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Comparison of speleothem fabrics and microstratigraphic stacking patterns in calcite stalagmites as indicators of paleoenvironmental change

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ABSTRACT

In the necessary task of obtaining high-resolution paleoclimate series from speleothems, the characterization of their internal microstratigraphy is a useful tool for: a) improving geochronology, and b) reaching a more complete knowledge of the speleothem formation and evolution through time and thus obtaining additional paleoenvironmental information. However, the development of standardized methodologies for microstratigraphic characterization is a pending task. In this paper, two different approaches allow construction of microstratigraphic logs for three stalagmites retrieved from two different caves. The logs correspond to vertical variations in speleothem fabrics and in microstratigraphic stacking patterns. The "fabrics logs" essentially provide information about the drip rate (sometimes used as a precipitation proxy) and the regularity or irregularity of each drip in the short-term. The "microstratigraphic stacking patterns logs" can be interpreted to obtain information about the changes in drip rates in the mid- and long-term. The results show a broad correlation between both kinds of logs that supports their validity as paleoenvironmental proxies. Fabrics formed under relatively constant and regular drips (columnar compact, open and elongated) usually constitute aggradational or progradational microstratigraphic stacking patterns. On the other hand, retractional stacking patterns are usually related with fabrics precipitated under more irregular drips (dendritic and columnar microcrystalline). However, this relation is not rigid and the information obtained from the logs is not equivalent, but complementary. The combination of both logs allows reconstruction of the hydrological history for each drip site. As all the obtained information derives directly from the drip conditions, drip effects result to be very important and can, in some cases, overwhelm the paleoclimate information recorded in each stalagmite.

1. Introduction

Speleothems (and particularly calcite stalagmites) are intensely studied as archives of Quaternary climate, as they can yield high-resolution time-series of multi-proxy records. For this reason, in the last two decades, an estimable effort has been done in improving the age-dating methods of speleothems (particularly, U-series; e.g., Dorale et al., 2004) as well as the extraction and interpretation of paleoclimate data from them, mostly of geochemical nature (e.g., trace elements, stable isotopes; for a general review see Fairchild and Baker, 2012). In contrast to those noticeable advances, the characterization and interpretation of the internal stratigraphy of the stalagmites have received less attention, despite their importance for the construction of paleoclimate series. This is puzzling because both age-dating and proxy data are framed in the speleothem stratigraphy which can vary from quite simple to very complex. The stratigraphic characterization has three main advantages: a) it allows a better planning for

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geochemical microsampling, b) it contributes to better chronologies, and c) the stratigraphic features can, by themselves, yield important paleoclimate information. Previously, “simple” stalagmites have been preferentially chosen for paleoclimate research rather than more complex ones, because of the simplistic assumption that the most favorable stalagmites for paleoclimate work are those that display a simple stratigraphy.

The influence of climate on the morphology and stratigraphy of speleothems was first analyzed by Dreybrodt (1988, 1999). He defined three main parameters more or less directly dependent on climate (water supply rates, chemical kinetics and flow conditions on the surface of the speleothem) that control the growth of speleothems in order to discuss how, under known growth conditions, the palaeoclimatic signals were inscribed into the morphology and stratigraphy of a stalagmite. However, given the counter-balancing effects of the three parameters, he concluded that it was difficult to read climatic conditions backward from the morphology or stratigraphy of speleothems only (Dreybrodt, 1999). In the last few years, however, some authors have paid attention to the stratigraphy of speleothems from different points of view. Different kinds of petrographic logs have been used as a complement to other geochemical analysis (Frisia et al., 1997, 2000; McDermott et al., 1999; Bertaux et al., 2002; Verheyden et al., 2008; Belli et al., 2013). Muñoz-García et al. (2006) introduced the use of “microstratigraphic logs” for stalagmite characterization and correlation. Those logs were based on different features, mainly “paleosurfaces”, “growth layers” and “calcite textures”. Luetscher et al. (2011) used the correlation of the microstratigraphic logs of four stalagmites to obtain a combined paleoenvironmental proxy. The logs recorded different features such as the presence of inclusions or bacterially mediated calcite. More recently, Frisia (2015) proposed a wider approach. It consists of the construction of “standardized” logs, based on the stratigraphic distribution of speleothem fabrics differentiated by petrographic observations. Concurrently, Martín-Chivelet et al. (2013; and in prep.) present a systematic method in which the microstratigraphy of stalagmites is studied under the perspective of “architectural element analysis”, which categorizes the internal stratigraphic heterogeneity of the speleothems on the basis of a hierarchical scheme that theoretically is able to incorporate any petrographic or stratigraphic feature. Architectural elements include individual crystallites, single growth layers, speleothem fabrics, growth layer sets, morphostratigraphic units, and major unconformities.

