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Invited review

Speleothems as high-resolution paleoflood archives

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ABSTRACT

Over the last two decades, speleothems have become widely utilized records of past environmental variability, typically through their stable isotopic and trace elemental chemistry. Numerous speleothem researchers have identified evidence of flooding recorded by detrital layers trapped within speleothems, but few studies have developed paleoflood reconstructions from such samples. Because they can be precisely dated, are generally immune to post-depositional distortion or erosion, and can be tied to a fixed elevational baseline, speleothems hold enormous potential as high-resolution archives of cave floods, and thus as proxies for extreme rainfall or other hydrologic drivers of cave flooding. Here we review speleothem-based paleoflood reconstruction methods, identify potential biases and pitfalls, and suggest standard practices for future studies.

1. Introduction

Floods represent the largest source of interannual risk to societies around the globe, affecting not only low-lying communities located on coasts (Hallegatte et al., 2013) and floodplains (Mallackpour and Villarini, 2015), but also along high energy streams in montane regions (Doocy et al., 2013). Direct impacts of rising floodwaters are amplified by secondary effects such as infectious disease transmission, drinking water pollution, crop loss, building destruction, and community displacement (Jonkman and Kelman, 2005). Thus, efforts to understand the nature, timing, and drivers of past flood activity are of enormous socioeconomic interest, and by expanding the temporal context of historical floods, they also play a valuable scientific role.

Numerous methods have been developed to reconstruct past flood activity but each has its own set of limitations. For example, historical documents can provide precise time constraints as well as observations useful for constraining flood magnitude and potentially also the associated weather conditions, but such records are geographically limited and typically restricted to the last few centuries (Kjeldsen et al., 2014). Sediments deposited in lakes (Schilleref et al., 2014), flood plains (Macklin et al., 2012), and abandoned stream channels (Munoz et al., 2015) are useful but some sedimentary records are subject to erosion, distortion, or difficulties in precise age determination (Moreno et al., 2008; Macklin et al., 2012; Munoz et al., 2015). Trees can develop a visually identifiable microstructure within growth rings when their base is submerged by floodwaters, but only for the long durations likely to exist during large flood events on high order streams (Wertz et al., 2013). While this research, including the integrated analysis of these proxies (Schulte et al., 2009), has led to a better understanding of the occurrence rates of extremely large and rare events, the need exists for the development of additional flood archives. Caves, in particular, offer an under-investigated domain for the reconstruction of past flood activity (Springer, 2012). While these highly transmissive systems respond quickly to hydrologic recharge, cave sediments stay well protected from surface erosion processes, and thus may archive sporadic changes in flow dynamics over long intervals. By providing a precise delineation of detrital layers, speleothems - cave formations such as stalagmites and flowstone - allow for accurate dating of discrete flood events.

Speleothems represent promising paleoflood archives on short and long time-scales. Caves are dispersed across large and diverse areas of the globe often subject to major floods (Fig. 1), including densely populated regions such as North America, Central Europe and East Asia. When caves flood, speleothems stop depositing calcium carbonate and may be coated with fine-grained sediment

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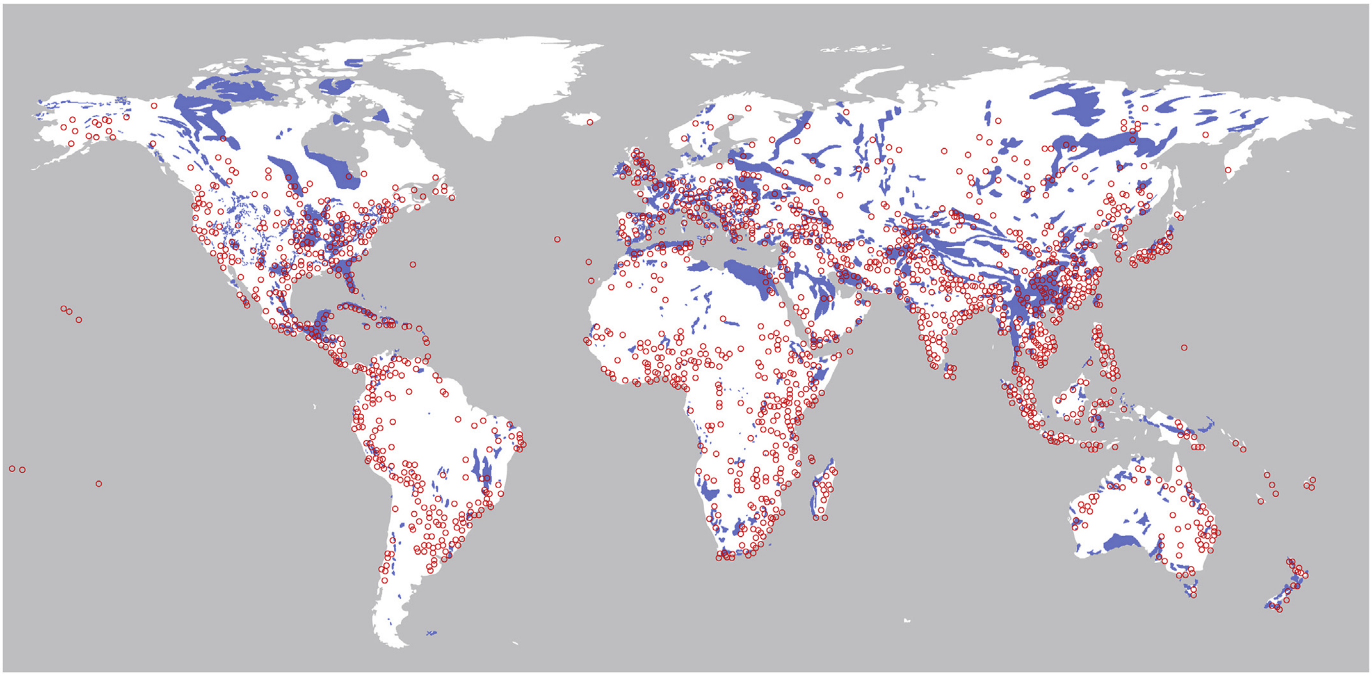

Fig. 1. Map of global karst distribution (blue) and geographical centers for major floods (red circles) observed between 1985 and 2010 (after Brakenridge, 2016).

mobilized by floodwaters that becomes trapped when speleothem growth resumes. As speleothems resist post-depositional alteration and are generally well suited for dating by ^{238}U-^{234}U-^{230}Th methods (henceforth referred to as U-Th) over the past ~500 ka, they are ideal paleoflood records, particularly for floods with moderate to long recurrence intervals.

