Long term alluviation and its contribuition to the development of distributary cave systems

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Abstract

This study characterizes an extensive sedimentary record occurring in Lapa Doce and Torrinha caves, NE Brazil. With more than 40 km of surveyed passages, these caves integrate a distributary cave system fed by allogenic recharge from the surrounding sandstone plateaus. Sediment petrography together with descriptions of depositional facies and architectural elements shows four depositional units related to fluvial and standing water environments. These include, from bottom to top: (1) a channel unit including lateral bars deposited during an ordinary flood regime; (2) a sandy flood unit including minor channel and scour fills derived from bank-full equivalent flood events; (3) mud caps deposited in standing water that often reach the ceiling; and (4) intraclast breccias associated with collapse of the mud caps under saturated conditions. Long term alluviation of the cave system seems to be important in forming passages, determining their configuration, and setting up a general distributary pattern evident in passage morphology and sedimentary sequences.

1. Introduction

Cave systems offer a unique environment for sediment transport, deposition and preservation. Because cave sediments are protected from weathering and bioturbation, caves often act as sediment repositories that may provide records of geomorphic events even where no river terraces can be found in the surface. Although there has been progress in understanding sediment transport through karst aquifer systems (Herman et al., 2012) there is still an enormous gap when compared to knowledge about clastic deposition in surface alluvial systems (Miall,2006; Bridge and Demicco, 2008).

In this study we characterize an extensive sedimentary record occurring in Lapa Doce and Torrinha caves, NE Brazil. Sediment petrography, facies descriptions and architectural elements of the deposits are presented. This work contributes to an understanding of clastic sediment transport and deposition within karst aquifers, especially those fed by surface fluvial systems.

2. Materials and methods

The Chapada Diamantina is an elevated region in the central Bahia state (Brazil) at the drainage divide separating waters flowing toward the São Francisco River from those flowing direct toward the South Atlantic Ocean. The region comprises a set of ranges and plateaus mainly formed on folded Proterozoic sedimentary rocks. The study area is located where Neoproterozoic rocks from Una Group and Mesoproterozoic sequences from Espinhaço Supergroup are folded into a narrow synform (CPRM, 1999).

The study area is drained to a local base level controlled by the Santo Antônio river and its main tributaries, which include intermittent and ephemeral streams as well as karst springs. The Santo Antônio is in turn tributary to the ocean-ward flowing Paraguaçu river. The Santo Antônio river flows out of the study area as a superposed drainage cutting toward the east through the siliciclastic rocks. Local streams include the Agua de Rega and Almas creeks, which sink into the west flank of the synform to form blind valleys. Although they behave at present as ephemeral streams, they were in the past major suppliers of sediment to the cave systems. Most of the drainage is confined to canyons with a flat alluvial floor. Despite the absence of a floodplain and terraces these streams store large amounts of sediments in the valley floor, especially when cutting through carbonate rocks.

Lapa Doce cave system is one of the most visited caves in Brazil. The whole system contains 25.8 km of surveyed galleries with multiple entrances associated with collapse dolines. It is characterized by a sinuous trunk passage and distributary branches generally associated with network maze sectors (Cruz JR, 1998; Auler, 1999). Scallops on the passage walls confirm a signature of divergent flow. The downstream decrease in trunk passage dimensions and increase in branching density is analogous to surface distributary rivers (Nichols and Fisher, 2007).

In both caves the profiles of trunk galleries often have a planar roof that cuts across carbonate bedding planes suggesting dissolution under a high water table in the past (Auler, 1999). The cross-sectional shape varies over those caves but remarkable wall notches can be observed as a result of lateral dissolution atop a sedimentary fill (Farrant and Smart, 2011). Some trunk galleries still contain a ceiling half-tube right above a sediment fill. Distributary branch arms and associated network sectors usually share the same flat sediment floor, but their ceilings are always lower than the ceiling of the adjacent trunk conduits. They are preferentially narrow passages not wider than a few meters. Pendants, cupolas, anastomosed half tubes and wall grooves are common features of these passages.

Six stepped trenches were excavated to expose the original sedimentary fill, where descriptions and sampling were preferentially performed. Five of them were located in trunk passages trying to follow general flow direction. Yet, in Torrinha cave, another excavation was made to characterize sediments in a minor passage that cuts across both trunk and mazes passages. Sedimentary successions were synthesized by stacking descriptive facies (Anderton, 1985) recognized over all vertical risers. In addition, exposures on the sides of the trenches were used to constrain the internal geometry and unconformities. Facies nomenclature and the hierarchy of erosional boundary surfaces were adapted from Miall (2006). Sand samples were impregnated with resin for further analysis under a petrographic microscope. Fine sediment grain size was analyzed by low angle laser diffraction using a Malvern Mastersizer S facility and mineral content was determined using total sample X-ray diffraction.

