Gypsum caves as indicators of climate-driven river incision and aggradation in a rapidly uplifting region

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ABSTRACT

Detailed geomorphological analysis has revealed that subhorizontal gypsum caves in the Northern Apennines (Italy) cut across bedding planes. These cave levels formed during cold periods with stable river beds, and are coeval with fluvial terraces of rivers that flow perpendicular to the strike of bedding in gypsum monoclines. When rivers entrench, renewed cave formation occurs very rapidly, resulting in the formation of a lower level. River aggradation causes cave alluviation and upward dissolution (paragenesis) in passages nearest to the river beds. The U-Th dating of calcite speleothems provides a minimum age for the formation of the cave passage in which they grew, which in turn provides age control on cave levels. The ages of all speleothems coincide with warmer and wetter periods when CO_2 availability in the soils covering these gypsum areas was greater. This climate-driven speleogenetic model of epigenic gypsum caves in moderately to rapidly uplifting areas in temperate regions might be generally applicable to karst systems in different geological and climatic conditions.

INTRODUCTION

Karst terrains are formed in areas underlain by soluble rocks, where weathering by dissolution gives rise to a distinctive suite of landforms (De Waele et al., 2011; Ford and Williams, 2007). The slow dissolution rates of limestone and, more particularly, dolomite result in relatively slow rates of landscape evolution in these terrains (Ford and Williams, 2007; Sauro et al., 2013), making it difficult to explore the effects of Quaternary climate changes on landscape development. Gypsum is much more soluble and therefore has excellent potential for investigating the effects of centennial- to millennial-scale climate change on karst evolution. A way of testing this is to use speleothem ages from abandoned cave passages that were originally formed close to or at local paleo–base levels.

Unlike hypogenic gypsum caves (Klimchouk, 2009), which have no direct relationship with the present climate and surface waters, epigenic caves are formed by dissolution and erosion by surface waters and strongly depend on changes in surface hydrology. Rivers draining epigenic caves can incise at different rates according to changes in local tectonic and climatic conditions (Granger et al., 2001). When base-level changes caused by river incision occur in the karst landscape, the carving of a new cave level may happen in a way similar to downcutting in surface rivers, resulting in new river strath terraces (Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002). The rate at which cave systems develop new cave levels in limestone is on the order of some thousands of years, one order of magnitude slower than in gypsum caves (White, 1988; Ford and Williams, 2007). The difference in the age of cave levels can thus be resolved in limestone caves only in slowly uplifting areas (on the order of 0.01 mm yr^{-1}), such as the Appalachian Mountains in North America (Granger et al., 2001), while in regions rising at moderate rates (>0.1 mm yr^{-1}) there is commonly insufficient time for this type of cave system to form distinct levels, perhaps with the exception of tropical areas, e.g., Malaysia (Farrant et al., 1995), or in sulfidic hypogenic caves (Mariani et al., 2007). The faster evolution of epigenic gypsum caves compared to those hosted in carbonate rocks allows cave levels to be formed also in areas uplifting at moderate to fast rates.

The age of cave levels can only be determined indirectly by dating of sediment infills or speleothems that were emplaced after cavern dewatering. Such dates give a minimum age of the galleries hosting these deposits. In most gypsum caves younger than 500 ka, U-Th dating on carbonate speleothems can be applied with success. This study explores the potential of epigenic gypsum caves in reconstructing climate-driven entrenchment and aggradation of rivers in the rapidly uplifting Northern Apennines (Northern Italy).

STUDY AREA

Karst in Emilia Romagna (Northern Italy) is mainly confined to Messinian gypsum that crops out on the northern flank of the Apennines (Fig. DR1 in the GSA Data Repository[1]). This actively growing mountain front has experienced an average uplift rate of around 1 mm yr^{-1} since ~150 kyr B.P., with a three- to five-fold lower rate during the middle Pleistocene (Cyr and Granger, 2008; Picotti and Pazzaglia, 2008). Regional studies on river terraces have allowed the reconstruction of phases of incision and aggradation and their links to local tectonics, climate, and vegetation changes in the catchment areas, and of the extent of anthropogenic influences (Gunderson et al., 2014; Picotti et al., 2009; Ponza et al., 2010; Wegmann and Pazzaglia, 2009; Wilson et al., 2009). Large epigenic caves have been carved in several of these catchments, with some hosting active channels and preserving a series of vertically stacked cave levels.