The number of studies using speleothems as paleoenvironmental records has risen dramatically over the past two decades owing to advances in instrumentation used for U-Th dating, the refinement of geochemical paleoclimate proxies including oxygen (Wang et al., 2013; Lachniet, 2009) and carbon (Fairchild et al., 2006; Ridley et al., 2015) stable isotopic ratios, trace element abundances (Fairchild and Treble, 2009), and fluorescent (Baker et al., 2015) and plain light-visible annual banding (Polyak and Asmerom, 2001; Asmerom and Polyak, 2004). Early mentions of flood layers in speleothems include those by White (1976) and Atkinson et al. (1986) who tied "internal mud layers" in speleothems to past flood events. Similarly, biogenic overgrowths were used as a proxy for submergence in coastal cave systems during periods of high sea level (Harmon et al., 1978; Gascoyne et al., 1979; Bard et al., 2002; Moseley et al., 2015). Because prolonged flooding of cave passages prevents deposition of calcite, dating speleothem growth hiatuses may also help constrain periods of submergence (Harmon et al., 1978; Richards et al., 1994). However, little work examining speleothems as proxies for episodic flood activity was performed until the past decade during which a number of studies have focused on this topic, including in the midcontinent of North America (Lepley et al., 2004; Dorale et al., 2005; Ray et al., 2005; Knight et al., 2006; Dasgupta et al., 2010), southwestern (Gázquez et al., 2014; Gonzalez-Lemos et al., 2015a, 2015b) and central Europe (Jaillet et al., 2006; Meyer et al., 2012), China (Cai et al., 2011), and the tropics of North America (Pyburn and Frappier, 2008; Frappier et al., 2014) and northern Australia (Denniston et al., 2015).

Several questions remain open related to the transport and sedimentation of fine-grained particles and their ability to be preserved in speleothems in a reliable and reproducible way. Given the importance of understanding past flooding activity and the potential of speleothems to advance this goal, it is the purpose of this manuscript to increase awareness of speleothems as paleoflood archives. Here we summarize the state of this research, including karst hydrological and mean climatological origins of cave flooding, discuss methods for identifying and dating flood layers, address techniques involved in calculating past flood magnitudes, and propose a set of best practices in future studies.

2. Background

2.1. Hydrological response of karst systems

A distinctive feature of karst areas is the absence of surface runoff that infiltrates either diffusively over the catchment or is concentrated into swallow holes (sink holes) (Ford and Williams, 2007). In mature systems, drainage occurs along a well-developed, highly transmissive conduit network, which accounts for rapid transport towards the karst springs. In contrast to many other aquifers, the high permeability/transmissivity associated with karst implies a subhorizontal water table at low flow (Fig. 2). Above this base level, the vadose zone may reach up to 2000 m in thickness and is essentially dominated by free water flow.

The hydrodynamics of a karst system are largely determined by the hydraulic properties of the conduit network (Jeannin, 2001) whose geometry is typically controlled by the regional geological setting (Palmer, 2007; Perrin and Luetscher, 2008; Filipponi et al., 2009). The response to aquifer recharge depends, therefore, on individual caves and requires site-specific calibrations. Depending on the head-loss in the conduit system, cave flooding may occur with even limited recharge. While some events may hardly be noticed in the outside environment, the hydraulic head rise in cave systems commonly reaches several tens of meters with extreme values of more than 450 m being reported (e.g. Grotte de la Luire, France; Morel et al., 2006). With increasing hydraulic head, epiphreatic conduits become progressively flooded and temporary karst springs may be reactivated (Fig. 3), responding within hours

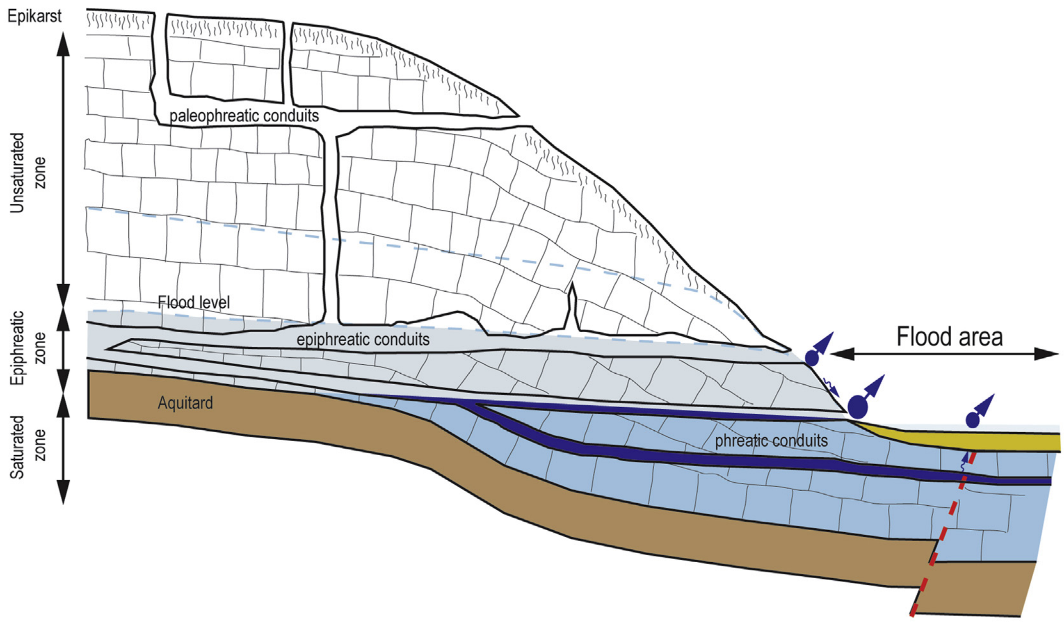

Fig. 2. Schematic of a karst system showing the unsaturated (vadose) and saturated (phreatic) zones. Hydraulic head rise may activate temporary springs that produce floods in the outside environment.

to a given pressure pulse (Luetscher and Perrin, 2005). The discharge of karst springs may thus vary within short periods over several orders of magnitude, sometimes producing significant flooding in the karst foreland (Bonacci et al., 2006; Kovačič and Ravbar, 2010).

Quantitative information about flow velocities is obtained either by physical observations using current meters (Jeannin, 2001) and artificial tracing experiments (Worthington and Ford, 2009) or from geomorphological observations in the cave including the mean size of pebbles (White, 1988) and dissolution scallops (Curl, 1974; Gonzalez-Lemos et al., 2015a). While tracing experiments typically underestimate the sinuosity of cave passages, morphological features are more likely to reflect the maximum discharge in a specific conduit. Overall, results suggest flow velocities of between 0.01 and 10 ms^{-1} in most active karst conduits (Jeannin, 2001).

Similar to fluvial environments, sedimentary in-fills, either in passages or in swallow holes may temporarily modify the geometry of cave passages thereby also affecting the hydraulic response (Fig. 4). Speleological observations from the Sieben Hengste karst, Switzerland, have shown that substantial portions of this cave network were devastated following a millennial flood (Funken and Decannière, 1988), thus favoring water drainage along different flow paths. With time, the reorganization of a karst conduit network may be even more complex with hydrological divergences and rerouting occurring frequently in response to the geomorphological evolution of the area (e.g. Jaillet et al., 2006; Häuselmann et al., 2007). Speleogenetic models suggest that dissolution-driven hydraulic changes may occur within as little as 10^{4-5} years (Dreybrodt et al., 2005). In addition, tectonic uplift and/or downcutting by streams (and associated lowering of the regional water table) can impact karst hydrology. While such processes are unlikely to affect speleothem records of flooding over short timescales, interpreting changes in flood frequencies from cave deposits may become challenging over longer time periods including glacial cycles. Interpretations of data over these intervals are thus, to some degree, dependent on a cave's geomorphological evolution (Jaillet et al., 2006). Of greater concern are blockages at swallow holes that can instantaneously alter recharge to, or flow within, a cave system (Bradley and Hileman, 2006).

