Italy samples having provided paleoclimate proxies [*Smith et al.*, 2006]. One implication of this continuity of growth (without hiatuses) is that for some of the stalagmites analyzed, groundwater storage is likely, probably in solutionally enlarged fractures, which maintains a drip water supply. Climate and environmental conditions relevant for determining stalagmite growth rate varies considerably between regions (see Table 1). Some insight into the groundwater flow path is possible from the type of annual laminae present. For example, stalagmites from North West Scotland, Italy and China have annual fluxes of fluorescent organic matter, providing evidence of a fracture or rapid flow component to transport fluorescent organic matter from the soil. In contrast, stalagmites from Ethiopia and New Mexico have laminae formed through variations in calcite texture. Theoretically, these laminae can be formed by variations in cave climate alone (e.g., changes in $CO_2$ concentration that control degassing) and where drip water flux and chemistry is constant.

[6] Annual stalagmite growth is usually log-normally distributed [*Tan et al.*, 2006]. Therefore, for analysis we use log-transformed data, which are also normalized and detrended using second-order polynomials. These processed data (see Text S1 in the auxiliary material), which we name $G$, are then used for the analysis of both short-range and long-range growth variability.[1]

## 3. Short-Range Variability

[7] For the high frequency variability, we considered the yearly stalagmite growth patterns using autocorrelation functions. This analysis of short-range variability is based on the change in thickness from one year to the next. Hence we consider the growth derivative $Y = dG/dt$ for analysis, where $t$ is the time. $Y$ represents the growth increments, or the growth acceleration of a stalagmite.

[8] It was observed that acceleration in growth tends to be systematically followed by a growth deceleration in the next lamina. This can be observed by analyzing the temporal correlation of $Y$ with autocorrelation functions. Figure 1a shows plots of the autocorrelation of $Y$ for 4 different stalagmites, and for a pure random component (uncorrelated white noise) centered on a fixed mean. The specific pattern, involving a significant negative correlation at lag 1 and no autocorrelation at other lags, is characteristic of what we call "flickering" growth. We quantify the intensity of the flickering by the value $f$, measuring the magnitude of the anticorrelation at lag 1. A value of $f$ close to $-1$ would indicate a perfect and regular oscillation between years of high growth and years of low growth. A white noise centered on a median value is an archetypal stable random process, which has a flickering intensity of $f = -0.5$. Qualitatively, flickering reflects that the process systematically tends to return to a mean value, which results in yearly oscillations around this mean value. In contrast, a process with low flickering (such as $f = 0$) shows significant accelerations and decelerations, which would correspond to patterns of growth instability (or intermittent growth). The stalagmites studied show flickering between $-0.24$ and $-0.39$, indicating significant return to a median growth

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL050986.

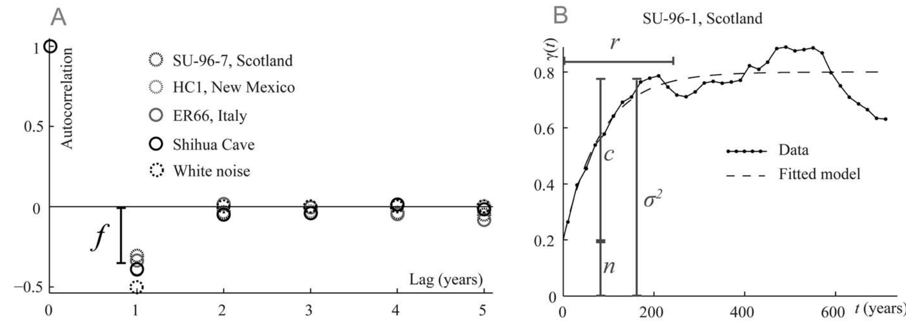


**Figure 1.** Representation of flickering intensity and variogram parameters. (a) Flickering intensity *f* defined as the lag 1 autocorrelogram of growth derivative, shown for four stalagmites and white noise, with typical negative correlation pattern. Flickering intensity is defined as the lag 1 value. Note that for white noise $f = -0.5$. (b) Variogram of *G* for a Scottish stalagmite, adjusted exponential model $\gamma(t)$ and graphical representation of the variogram parameters range (*r*), nugget (*n*), sill contribution (*c*). $\sigma^2$ represents the growth rate standard deviation.

rate, and therefore overall stability of the system (see Table 1).