Despite the enormous potential of these microstratigraphic methods, they have been only partially tested. The aim of this paper is to make some progress in their application to real study cases, which will allow an objective discussion and evaluation of their utility. We have chosen two different approaches for the construction of microstratigraphic logs from stalagmites. These are respectively based on speleothem fabrics and on growth layer sets, the latter defined by the microstratigraphic stacking patterns. Both elements are believed to be key features for accomplishing the stratigraphic characterization and genetic (paleoenvironmental) interpretation of speleothems.

For this test, a specific stratigraphic interval has been chosen in three coeval calcite stalagmites retrieved from two different caves. The selected intervals display continuous growth characterized by similar well-defined annual banding (i.e., individual growth layers in the sense of Martín-Chivelet et al. (2013)) in the three samples.

2. Material and sampling sites

The three selected stalagmites are currently used for paleoclimate research and were retrieved from two karstic caves that have been monitored and investigated in the last decade in the framework of a broader paleoclimate project. Both caves are in Burgos province, in northern Spain (Fig. 1a), ~90 km apart. Two stalagmites (SLX1 and SLX2) come from Cueva Mayor (Sierra de Atapuerca Karst System), and the third one (Buda-100) from Kaite Cave (Ojo Guareña Karst System). The climate of the region is warm-temperate, within the transition between Atlantic and Mediterranean zones. The Cueva Mayor area is located in the northern spurs of the Spanish Meseta and presents a significant continental influence (see the differences in vegetation cover in Fig. 1a). Annual mean temperatures are in the range of 10–11 °C in both places, although these vary notably along the year: winters are quite cool (mean temperature Dec–Jan: 3.5 °C) and summers are warm (mean temperature Jul–Aug: 19.5 °C). Annual rainfall for the period 1990–2002 averages 630 mm in the Atapuerca meteorological station (Agencia Estatal de Meteorología, N42°22′35″, W3°30′27″ 966 m a.s.l.), and ~720 mm in the Kaite area (Villarcayo meteorological station, Agencia Estatal de Meteorología, N42°56′26″, W3°34′20″ 595 m a.s.l.). Maximum precipitation occurs from November to January but is also notable in April–May, and summers are quite dry. During winter, part of the precipitation falls as snow, which never lasts on the ground more than a few weeks.

Stalagmites SLX1 and SLX2 (Fig. 1b) were collected in the Sílex Gallery, one of the most isolated galleries in Cueva Mayor. SLX1 was slightly moved from its drip point in 1990 during pioneer speleological exploration works, and latterly collected in 2002. SLX2 was retrieved in 2007. Both stalagmites were growing on limestone blocks that belong to a cone formed by a karstic collapse (Fig. 1c). This collapse increased the isolation of the Sílex Gallery from the rest of the cave about 3000 years ago (Ortega, 2009). The gallery is located at around 1020 m above sea level and between 12 and 46 m below the topographic surface (Ortega, 2009). The temperature remains almost constant throughout the year around 10.6 ± 0.1 °C, the relative humidity is close to 100%, and there are no significant air currents at any season of the year. Stalagmites SLX1 and SLX2 can be considered as “sister” stalagmites (Fig. 1b). They grew approximately during the same time interval and at the same spot within the Sílex Gallery. Besides, they both consist of translucent calcite, and present comparable size, shape and outer aspect. The environmental conditions during the growth of both stalagmites can be assumed to be identical. Therefore, any compositional or stratigraphical differences must arise from the specific features of the corresponding drip site (drip rate, drip stability, water chemistry, etc.), whose influence on the speleothem features are usually known as “drip effect”. Both SLX1 and SLX2 are cylindrical stalagmites, 43 and 42 cm long along the growth axis, respectively. SLX1 grew from ~1550 BP to the present during two growth phases separated by a prominent internal stratigraphic unconformity (Martín-Chivelet et al., 2011; Fig. 1b). SLX2 grew from 4150 BP to the present in three growth phases separated by unconformities (Fig. 1b; unpublished data).

Stalagmite Buda-100 (Fig. 1b) is very elongated (112 cm long, 4–6 cm wide), cylindrical, and mainly consists of milky opaque calcite. The internal stratigraphy shows a well-defined pattern defined by sub-millimetric annual lamination (from 100 to 400 μm thick). The stalagmite was fallen and broken into several pieces when collected in 2011. It grew in the Buda Hall, a site located in the most isolated part of the Kaite cave (Martín-Merino, 1986). Its topographic height is 870 m a.s.l. and is separated from the surface by 12–18 m of Cretaceous carbonates. The temperature remains almost constant throughout the year (10.40 ± 0.04 °C), the relative humidity is close to 100%, and the site lacks significant air currents (Turrero et al., 2004, 2007, 2014). Seepage water is frequent, with permanent dripping throughout the year. Speleothems are abundant in the cave (Fig. 1d) and many of them are active at the present