2.2. Sediment transport in caves

Clastic sediments transported through karst systems may either be of allochthonous origin or produced *in situ* by erosion or as insoluble residues leftover after carbonate dissolution (Bosch and White, 2004). Detailed monitoring campaigns and field observations have shown that sediment transport reaches up to 1 kg/m^3 (Herman et al., 2008; Reed et al., 2010) for particle sizes ranging between <2 μm and several m^3 (Herman et al., 2012). While larger clasts, including pebbles and boulders, are mainly transported as bedload (Dogwiler and Wicks, 2004), fine grained sediments are more easily maintained in suspension as evidenced by frequent turbidity peaks monitored at karst springs (Fig. 4). Storm flows, during which the hydrological discharge may increase by a factor of 100 within hours, are particularly efficient at remobilizing large amounts of sediments from the cave riverbed and banks. Evidence for sediment mass flow has also been reported by speleological observations on several occasions (Bättig and Wildberger, 2007; van Gundy and White, 2009; Gonzalez-Lemos et al., 2015a,b). Open cave passages have suddenly become filled with sediments, while others have been re-opened following a flood. Occasionally, damage to well-decorated caves has resulted from water and sediments transported through passages that were otherwise dry (Wildberger et al., 2015).

The suspended sediment load depends primarily on the particle size and the shear stress associated with turbulent flow. Because of the cohesive forces characterizing clay and silt deposits, the critical shear stress needed for mobilizing fine-grained sediments is comparatively high (Herman et al., 2012). However, once in suspension, these particles may be transported over long distances and will settle out only when gravity forces exceed buoyancy forces. This may be the case during flow-recessions but also during backflooding when water becomes ponded in epiphreatic conduits. Providing they are not entirely eroded by dripwater following floods, silt and clay deposits on top of speleothems can serve as records of past flood events (Fig. 4).

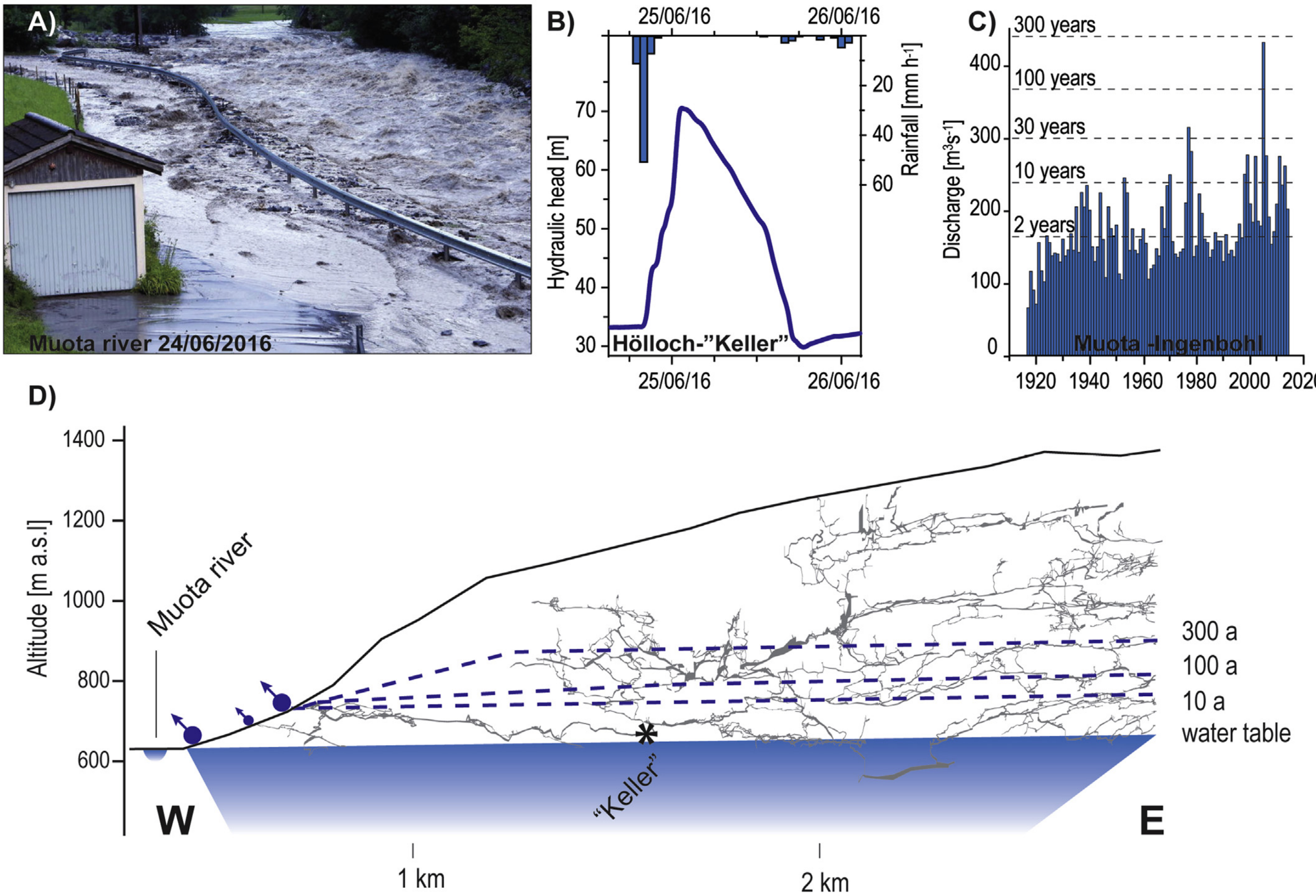

Fig. 3. Hydraulic response to precipitation events. (A) Heavy rainfall on 24/06/2016 prompted flooding of the Muota River outside Hölloch (Switzerland), the most extensive cave system in Central Europe. (B) Less than 2 h after the rainfall started, flooding was observed also in the cave network, with a hydraulic head rise of ca. 40 m monitored at the station "Keller". (C) In comparison, annual peak discharges measured since 1917 at Ingenbohl, 13 km downstream of Hölloch, suggest that this event was still ca. 8× smaller than the 300-year flood in 2005. (D) Detailed speleological observations in Hölloch cave (here on a vertical cross section) revealed that the water level rose by more than 180 m at this occasion (Bättig and Wildberger, 2007). Photo courtesy of W. Schelbert - LZ; Hölloch cave survey after AGH (2014); hydrological data for Hölloch and Muota after AGH (2016) and FOEN (2016), respectively.