## 4. Long-Range Variability

[9] We used variograms to analyze the long-term growth variability and to quantify the information content of the stalagmite signal. A variogram is a statistical tool used for spatio-temporal modeling. It is a representation of the variability between any two points as a function $\gamma(t)$ of the temporal lag distance *t*. Variograms can be seen as a temporal decomposition of the variance. We fit an exponential mathematical model to the log-transformed data *G*, which is parameterized with a nugget effect *n*, a sill contribution *c* and a range *r*. Figure 1b shows a representative variogram of one of the stalagmites, the adjusted mathematical model of variability and the different variogram components. The variance of the data can be separated into two parts: 1) the nugget effect *n* is the uncorrelated part of the signal that can be related to noise (or measurement error), and 2) the sill contribution *c*, which is the temporally correlated, non-random part containing a signal, either hydrologic or climatic. The sum of the nugget effect and the sill contribution is equal to the variance of the data. We define the information content *IC* of each stalagmite as the proportion of the variance that can be attributed to the sill. At one extreme, a pure noise would have an *IC* of 0%, and at the other extreme the *IC* of a very smooth signal would be close to 100%. Results of the variogram analyses are presented in Table 1. The sill contribution varied from 0.2 to 1.0 and the nugget from 0.05 to 0.66, resulting in an *IC* which varies from 23–87%. Highest *IC* (>70%) is observed in the Scottish and Italian stalagmites, and the lowest (<40%) from stalagmites from Oman, Ethiopia and New Mexico. The range, the period where annual growth rate is autocorrelated, varies from 60 to 290 years. Range varies significantly between stalagmites from a single cave (for example, North West Scotland stalagmites have ranges of 60, 200 and 250 years), suggesting that this property is related to hydrological properties of individual samples.

## 5. Laminated Stalagmite Growth Properties

[10] Stalagmite growth comprises two components, the growth rate, which is autocorrelated over several years (the sill contribution), and the change in growth rate, which is not, and which has a flickering nature (Figure 2). The universality of both the long-range variability (the autocorrelation over the period *r*) and the flickering, for a wide variety of lithologies and climate regimes (Table S1), suggests that these are properties of laminated stalagmites and that they have a common driving process. In particular the flickering, being observed in various regions and under different climates, cannot be a due to external forcing such as yearly variability in rainfall.

[11] We propose that the cause of flicking is the nature of unsaturated zone groundwater flow in fractured carbonate rocks, where karstification generates enhanced secondary porosity such as solutionally enlarged fractures or cavernous porosity. We conceptualize the system in Figure 3. To continuously form annual lamina series for hundreds or thousands of years, observed in the stalagmites analyzed here, a suitably large water store is required, such as that

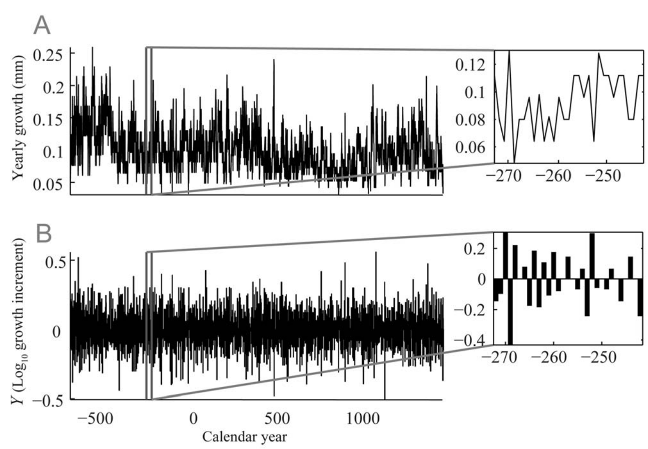


**Figure 2.** Flickering of stalagmite growth for New Mexico BC2. (a) Raw growth data, with insert showing yearly oscillations. (b) Derivative of growth increments. Inserts highlights growth acceleration/deceleration (flickering) for the period 242 BC to- -272 BC. In Figure 2b, a positive bar represents a growth increase, a negative bar a growth decrease and an identical growth for consecutive results in the absence of bar.

