Insights in paleoclimate variability through the variographic analysis of stalagmite time series

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Abstract Stalagmites are an increasingly important archive of paleoenvironmental change. The rate of annual growth rates of stalagmites is recorded in changes of calcite fabric, annual fluxes of fluorescent organic matter or annual variations in trace element composition. The determining processes governing stalagmite growth are increasingly well understood and modeled. At the scale of chemical processes, the physical controls of stalagmite growth are the flux of water, the CO_2 saturation of drip water relative to the cave atmosphere, and the temperature. The processes determining all three are complex and inter-related. Therefore, although past climates are recorded in the growth laminaes, the climatic signal is perturbed by a noise component related to local hydrologic factors. To separate local from global factors, we used geostatistical tools to analyze annual growth rate data from 11 stalagmites located on 4 different continents. The records range from 200 to 2500 years before present. Detailed variographic analyses showed that the temporal correlation of growth rates is of a specific type in all 11 stalagmites, which has never been observed before. The growth derivative is highly anticorrelated at a lag of 1 year, meaning that an increase in growth rate tends to be systematically followed by a decrease in growth rate. We call this behavior a "flickering" growth. Flickering cannot be explained by climatic factors that tend to vary on larger time scales, and therefore must be related to changes in local hydrologic conditions. We show that the intensity of flickering fluctuates in the last millennia, giving insights in the temporal scale of variability of hydrologic systems under natural conditions.

Introduction

Past climates are recorded in stalagmite growth rings. Such stalagmites are an increasingly important archive of paleoenvironmental change [1, 2]. The rate of

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annual growth rate of stalagmites is recorded in changes of calcite fabric, annual fluxes of fluorescent organic matter or annual variations in trace element composition [3]. The determining processes governing stalagmite growth are increasingly well understood and modeled.

At the scale of chemical processes, the physical controls of stalagmite growth are the flux of water, the CO_2 saturation of drip water relative to the cave atmosphere, and the temperature. The processes determining all three are complex and interrelated. Therefore, although past climates are recorded in the growth laminates, the climatic signal is perturbed by a noise component related to local hydrologic factors.

In order to separate local from global factors, we used geostatistical tools to analyze annual growth rate data from 11 stalagmites located on 4 different continents. The records range from 200 to 2500 years before present. 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 [4]. Little attention, however, has been paid to variations on short time scales.

Methodology

We analyze the time variograms of the stalagmite growth rate and use the variograms characteristics to classify the stalagmites according to the potential climatic signal that they contain. 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), it seems 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 [5, 6].

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.

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. 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 rate, and therefore overall stability of the system.

We used variograms to analyze the long-term growth variability and to quantify the information content of the stalagmite signal. 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%. The resulting IC 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.

Results and implications for stalagmite paleoclimatology

The statistical measures developed are important 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.

The presence of flickering in all stalagmite series with intensity f ranging between -0.24 and -0.39 indicates significant return to a mean growth rate value, and therefore the overall stability of the system. This 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 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 1, group A), whereas the ones with larger ranges are more likely to reflect only very long-term trends in local groundwater quantity and quality (Figure 1, group B). 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 1, group C).

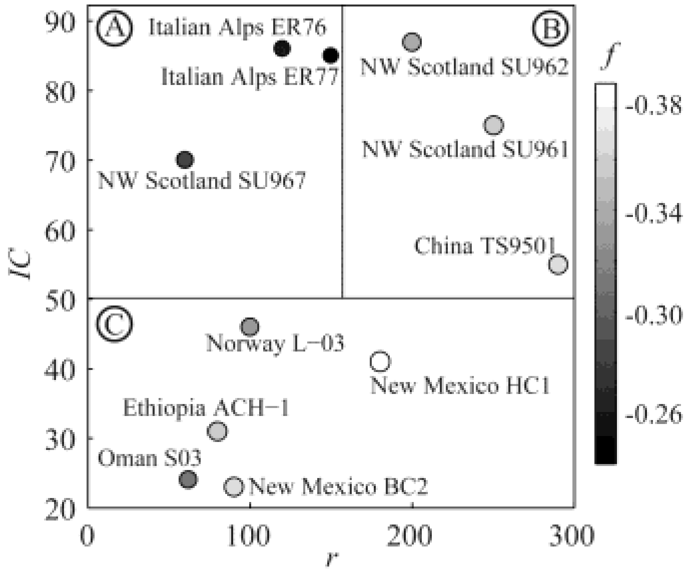

Figure 1. Classification of the stalagmites analyzed considering range, information content and flickering. A: Short range and High IC, potentially carrying information on decadal-scale variability. B: Large range and High IC, potentially informing long-term trends. C: Low information content. Stalagmites in A show less flickering, indicating an external, non-random component.

Bibliography

1. Trouet, V., et al., *Persistent positive north atlantic oscillation mode dominated the medieval climate anomaly.* Science, 2009. **324**(5923): p. 78-80.
2. Woodhead, J., et al., *Speleothem climate records from deep time? Exploring the potential with an example from the Permian.* Geology, 2010. **38**(5): p. 455-458.
3. Baker, A., et al., *Testing theoretically predicted stalagmite growth rate with Recent annually laminated samples: Implications for past stalagmite deposition.* Geochimica et Cosmochimica Acta, 1998. **62**(3): p. 393-404.
4. Tan, M., et al., *Applications of stalagmite laminae to paleoclimate reconstructions: Comparison with dendrochronology/climatology.* Quaternary Science Reviews, 2006. **25**(17-18): p. 2103-2117.
5. Goovaerts, P., *Geostatistics for Natural Resources evaluation*1997: Oxford University Press, Oxford.
6. Chilès, J.-P. and P. Delfiner, *Geostatistics - Modeling Spatial Uncertainty*. Wiley Series in Probability and Statistics1999, New York, USA: John Wiley & Sons, Inc.