2.3. Recording flood events in speleothems

Detritus within stalagmites can originate from a variety of sources including bat or bird guano (Martinez-Pillado et al., 2010), soot from cave fires (Gradzinski et al., 2007; Martinez-Pillado et al., 2010), soil particles carried through fractures by infiltrating waters (Railsback et al., 1999; Belli et al., 2017), air-born silts and clays near cave entrances (White, 1988; Railsback et al., 1999), other aerosols transported by cave ventilation (Dredge et al., 2013; Festi et al., 2016), iron oxyhydroxide mineral grains precipitated *in situ* on stalagmite surfaces (Rusanov et al., 2000; Gazquez et al., 2014) or by fine-grained sediments suspended by floodwaters (Atkinson et al., 1986). Uniquely identifying flood layers requires differentiation between these types of materials.

Perhaps the first detailed study to investigate sediment layers in speleothems was that of Railsback et al. (1999) who utilized multiple optical methods to analyze detritus accumulations in an African stalagmite. These techniques included grey-scale analysis to differentiate between matrix calcite and Fe-rich detrital layers, cathodoluminescence to distinguish the largely non-luminescent speleothem calcite from luminescent detrital layers, and mineralogical identifications and grain shape analysis (using transmitted light petrography and scanning electron microscopy) to discriminate between aeolian and fluvial grains based on micromorphological features. Detrital layers are often rust-colored, helping them to stand out from matrix calcite even macroscopically (Fig. 5), but stalagmite growth rates are typically sufficiently slow and detrital layers thin to require thin section petrography (Railsback et al., 1999; Lepley et al., 2005; Ray et al., 2005; Jaillet et al., 2006; Dasgupta et al., 2010; Zhornyak et al., 2011; Gazquez et al., 2014; Finné et al., 2014; Frappier et al., 2014; González-Lemos et al., 2015b). In some systems, however, rapid stalagmite growth rates are associated with more massive flood-derived sediment packages allowing for detailed analysis without the need for thin section petrography. Denniston et al. (2015) documented mud layers up to 10 mm thick in fast-growing (>1 mm/yr) aragonite stalagmites from the Australian tropics (Fig. 5).

Cessation of growth can also result in accumulation of detritus, creating a speleothem surface that appears similar to a flood horizon (Fig. 5) (Railsback et al., 2013). In some cases, high precision dating will reveal offsets in age above and below this layer, but dating hiatuses can be complicated by (1) open system behavior in calcite below a long-lived hiatus, (2) hiatuses so short as to lie within the errors of U-Th dates, and (3) large age uncertainties arising from detrital material associated with the hiatus. In these cases, thin section petrography can play an important role. Frisia et al. (2012) noticed that the presence of micrite, which is often associated with the microbial colonization of speleothem surfaces,

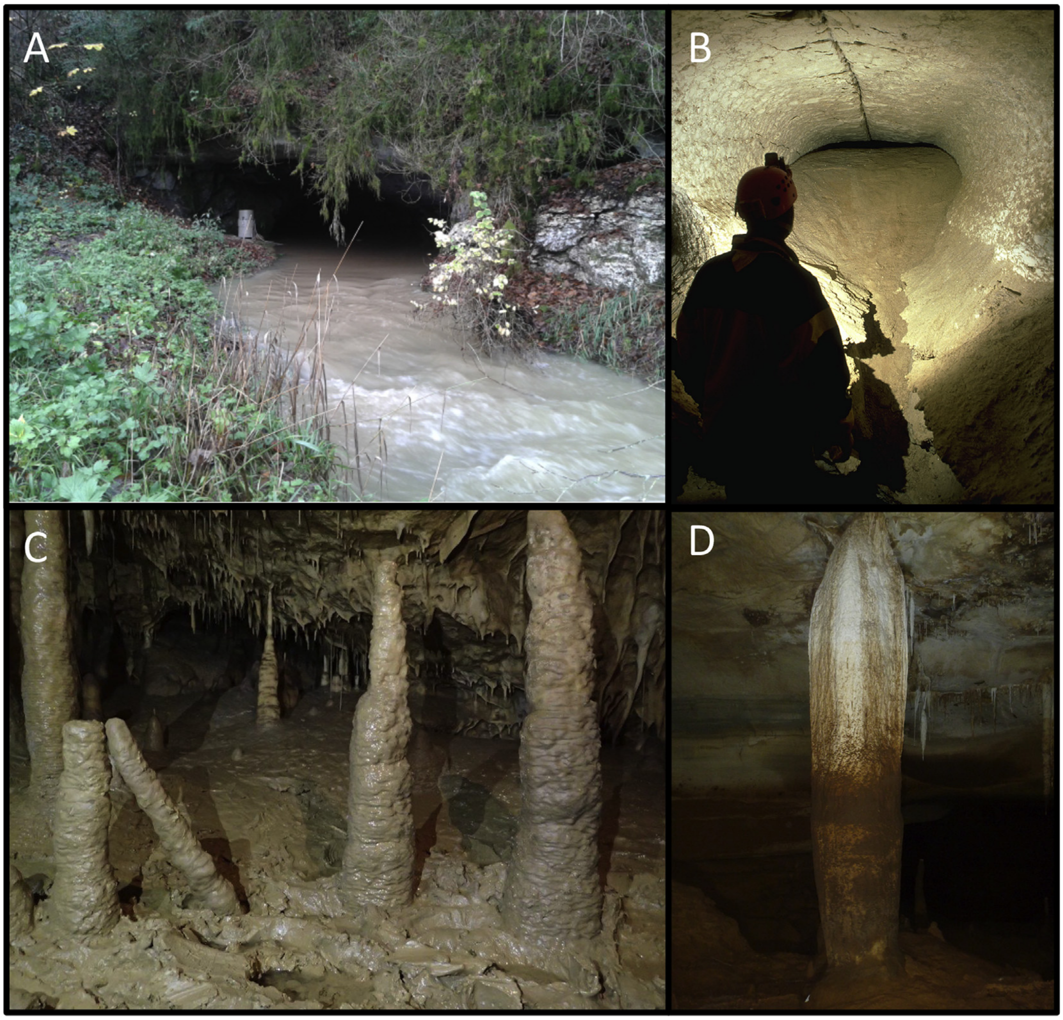

Fig. 4. (A) The Milandrine cave spring (Photo courtesy of C. Vuiellemier) and turbidity changes associated with a flood event. (B) Change in cave passage morphology due to sedimentation. Photo courtesy of R. Wenger – ISSKA. (C) and (D) Photos of sediment deposited on stalagmites after a flood (Photo courtesy of M. Luetscher) and flood stains on cave walls (Photo courtesy of R. Denniston).

may hint at prolonged periods of growth interruption. The presence of impurities can also change crystal habits and crystallographic orientation especially when the supersaturation of the dripwater is low (Frisia et al., 2000). In contrast, prolonged flooding is often associated with post-depositional dissolution processes that lead to typical mosaic calcite fabrics (Frisia, 2015). But even if the growth surface marking a hiatus is underlined by signs of dissolution, distinguishing between a prolonged growth stoppage and a flood layer is sometimes difficult. As one example, Gonzalez-Lemos et al. (2015b) noted that flood-deposited detritus was sufficiently thin and discontinuous so as to maintain calcite crystal growth across the flood horizon. In contrast, renewed calcite nucleation associated with a hiatus is typically marked by different crystal morphologies and extinction angles above versus below a detrital layer. Eventually, it is a conjunction of petrographic and mineralogical evidence that allows associating a detrital layer with flooding.