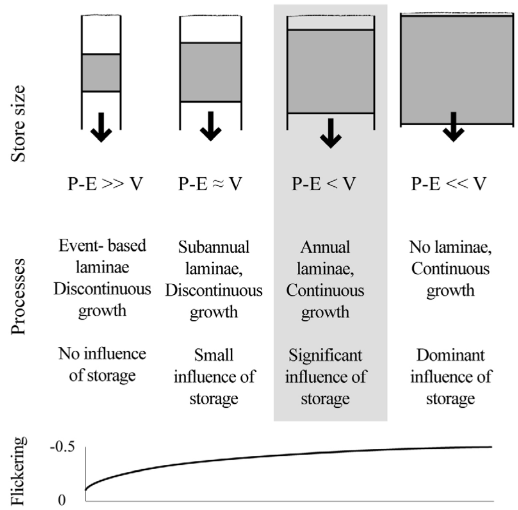


**Figure 3.** Conceptual model for the interpretation of flickering intensity. Our conceptual model identifies four categories of processes where the relative volume of the store affects the continuity of the growth rate. P-E: recharge, V: store volume.

provided by these secondary porosity features. The stalagmites quantified in this study are therefore typical of Type III in Figure 3. With proportionally smaller stored water, growth would be less continuous (Types I and II in Figure 3). Stalagmites supplied predominantly from stored groundwater (Type IV) are less likely to contain annual laminae. This stored water source explains the autocorrelation in the growth rate data over the period *r*, and the ability of stalagmites to preserve low frequency climate information. A certain amount of flickering is therefore a prerequisite to the existence of laminated stalagmite.

[12] A direct flow routing to stalagmites is also evident in many samples through the presence of annual laminae formed from fluorescent organic matter and soil-derived trace elements. The degree of regularity of this direct flow component (i.e., a yearly organic matter flush vs extreme recharge events) would affect flickering. The relative importance of this water source decreases with increasing storage volume (Types I to IV in Figure 3). The flickering intensity reflects that the growth rate is attracted to a stable state determined by the volume and geochemical composition of the stored water. Flickering is therefore an indication of the presence of a groundwater store, but is also dependent on the stalagmites having a direct flow component, especially when the store is relatively small (Types I and II in Figure 3). Different magnitudes of both the flickering and range between stalagmites within one cave, mean that there are stalagmite-specific variations in the processes that control growth rate, with individual samples having different volumes of stored groundwater, as well as varying proportions and variability of direct flow routed water (which may, for example, have highly variable calcite saturation). For example, Scottish stalagmites SU967 and SU961 show different values of *f* and *r* (Figure 4), although they are both within the same cave, therefore affected by the same annual direct flow component. These differences can only be explained by a larger store for SU961, causing momentum in growth rate that is expressed as increased flickering (because of a lesser influence of the direct flow component) and a longer range *r*.

## 6. Implications for Stalagmite Paleoclimatology

[13] The nugget effect, *n*, is the uncorrelated part of the variogram that can be related to noise, and Table 1 shows that the correlated part of the signal compared to *n* is in the range 23 to 87%. This has important implications for the use of stalagmite growth rate as a paleoclimate proxy, as it demonstrates for the first time the extent to which the growth rate of a specific stalagmite can potentially correlate with climate. The stalagmites where annual growth rate has provided a paleoclimate proxy have a correlated part of the signal (or information content, *IC*) of 70% (NW Scotland), 85 and 86% (Italy) and 55% (China); these high values confirm that these samples would be expected to contain a paleoclimate signal. For paleoclimate reconstructions, not all of the *IC* need be climatically forced. We recommend that samples with low *IC* are likely to be of little use for paleoclimate reconstruction from annual vertical growth rate. Our observation of the presence of flickering over short timescales demonstrates that smoothing of stalagmite growth rate data is necessary to improve the analysis of long term variability.