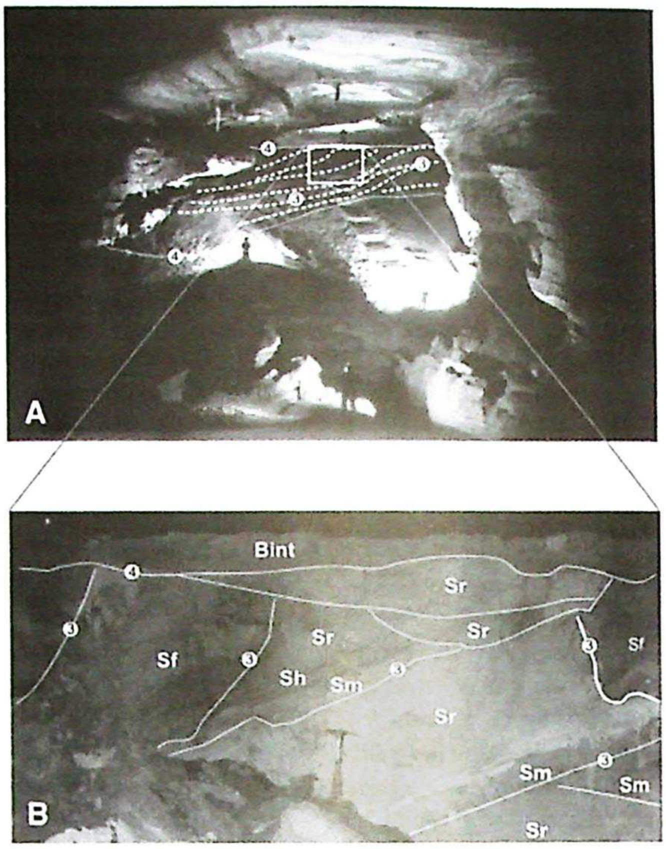

Figure 1 : *A - Step trench digged in Lapa Doce II, Sifão de Areia, where sediment were partially removed. B - Flood facies : 3rd order erosional surfaces showing lateral accretion of channel cutting structures within scours fill Circumscribed numbers are related to hierarchy of bounding surfaces.*

3. Results

The bulk sedimentary data allows the identification of four distinct depositional units bounded by 4th order (or higher) erosional surfaces. Two of them are assumed to be the result of sedimentation under fluvial conditions while the others are related to standing water deposition within conduits under phreatic to epiphreatic conditions (Figure 2).

Those derived from fluvial processes can only be distinguished in terms of architectural elements. Standing water depositional units are single descriptive facies successions located at the top of the sedimentary column, often reaching the ceiling of the passages and sometimes blocking them.

Channel deposits are present at the bottom of all trunk galleries; the basal contact with bedrock was recorded in both caves, and it is not much deeper than the general sandy, flat cave floors. From bottom to top, channel facies begin with one or more fining upward cycles or co-sets of cross-bedded sand, both followed by laminated silt. Where exposed along the cave wall, which is rare, this basal part of channel deposits has internal erosional surfaces suggesting downstream accretion. At the location of the cross-section, third order surfaces propagate from basal sand beds into superposed laminated silt, showing that they are part of a common macroform, in this case, a lateral bar. Internal fourth order erosional surfaces in upper laminated silt package reveal that the river channel has abandoned and reoccupied the same passage, leading to a superposition of two successive bars.

Flood depositional units comprise sand beds that were recognized in the middle of the sediment piles in trunk galleries of both caves and at the bottom of minor passages in Torrinha . Horizontal, plane laminated centimeter scale sand beds accumulated over climbing ripples often showing a high angle of climbing. Fine sand with horizontal lamination is present as well as massive sand. They are represented by approximately 3 m-thick rippled and massive sand showing an abundance of internal erosional surfaces. The cross-section views of these two sites reveal concave up 4th order erosional surfaces derived from successive minor ephemeral channels (Figure 1). However, these sediments are strictly composed of channel related bedforms. Descriptive facies succession and three-dimensional arrays of erosional surfaces suggest deposition related to minor channels or scours that filled during bank-full flood events. This would lead to deposition over active channel bars and galleries previously abandoned from the main river channel. This interpretation is also supported by another important distinctive element: a topmost flat surface developed independent of conduit morphology, level or size. Top flat surfaces usually derive from deposition in floodplains in surface fluvial systems (Bridge and Demicco, 2008) and although one should not expect to observe a floodplain in cave passage containing a stream; a flat surface would be the result of recurrent and successive flood events occurring in laterally displaced but interconnected passages. In the study caves, this top flat surface is also concordant with wall notches in some trunk galleries, and the general ceiling elevation of adjacent single or maze conduits.