As a complement to visual identifications, geochemical analysis represents a high precision and high-resolution method for identifying even narrow detrital layers. Because they may be maintained in suspension for long periods of time, clays and other fine-grained aluminosilicates represent substantial components of the flood-derived detritus in speleothems. Finné et al. (2015) used XRF-scanning to identify flood layers based on Fe concentrations, which are characteristically high in cave sediments. Laser-ablation mass-spectrometry, synchrotron-radiation micro X-ray fluorescence, and electron microprobe analysis are additional methods for identifying peaks in Al and Si, elements with low solubilities in natural waters (Driscoll and Postek, 1996; Frisia et al., 2012), which are typically bound to colloids (Hartland et al., 2012) and often associated with clay and thus flood-born detritus (Dasgupta et al., 2010; Gonzalez-Lemos et al., 2015a) (Fig. 6). It is important to note, however, that soil-derived particles have been observed trapped within stalagmites that are argued to have traveled via fractures during extreme rainfall events, particularly during cold intervals with reduced vegetation (Belli et al., 2017).

3. Constructing cave flood events chronologies

One of the primary reasons behind the dramatic increase in speleothem studies over the past two decades involves advances in U-Th dating techniques (Drysdale et al., 2012), including refinement of the ^{234}U and ^{230}Th half-lives (Cheng et al., 2013) and enhancements in the ability to precisely measure ^{230}Th (Hoffmann, 2008). However, despite this progress, a principal stumbling block in the construction of some stalagmite chronologies is the correction for detrital ^{230}Th, the portion of radiogenic Th that is

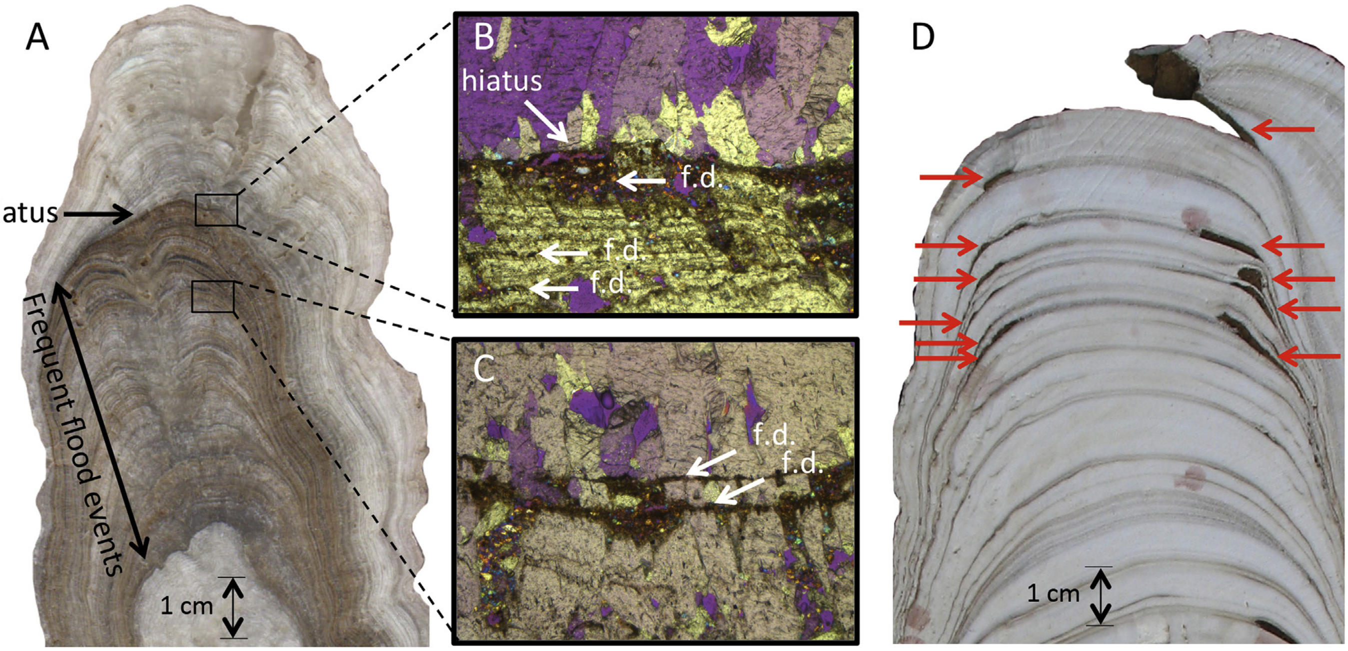

Fig. 5. Comparison of flood sediment layers at different scales. (A) Interior view of stalagmite DIB-6 from Devil's Icebox Cave, Rock Bridge Memorial State Park, central Missouri, USA. The brown area in the center of the stalagmite is characterized by numerous flood events and is capped by a hiatus. (B) Thin section photomicrograph image (crossed polars) of flood debris (f.d.) layers below growth hiatus. Note change in crystal morphology above and below the hiatus. (C) Flood debris layers maintaining consistent calcite crystal morphology. (D) Flood layers in fast-growing aragonite stalagmite from the Australian tropics. Red arrows denote sediment accumulation on growth cap margins.

incorporated into speleothem carbonate when it is precipitated. Despite the fact that the solubility of Th in cave dripwater is low, some amount of Th is transported by infiltrating fluids into the cave (Schwarcz and Latham, 1989). Correcting for this inherited ^{230}Th is typically performed through measurement of the overall ^{232}Th abundance (an extremely long-lived and non-radiogenic isotope that represents the overwhelming Th in the system) of speleothem carbonate and a constrained (or assumed) ^{230}Th/^{232}Th ratio. The inherited ^{230}Th/^{232}Th atomic ratio is typically assumed to be equal to the average value of crustal silicates (4.4×10^{-6}) and is assigned an uncertainty of ±50–100%, although values orders of magnitude higher have been documented (e.g. Hellstrom, 2006; Carolin et al., 2013; Moseley et al., 2015).

In general, speleothems with high detrital content are avoided by researchers owing to the impact of unsupported ^{230}Th on U-Th ages. While high abundances of unsupported ^{230}Th may be present in samples without visually identifiable amounts of insoluble residue (Denniston et al., 1999), a strong correlation generally exists between the amount of detritus and the ^{232}Th abundance (Asmerom et al., 2007). Thus, flood detritus, if not divided from the surrounding carbonate prior to dissolution, complicates the refinement of precise U-Th ages. And when flood events are frequent and/or speleothem growth rates are slow, it becomes increasingly difficult to avoid incorporating detritus into the material milled for U-Th dating. These issues are particularly acute in young stalagmites with low U concentrations that also contain low abundances of ^{230}Th, making the final age determination overwhelmingly reliant on the initial ^{230}Th/^{232}Th ratio (and the uncertainty assigned to it). This, in turn, complicates developing meaningful comparisons with historical climate records, a necessary step in evaluating the magnitude of precipitation events required to trigger a cave flooding.