[14] The presence of flickering in all stalagmite series with intensity *f* ranging between $-0.24$ and $-0.39$ (Table 1) indicates significant return to a mean growth rate value, and therefore the overall stability of the system. This stability is demonstrated in the 60–290 year range of autocorrelation in the variograms (Table 1 and detail of variogram fits in Text S1). The range represents the stability of water supply to all the stalagmites, probably through a groundwater store component. Stalagmites with a large correlation range *r* (>100 years) have a large momentum in their behavior. They are not sensitive to decadal-scale climatic changes, but are a smoothed reflection of the groundwater input, therefore reflecting slower (centennial-scale or longer) changes. Conversely, stalagmites with short correlation ranges are

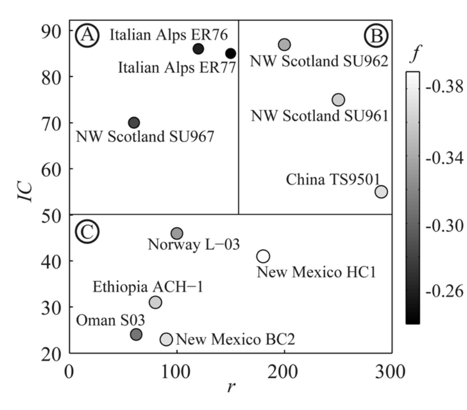


**Figure 4.** Classification of the stalagmites analyzed considering range, information content and flickering. (a) Short range and High *IC*, potentially carrying information on decadal-scale variability. (b) Large range and High *IC*, potentially informing long-term trends. (c) Low information content. Stalagmites in Figure 4a show less flickering, indicating an external, non-random component.

able to record decadal-scale climatic fluctuations. Hence the stalagmites that can potentially discriminate climate variability over decadal scales are the ones with high *IC* and relatively short ranges (Figure 4a), whereas the ones with larger ranges are more likely to reflect only very long-term trends in local groundwater quantity and quality (Figure 4b). Stalagmites in group A show less flickering, indicating a larger proportion of an external, non-random signal component. The stalagmites having lowest *IC* are less useful in terms of paleoclimate reconstructions (Figure 4c).

[15] Inspection of flickering over time can also provide information about changes in the stability of the groundwater system. For example, Scottish stalagmite SU967 stops flickering for a 30 year period from 1615 AD (Figure S2 in Text S1), which is simultaneous with a period of very slow growth (interpreted as wet conditions). This suggests that a hydrological threshold was passed and that climate calibrations which apply at other times might not be applicable under this changed hydrological state.

## 7. Conclusions

[16] Variogram analysis of annual stalagmite growth rate time series data demonstrates that there is a trade-off between the need for annual lamina to provide a precise chronology, and an associated decrease in the strength of low-frequency climate signal. Where annual laminae are found (our Type III in Figure 3), their presence indicates a sub-annual variability in cave hydrochemistry and/or cave climate in order to form them. We statistically demonstrate that this leads to a degradation of the low-frequency climate signal, which we propose is provided by a stored groundwater component. Such behavior is to be expected given the nature of unsaturated zone groundwater flow in fractured carbonate rocks, where karstification generates enhanced secondary porosity such as solutionally enlarged fractures or cavernous porosity.

[17] Our geostatistical analysis of annually laminated stalagmites demonstrates stalagmite growth rate will always be an imperfect paleoclimate archive, with calcite deposited in any particular year likely to preserve a record, both of the climate of that year, as well as an average of the preceding *n* years. We recommend that future research includes geostatistical analysis of stalagmite growth rate series, which helps quantify the extent and timescale to which a potential climate signal might be contained within the sample, alongside other screening methods [for example, *Frappier*, 2008]. Samples with a low flickering intensity *f* (smaller groundwater store volume) and short correlation range *r* might be the most useful to investigate annual climate variability. Applications would lie for example in the field of paleotempestology, where annual growth rate variability could be extracted using a high-pass filter. Alternatively, if speleothem samples were being chosen to obtain records of low-frequency climate variability, samples with more flickering *f* (larger groundwater store volume), long range *r* and high information content *IC* would be appropriate. Most importantly, the widespread observation of "flickering" in annually laminated stalagmite growth series (Type III in Figure 3), and our understanding that this is a ubiquitous characteristic of karst drip waters, implies that these statistical properties potentially affect other stalagmite climate proxies, not just growth rate. The most affected proxies should be those that rely on their integration and geochemical evolution within groundwater stores (e.g., $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Sr/Ca).

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