Massive to finely laminated well-sorted mud caps occur upon fluvial deposits, sometimes reaching >4 m thick. They systematically lay over the top flat surface of flood deposits with an abrupt contact, although in Torrinha successive interbedding of rip-pled fine sand and massive mud suggests a gradual transition. Except for light brown discontinuous lamination, the red to dark brown mud package does not preserve significant syn-sedimentary structures, and is otherwise intensely cracked. Clods are often covered by post-depositional iron/manganese precipitates and show remarkable gypsum crystal growth in between. Unlike fluvial deposits, mud packages may regularly be observed interbedded and superposed by calcite crusts, or even showing diverse erosional relationships with flowstones and speleothems. This is important because it indicates that the mud caps are not derived from a single depositional event. Nevertheless, these events should be longer than the flood events previously described. There must be sufficient time for base level to rise and stand, sustaining the caves in phreatic or epiphreatic conditions. This facies often fills passages near to the ceiling and is closely associated with paragenetic features such as ceiling half-tubes and anastomoses.

Ungraded, matrix-supported intraclast breccias are found on the top of all 3 sections from Lapa Doce (Fig. 3). Away from the trenches, this facies transitions laterally to mud caps and it is a clear result of gravitational reworking of the mud caps. It may reach 2 m in thickness and is quite different from gravitational diamictons described elsewhere (Gillieson, 1986; Bosch and White, 2007). This sediment is interpreted to be derived from slide or fall events that disrupted the original mud caps. Clast shape and fabric point to limited displacement and the presence of unsorted muddy matrix indicates water availability. The detachment of saturated muddy sediments could be triggered by rapid water table lowering or ceiling breakdown, but it clearly demonstrates that sediment piles were higher than at present and there was available space in aggraded conduits for sediment migration.

Depositional unit	Depositional environment	Distinctive elements	Interpretation
Channel	Fluvial system	Accretion of channel mesoform (dunes) and macroform (bars)	Migration of channel and lateral bars during ordinary floods in active river passages.
Flood		Accretion of scour and minor channel fills; overbank top flat surface	High sediment load influx during episodic bank full flood events affecting the whole cave system.
Mud caps	Standing waters	Absence of bedload deposits	Suspended load deposition on epiphreatic conduits. May experience moments of aerial exposure.
Intraclast Breccia		Ungraded angular intraclasts breccia	Slide or fall of saturated cracked mud packages due to slope instability or breakdown.

Figure 2 : Distinctive elements and interpratation for recognized depositional units.

4. Discussion

The role of sediments in speleogenesis has been reviewed by Farrant and Smart (2011) who recognized two main processes: paragenesis and alluviation. The first is a phenomenon relevant to phreatic conduits where sediments restrict their cross-sections, forcing upward dissolution (Renault, 1968). The second is derived from alluviation of passages in a vadose environment, where enhanced lateral corrosion sculpts wall notches. Paragenesis and alluviation processes may also develop simultaneously in a given evolving cave system. An example could be the sediment fill of loops within phreatic zone and the development of a bypass passage at upper vadose zone (Ford and Ewers, 1978). Both paragenesis (ceiling half tubes, pendants and cupolas) and alluviation (wall notches and bypass passages) derived features can be recognized in the studied caves, but the timescale and ordering of processes cannot be solved without an understanding of clastic deposition.

Together, the downstream decrease in trunk passage dimensions, the increase in branching density, the distributary flow signature recorded by scallops in cave walls, and the sedimentary record group to represent the medial to distal zones of a subterranean fluvial distributary system (Nichols and Fisher, 2007).

Cosmogenic burial dating fo these deposits (Laureano et al., 2016) has show that during the Early and Middle Pleistocene, the Lapa Doce and Torrinha cave system were linked to surface drainage in terms of water and sediment transport, which in turn was governed by the flood regime in Agua de Rega creek and Santo Antonio river (base level). As observed presently, because the Santo Antonio river has a larger watershed it rises and blocks groundwater flow during floods, sometimes promoting back flooding in the karst aquifer (Auler and Farrant, 1996). This backwater effect in part explains why sediments have aggraded within caves and also can be invoked to understand the maze network and narrow passages that are associated with trunk passages (Palmer, 1975).

Cave alluviation took course during at least 1.5 million years with successive input and flush of fluvial sediments. It seems to have been interrupted during the Middle Pleistocene, the two youngest burial ages point to a timeframe around 300 ky (Laureano et al., 2016). When studying sediments in caves fed by sinkholes in Brazil, Auler et al. (2009) have argued for a climate control for sediment input, but that should not be assumed in relation to the long term cave alluviation recorded here because depositional units related to fluvial deposits may be derived from ordinary flood regime (Herman et al., 2012).

5. Conclusion

Fluvial deposits can be distinguished in two units: the first is related to channel meso and macroforms deposited during base flow, the second is associated with scours and minor channel fills deposited in bank-full flow conditions. This long-term alluviation of cave systems is important in generating passages, determining their configuration, and setting up a general distributary pattern evident in passage morphology and sedimentary sequences.

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