The Re Tiberio cave system is hosted in the Vena del Gesso gypsum ridge, located 40 km east of Bologna (Fig. DR1). It consists of an 11 km network of cave passages developed at five clearly distinguished cave levels (De Waele et al., 2013); much of the network is exposed in an underground gypsum quarry. The caves develop more or less parallel to the strike of the bedding and perpendicular to the nearby Senio River, the local base level. Calcite speleothems have been found in many places in and around this cave (Figs DR2 and DR3; Table DR1). A thick flowstone has been sampled in the open-pit gypsum quarry at 340 m a.s.l. (above sea level). Its original position was most probably higher than 340 m a.s.l. Other speleothems have been recovered at cave levels corresponding to 275, 215, 190, 179, 160, and 130 m a.s.l. The 160 m a.s.l. sample was found detached from the bedrock at the base of a 60–70-m-high vadose shaft, and came from an altitude of 190 m a.s.l., while the other speleothems were sampled in situ in more or less horizontal cave passages.

U-SERIES DATING METHODS

Sampling of all known carbonate speleothems was carried out in the Re Tiberio cave

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[1]GSA Data Repository item 2015189, U/Th ages of samples from the Re Tiberio cave system, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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system from all accessible cave levels to obtain the minimum formation age of the cave passages in which they formed. The speleothems were cut perpendicular to the growth layers, yielding several 0.5–2-cm-thick slices. The ages of the samples were determined by U-series dating at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) at Gif-sur-Yvette (France) and the School of Earth Sciences, Melbourne (Australia).

At the LSCE, prior to analysis the samples were carefully cleaned using a fine diamond saw to remove any visible contamination and then leached with 0.1 M HCl. The samples were then dissolved with diluted HCl, equilibrated with a mixed ^{236}U-^{233}U-^{229}Th spike, and the U and Th fractions separated using UTEVA resin (Eichrom Technologies, USA). The U and Th separation and purification followed the procedure of Douville et al. (2010). Uranium and thorium isotopes were analyzed using a ThermoScientific Neptune^{Plus} multi-collector–inductively coupled plasma–mass spectrometer (MC-ICP-MS) following the protocol developed at LSCE (Pons-Branchu et al., 2014).

The U-Th analysis at Melbourne University followed the procedure set out in Hellstrom (2003), modified as described in Drysdale et al. (2012). Samples were extracted using a 1 mm drill bit following the growth layering. Subsamples of ~10 mg were dissolved in HNO_3 and equilibrated with a mixed ^{236}U-^{233}U-^{229}Th spike prior to chemical separation of the U and Th fraction using Eichrom TRU ion-exchange resin. All U and Th isotope ratios were determined simultaneously using a Nu Instruments Plasma MC-ICP-MS. Corrected U-Th ages were determined for all samples using the ^{230}Th and ^{234}U decay constants of Cheng et al. (2013) and equation 1 of Hellstrom (2006).