Constraints on the initial ^{230}Th/^{232}Th ratio may be tightened through analysis of dripwater, zero-age carbonate, ^{230}Th/^{232}Th-^{234}U/^{232}Th isochrons, or by constraining it using the principle of superposition within a speleothem (Hellstrom, 2006). However, some evidence exists for multiple sources of detrital Th, each with its own ^{230}Th/^{232}Th ratio (Edwards et al., 2003; Asmerom et al., 2007), and thus dripwater or clean, modern calcite may not adequately describe the Th contribution from flood-derived sediments. The ideal scenario involves high U abundances, low detrital Th abundances, and sufficiently rapid stalagmite growth or long flood recurrence intervals to allow for isolation of stalagmite material for dating that is devoid of flood detritus. An example of such a system includes the fast growing aragonite stalagmites discussed in Denniston et al. (2015) with growth rates in excess of 1 mm/year and ^{238}U abundances between 5 and 15 μg/g. However, care must be taken to account for flood-deposited sediment when constructing stalagmite growth models using depth-age relationships. Intervals with elevated numbers or thicknesses of sediment may appear to artificially inflate growth rates between dated intervals.

Open-system behavior with respect to the uranium-series is another issue likely to bias the chronology of speleothems subject to prolonged flooding. This may have been particularly the case for alpine samples exposed to backflooding by glacial meltwater (Borsato et al., 2003; Wildberger et al., 2010). Petrographic and micro-structural observations, however, help identifying post-depositional diagenetic processes associated with undersaturated water percolating along the speleothem intercrystalline porosity (Railsback et al., 2013). This approach is mostly recommended when working with high-Mg calcite and aragonite, both prone to recrystallization (Frisia et al., 2002).

When ^{232}Th/^{234}U ratios are sufficiently high so as to preclude accurate and precise age determinations, alternative methods can, under some circumstances, be applied. Annual banding in speleothems has been identified using a variety of methods (Baker et al., 2008) including fluorescence (Baker et al., 2015), mineralogy (Railsback et al., 1994), mineral fabric (Genty and Quinif, 1996; Frisia et al., 2003), and fluid inclusion abundance (Polyak and Asmerom, 2001), as well as through seasonal cycles in trace elements (Fairchild et al., 2001) and carbon (Ridley et al., 2015) or oxygen isotopic ratios (Frappier et al., 2007). For example, annual

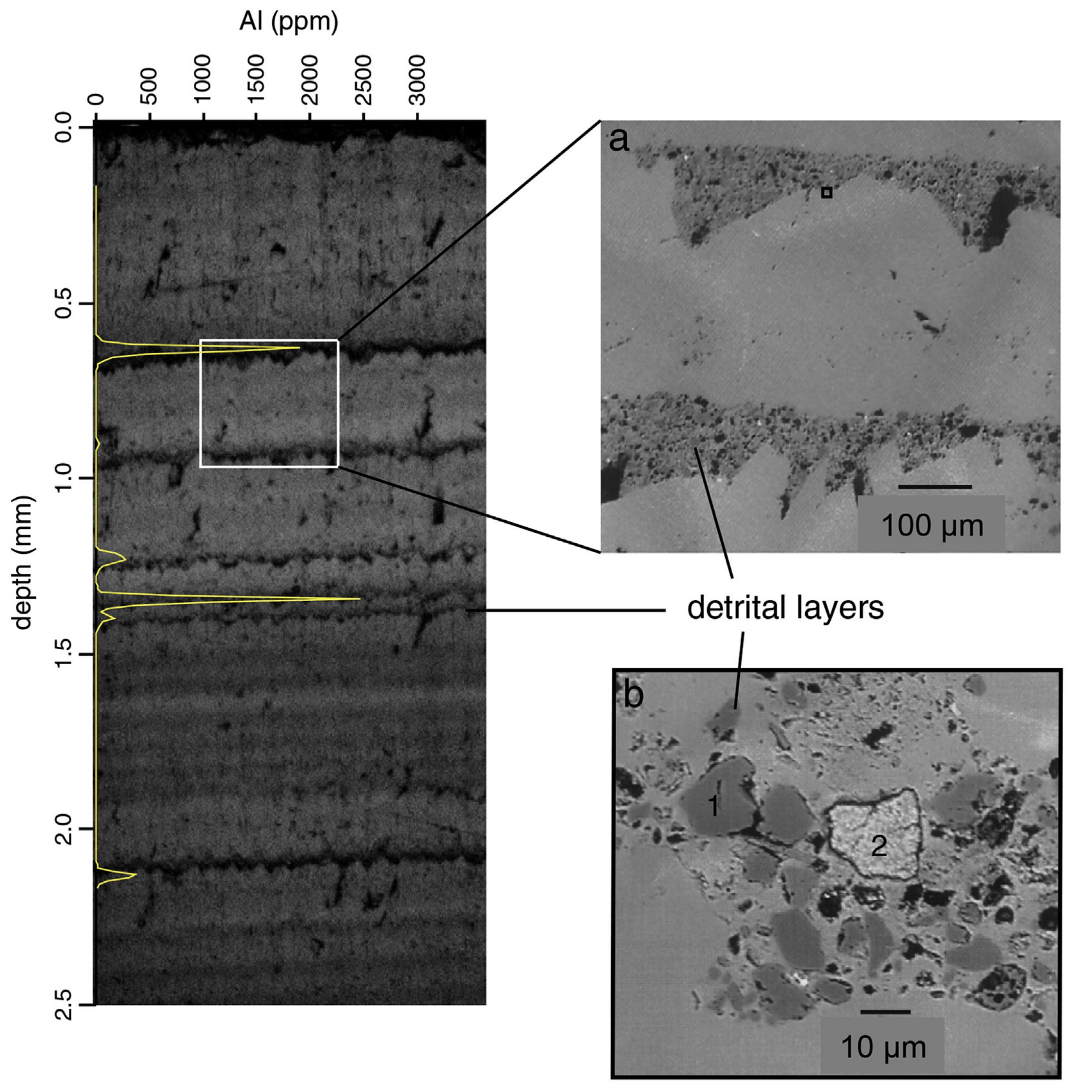

Fig. 6. (Left) Al abundances as a proxy for clay superimposed on a fluorescent banding image of a Midwestern stalagmite. Dark layers are detritus-rich layers. (Right) Insets showing enhanced scale images of quartz (1) and iron-rich phase (2) grains. From Dasgupta et al. (2010). Unlike original publication, scale bars in both righthand panels are now presented in microns. Image courtesy of EPSL.

fluorescent laminae provided additional constraints on U-Th chronologies from Midwestern (Dasgupta et al., 2010) and Mexican (Frappier et al., 2014) stalagmites (Fig. 6). Plain light-visible banding has also been used to refine age models, although interruptions in growth or deposition of false or duplicate bands have been identified (Shen et al., 2013). Radiocarbon dating of speleothem carbonate has also been utilized in speleothems with high detrital Th content, but complications with the dead carbon fractionation in cave dripwater have generally limited the utility of this approach (Lechleitner et al., 2016). The correction for dead carbon is further complicated in stalagmites containing fine-scale flood detritus composed of carbonate bedrock.