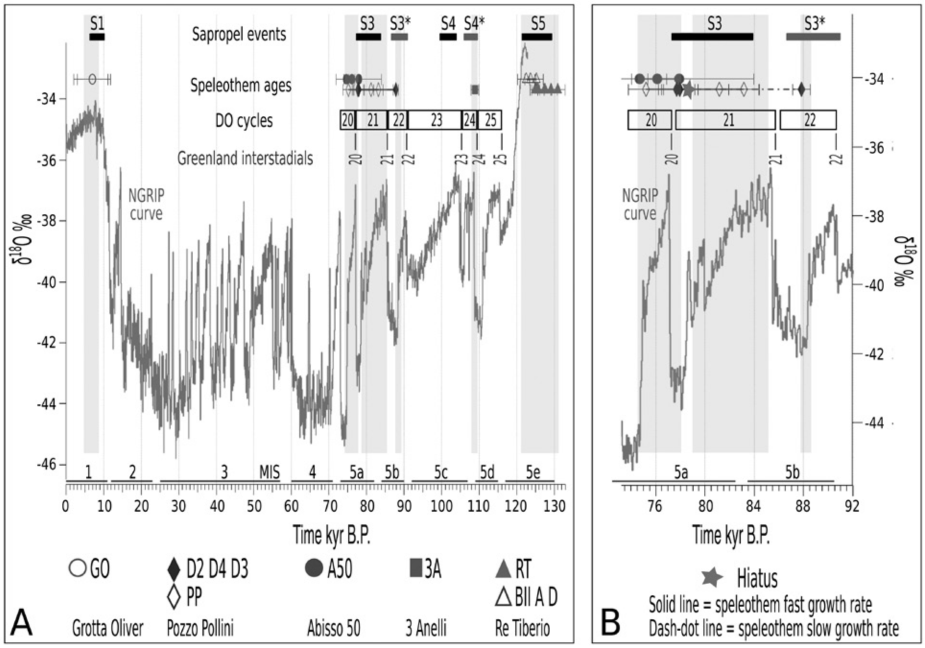

Figure 1. A: Speleothem ages (see Table DR1 [see footnote 1]) from five caves in the Northern Apennines, Italy (Grotta Oliver, Pozzo Pollini, Abisso 50, 3 Anelli, and Re Tiberio), compared with main climate oscillations over the last 130 k.y. B: Detail of period between 72 and 92 ka. Gray vertical bars correlate speleothems with relative warmer and/or wetter climate pulses. Age of Dansgaard-Oeschger (DO) cycles and Greenland interstadials and of marine isotope stages (MIS) are from North Greenland Ice Core Project (NGICPM, 2004) and Lisiecki and Raymo (2005) respectively. Asterisk (*) indicates precursory sapropel events (see Ziegler et al., 2010). Only reliable ages are used in this graph.

RESULTS

Corrected ages and U-Th summary data are reported in Figure 1 and Table DR1. The flowstone at 340 m a.s.l. grew over a period of ~8 k.y. during marine isotope stage (MIS) 5e (122–130 ka), a period of interglacial conditions in southern Europe (Drysdale et al., 2005) and coinciding with sapropel 5 deposition in the Mediterranean (Ziegler et al., 2010). The flowstone sampled at 215 m a.s.l. yielded an age of 108.9 ± 1.0 ka, corresponding to the Greenland Interstadial 24 of Dansgaard-Oeschger (DO) cycle 24 (Drysdale et al., 2007) at the warming transition from MIS 5d to 5c, during the deposition of precursory sapropel 4. The Pozzo Pollini cave flowstone (190 m a.s.l.) returned ages ranging between 88 and 75 kyr B.P., corresponding to MIS 5b and 5a, from the end of DO cycle 22 until DO cycle 20 (Boch et al., 2011). This prevalently warm phase has also been recognized by Meyer et al. (2012) within a speleothem from the Alps. The cold intervals between Greenland Interstadials 22–21 and 21–20 correlate respectively with slow growth rate and a deposition hiatus detected in the flowstone (Fig. DR3). Similarly, the speleothem collected from Abisso 50 cave at 275 m a.s.l. was dated to between 74 and 77 ka (MIS 5a), corresponding to the warm limb of DO cycle 20 (Greenland Interstadial 20) (Boch et al., 2011). Finally, the speleothem taken in Grotta Olivier at 130 m a.s.l. (only 35 m above the active Senio River thalweg) returned an age of ca. 3–11 ka, and grew during the Holocene climatic optimum.

DISCUSSION

Dating of calcite speleothems in various levels of Re Tiberio cave system and geomorphological observations allow us to develop a model that links speleogenesis to river incision and aggradation. All dated speleothems yielded ages corresponding to relatively warm periods or stages during MIS 5 and the Holocene, in agreement with the North Greenland Ice Core Project (NGRIP) oxygen isotopic record (NGICPM, 2004) (Table DR1 and Fig. DR1). The correlation with sapropel events indicates that the speleothems grew during conditions of enhanced rainfall in the Mediterranean basin (Kallel et al., 2000). During cold periods, when vegetation cover was likely reduced, lower CO_2 levels would have inhibited or significantly decreased the growth of carbonate speleothems (Fairchild and Baker, 2012), as suggested by the hiatus and the slow growth rates detected in the Pozzo Pollini flowstone.

The highest cave level appears to have formed during a cold period prior to MIS 5e. The most developed and extensive cave level at 180 m a.s.l., almost 80 m above the Senio River, and the one at ~215 m a.s.l. both formed during cold phases in MIS 5 (5b and 5d respectively). The lower passages at 160 and 130 m a.s.l. probably formed during MIS 4 and MIS 2 respectively.

Rivers flowing in the uplifting Northern Apennines toward the Po Plain adjust their stream profiles to variable tectonic rates on scales of 10–100 k.y. (Gunderson et al., 2014). Over shorter time scales, entrenchment and aggradation depend on stream discharge (Q_w) and the relative proportion of bedload (Q_s) (e.g., Bull, 1979; Hancock et al., 1998; Wegmann and Pazzaglia, 2009) (Fig. 2). Stream discharge depends on climate, with warmer and colder periods generally being wetter and drier, respectively (Fairchild and Baker, 2012). Apenninic hillslopes during dry and cold periods produced abundant regolith that is available for remobilization at the end of those periods, when increasing rainfall can rework these sediments down to the main channels, eventually depositing them at the lower reaches of the trunk river (Simoni et al., 2013). These high bedload discharge periods allow the valley to

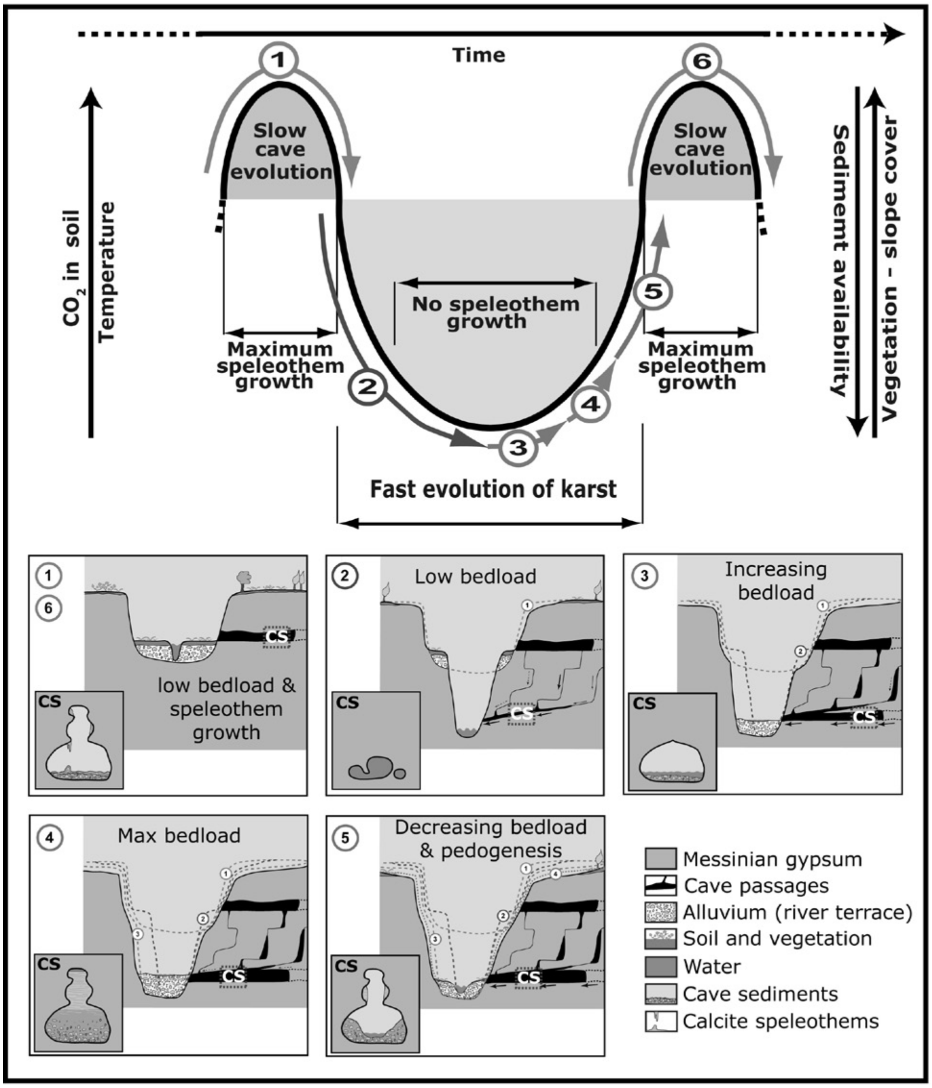

Figure 2. Proposed model of climate-driven speleogenesis of epigenic gypsum cave systems (above) and evolution of river valleys and adjacent gypsum cave systems in Northern Apennines. Insets show typical cross-sections (CS) of cave passages. See text for discussion.

widen by lateral erosion, carving strath terraces and aggrading terrace fills. Recent dating of late-glacial to Holocene terraces in the Northern Apennines documents their formation at the major climatic turnover following dry and/or cold periods and a duration of aggradation of around 2–3 k.y. (Wegmann and Pazzaglia, 2009). The so-formed alluvial valley acted as a stable local base level and during these periods of stability, underground tributaries have been able to carve horizontal gypsum cave levels.

Relatively warm and wet climate periods are favorable for the growth of vegetation on catchment slopes, while the contrary occurs during cold and dry periods. Widespread vegetation cover during warm and wet periods decreases the supply of hillslope sediments to the river. The channel bedrock is poorly protected during low bedload discharge periods, leading to vertical incision, entrenchment, and terrace formation.