4. Reconstructing paleoflood magnitudes

The ability of individual speleothems to preserve sediment mobilized during cave flood events is subject to a variety of influences including position of the speleothem relative to flood stage, hydraulics during flood recessions, the abundance and nature of the suspended sediment, the geometry of the speleothem growth surface, and the total energy delivered to the speleothem growth surface by dripwater following flooding (Denniston et al., 2015). Thus, constructing multiple, overlapping speleothem flood time series represents the most accurate approach to reconstructing paleoflood events. The ubiquity of flowstones in many cave systems would suggest that they represent ideal candidates to replicate singular records. However, the complex growth dynamics and morphology of these speleothems is often associated with some spatial variability hindering precise correlation between individual samples (Boch and Spötl, 2011). Flowstones are also more likely to incorporate colloidal fractions and detrital sediment transported by normal water flow (e.g. Meyer et al., 2012). This issue is less likely to arise in stalagmites, however, making them potentially more reliable.

The magnitude of cave floods is best assessed via the hydraulic head rise in the karst system: the higher above the water table, the less frequently speleothems will be exposed to flooding. However, because the hydraulic response may be strongly non-linear in extensive cave networks (Jeannin, 2001), characterization of modern hydrodynamics is essential. Discharge measurements at the spring combined with water level monitoring inside the cave allow for development of a rating curve (Fig. 7) that can be

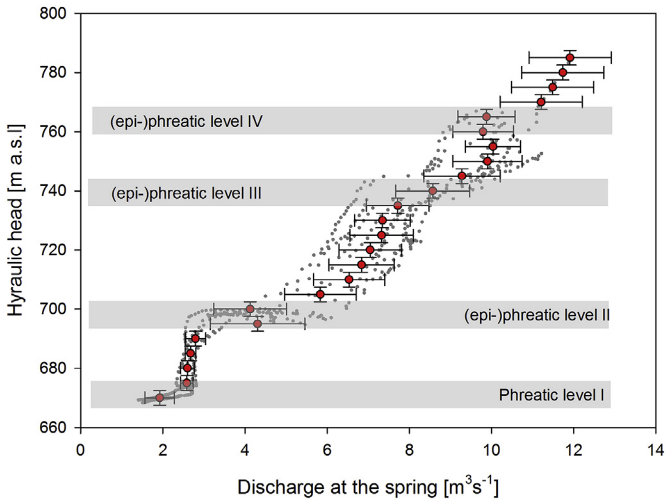

Fig. 7. Rating curve constructed from spring discharge measurements at Hölloch cave, Switzerland during flood recessions. The presence of epiphreatic conduits accounts for non-linearity effects. Hydrological data for the Schlichenden Brünnen karst spring and Hölloch after FOEN (2016) and AGH (2016), respectively.

validated against speleological observations, especially for extreme events (Bättig and Wildberger, 2007). When cave geometries are well known, these data allow for detailed modeling of the karst hydrodynamics (Jeannin, 2001) that, in turn, contribute to a better assessment of the hydrological response in the outside environment. Alternatively, flood-deposited organic detritus or stains on cave walls may provide constraints on past water levels (Cai et al., 2011; Gonzalez-Lemos et al., 2015b).

Some attempts have been made to use the nature of flood-deposited sediment as an indicator of flood magnitude. For instance, Gonzalez-Lemos et al. (2015a) assumed that only bigger floods were capable of transporting large quartz grains to an elevated level hosting stalagmites in a cave in northern Spain and, as these larger floods would regress more slowly, thicker sedimentary packages could be deposited onto stalagmite caps. Consequently, these authors distinguished between major and minor floods by assuming that major events would lead to laterally continuous detrital layers thicker than 0.1 mm while minor floods are characterized by thinner and/or discontinuous detrital layers. Petrographic analysis was supported by LA-ICP-MS methods, which mapped the spatial characteristics of detrital layers by measuring Al and Si abundances.

5. Forcings behind cave floods

Because speleothems can record discrete flood events simultaneous to other paleoenvironmental proxies at equivalent time scales, they hold the potential to provide rare insight into the drivers of extreme rainfall events, including monsoon rainfall (Ridley et al., 2015), individual tropical cyclones (Frappier et al., 2007), and Southern Oscillation Index values (Frappier et al., 2002). In the absence of cave monitoring, detailed flood layer analysis coupled with an age model based on a high density of extremely precise dates can allow calibration with the historical record. Dasgupta et al. (2010) modeled cave flood intensities by constructing a cave flood index that was then compared with paleohydrological reconstructions from a nearby peat bog. During the calibration period (1950–1988 CE), this study revealed that many, but not all, rainfall events were ascribed to flood levels above a benchmark value. Similarly, Gonzalez-Lemos et al. (2015a) tied extreme rainfall events to mud layer analysis of stalagmites from northern Spain. Results revealed recurrence intervals of 311 years for major floods (9 events in 2800 years), and of 108 years for minor floods (26 total floods), values consistent with a smaller, late Holocene (approx. 400 year old) stalagmite.

Attribution of flood activity to particular climatic phenomena represents an important next step after reconstructing flood layer frequencies. As one example, Denniston et al. (2015) developed a 2200-year-long flood reconstruction from the central Australian tropics, an area in which analysis of regional climatology reveals that the majority of the largest single and multi-day extreme rainfall events are tied to tropical cyclones. Links between extreme rainfall events, tropical cyclones, and flood layers were tested by comparing a high precision (±1 yr) U-Th dated stalagmite that grew over the 20th century with historical rainfall data from a nearby weather station. This approach was limited by the three-year window to which any mud layer could be attributed and the distance (~30 km) between the weather station and the cave site. However, a statistically robust relationship was identified between the timing of tropical cyclones and stalagmite flood layers. Lepley et al. (2005) tied changes in flood event activity over the Holocene in the central United States to changes in the El Niño-Southern Oscillation, with enhanced flooding linked to increased frequency of El Niño events and associated fall/winter precipitation in the central Mississippi Basin. In other cases, climatic controls are more broad. For example, Spötl et al. (2011) linked increased recurrences of sediment in Alpine stalagmites to prolonged backflooding during glacial periods.

6. A conceptual framework for speleothem-based paleoflood analysis

The utility of speleothems as paleoflood records is high, and this method will likely be used with increasing frequency in the future. Selecting the appropriate cave site, however, is a critical step for successful paleoflood reconstructions. General consideration at the hydrological catchment scale may help to identify locations likely to respond sensitively to hydrological recharge. In particular, long-term changes in land-use represent a critical factor not only because of the potential modification of infiltration regimes but also in terms of sediment influxes into the karst system. A sound knowledge of the hydrogeological functioning of a karst aquifer is essential, but even more, detailed speleological observations will support a scientifically robust sampling strategy. Here, we present a set of best practices to guide future studies on paleoflood reconstructions from speleothems.