In our model (Fig. 2) starting at the close of a cold and/or dry period, the valley bottom is wide and filled with alluvial deposits (stage 1, Fig. 2). The adjacent caves form near-horizontal passages in which the underground stream flows gently toward the resurgence, which is located at the altitude of the thalweg (Fig. 2). Warming allows soil development and speleothem growth and a stable vegetation cover, decreasing bedload and eventually leading to vertical incision. When the river entrenches (stage 2 of Fig. 2), the underground streams adjust to the deepening base level by incising new pathways, rapidly abandoning the previous cave level. A renewed cooling and/or drying period brings about a slowdown of entrenchment and a fast evolution of the karst, with widening of the underground pathways. Valley widening prevails at the end of these cold and/or dry periods (stage 3, Fig. 2), when increasing discharge brings hillslope material to the main thalweg. During these periods of stable base level, a new cave level is formed. Subsequent aggradation in the thalweg also causes sedimentation in the cave passages (stage 4, Fig. 2), forcing the underground streams to dissolve upward (Pasini, 2009) (Fig. DR4). When the river starts entrenching again, these cave passages are partially emptied (stage 5, Fig. 2).

Our data suggest that, in temperate areas, cave evolution in gypsum appears to be controlled mainly by climate, with passage enlargement mostly occurring at the end of cold periods, and a very slow or subdued evolution during warm and wet periods. Carbonate speleothems, in turn, form during the intervening warm and wet periods, when CO_2 levels in the soils reach their highest levels; this is because low concentrations of dissolved CO_2 in equilibrium with the external atmosphere, typical of cold periods and poor vegetation cover, cannot induce calcite precipitation in a gypsum environment (Forti and Rabbi, 1981). This is further documented by these calcite deposits sealing alluvial deposits within the cave (stage 5, Fig. 2).

CONCLUSIONS

This study provides evidence for climate control on evolution in multi-level epigenic gypsum cave systems in a rapidly uplifting area. The evolution of these gypsum caves in response to base-level changes is sufficiently fast to distinguish lowering and/or aggrading events on a scale of 10^2–10^3 yr. This evolution can be chronologically constrained by dating terrace fills and carbonate speleothems. Gypsum cave enlargement appears to be confined largely to cold periods, while carbonate speleothems have formed during warmer and wetter climate periods due to the greater availability of CO_2. The correlation between the speleothem ages and the warm stages over the last 130 k.y. underlines that the Re Tiberio karst system directly reacted to global climate forcing. U-Th dating of carbonate speleothems in rapidly evolving gypsum caves allow us to chronologically extend the record of river terraces in the study of climate-driven river evolution.

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Notes