6.1. Monitoring cave hydrology

Integrated analysis of climate and cave hydrology represents a critical component in the transfer of speleothem flood data to a reconstruction of extreme precipitation events, the overarching goal of most paleoflood analyses. The discharge of major karst springs is routinely monitored by national hydrographical services and provides a powerful tool for assessing the extent of cave flooding when combined with rain gauges and hydraulic measurements inside the cave system. Compensation for barometric pressure variations may be required for precise reconstructions of water levels. However, in most cases autonomous pressure probes will suffice to reconstruct the amplitude and recurrence interval of floods, although additional housing may be required in cases of larger head rise (typically >150 m).

Knowing the flow velocity in sporadically flooded cave passages is of particular interest as velocity may change as a function of hydraulic head. These results can be advantageously combined with records of turbidity changes to identify most favorable conditions for slackwater deposits in transient hydrological regimes. Such monitoring may also help to identify changes in the morphology of the cave system (e.g. associated with the opening of passages in tourist caves) or in the hydrological catchment (e.g. land use practices influencing the aquifer recharge) that could possibly impact on the speleothem record.

6.2. Analysis of samples with known growth positions

Careful selection of stalagmites is critical for identifying samples with flood layers. Overall, cave conservation issues will drive the sampling strategy and, therefore, emphasis shall be placed on already broken speleothem formations lying at or near their growth location. Preference will be given to vertical conduit sections acting as piezometers during water level rises. In the presence of sufficient head loss, these sections are more likely to show slow recessions favoring progressive sedimentation of suspended clay. Actively growing speleothems allow modern calibration with identified flood events important for assessing the impact of any recent changes in cave geometry or land surface hydrology. Because stalagmite deposition can be intermittent, preliminary dating of cores drilled from the base or other sections of a stalagmite may help to identify suitable samples prior collection (Scroxton et al., 2016). The hydrology of a speleothem-feeding drip is an important point to consider as supersaturation is necessary to ensure active calcite precipitation, and drip discharge needs to be sufficiently small to avoid complete erosion of newly deposited sediment. In most cases, visual inspection of potential candidates will provide this preliminary information. Eventually, the ideal sampling site depends much on the formulated research questions. The appropriate elevation within the cave is selected relative to modern flood regimes – too low and too many flood layers may be preserved, complicating U-Th dating; too high and too few floods are recorded, limiting the utility of flood reconstruction analysis.

6.3. Identification of flood layers

Once collected, speleothems are sectioned longitudinally along their growth axis. In order to help distinguish between primary porosity and gaps left by sediment lost during the sawing process, low-speed diamond saws should be considered for sectioning.

Visual inspection supported by grey scale analyses of high-resolution scans from polished slabs provides first identification of potential flood-layers. Thin section petrography will ultimately reveal modifications in the speleothem fabric that can be associated with the incorporation of detritus. A broadband fluorescent excitation lamp or Confocal microscope can also distinguish mud layers that contrast with speleothem calcite in their degree of luminescence.

Characterization of the detrital component is best achieved by Raman spectroscopy or, alternatively, XRD analyses on insoluble residues. In the presence of elements that are distinct of the carbonate matrix, (μ-)XRF scanning represents an efficient method for identifying flood layers (Dandurand et al., 2011). However, more sophisticated methods including laser ablation-ICP-MS, synchrotron-XRF and electron microprobe may be necessary to unambiguously determine the chemistry, and thus the origins, of detrital inclusions.

6.4. Replication

The importance of replication of stable isotope, trace element, and petrographic data among coeval speleothems has been demonstrated by a number of researchers (Dorale and Liu, 2009; Baker et al., 2015; Cheng et al., 2016). The need for replication exists also with flood records owing to a variety of potential biases inherent to individual stalagmites (Denniston et al., 2015). First, the shape of the speleothem growth surface influences its ability to preserve mud layers: broad diameter stalagmites with horizontal (rather than convex) growth surfaces are better suited for the deposition of suspended particles. However, physical abrasion of sediments following recession of floodwaters has been observed under active drips while sediments on the cap margins are preferentially preserved (Denniston et al., 2015; Gonzalez-Lemos et al., 2015a). Therefore, the plane along which a stalagmite is bisected introduces a degree of uncertainty into the mud layer analysis. Also, differences may exist between the deposition/preservation of sediment on stalagmites relative to flowstones, the material used in some paleoflood studies (Gázquez et al., 2014). It is thus advisable to section the stalagmite along two vertical planes, either parallel or at right angles to each other, in order to increase the chance of identifying sporadically preserved flood deposits. Second, thick mud deposits may form a layer of reduced strength that is subject to fracturing by later floods, perhaps removing carbonate (and flood layers) deposited over subsequent years. Third, increasingly deep floodwaters are required to submerge an active stalagmite over time. This issue is particularly acute in exceptionally fast-growing stalagmites such as tropical aragonite stalagmites where rates approaching 2 mm/yr have been reported (Denniston et al., 2015). At this rate, a few centuries of growth may extend the top of a stalagmite above the mean flood elevation, thereby producing an apparent secular decrease in flood recurrence intervals if the head rise is small (Denniston, 2016). Finally, given that restarting stalagmite deposition requires exposure of the stalagmite cap above floodwaters (along with resumption of dripwaters onto the speleothem cap), consideration must be given to possible lags between deposition of flood detritus and resumption of stalagmite growth.

For these reasons, replication of flood layer time series among coeval stalagmites is necessary to ensure an accurate accounting of flood events. Dasgupta et al. (2010) replicated flood time series using two stalagmites spanning ~650 years. Flood layers in these samples were discerned using thin section petrography (and geochemical analyses), but a high density of precise U-Th dates, coupled with fluorescent annual laminae, allowed for remarkably detailed chronology (Fig. 8). Denniston et al. (2015) documented similar values and trends in seven stalagmites, several of which overlapped in age. One of these samples was, however, characterized by higher flood recurrence intervals than two coeval stalagmites (Fig. 8). Because each of these stalagmites was broken and down when collected, their relative growth positions cannot be precisely reconstructed and compared, although it is likely that either biases in the preservation of flood detritus or the elevations of the stalagmites are responsible for this offset.

Finally, the manner in which flood time series are calculated and presented is to some degree subjective. The bimodal nature of flood layer data may complicate comparisons with other time series sets such as stable isotopes or trace elements (which vary across a spectrum of values). Dasgupta et al. (2010) formulated their comparison of two coeval stalagmites by grouping flood layer data into a variety of multi-decadal bins. Denniston et al. (2015) used a 30-year running mean. Frappier et al. (2014) and Gonzalez-Lemos et al. (2015a) neither binned nor averaged their flood layer data but instead presented them as bimodal values (flood vs. no flood) for given time intervals (Fig. 9), although Gonzalez-Lemos et al. (2015a) also differentiated between minor and major flood events based on the thickness of the mud layer accumulation. The method should be selected based on a number of factors including the type of any data (e.g., stable isotopic ratios) that the flood layer time series is being compared against, the precision of the age model, and the nature of the research questions.

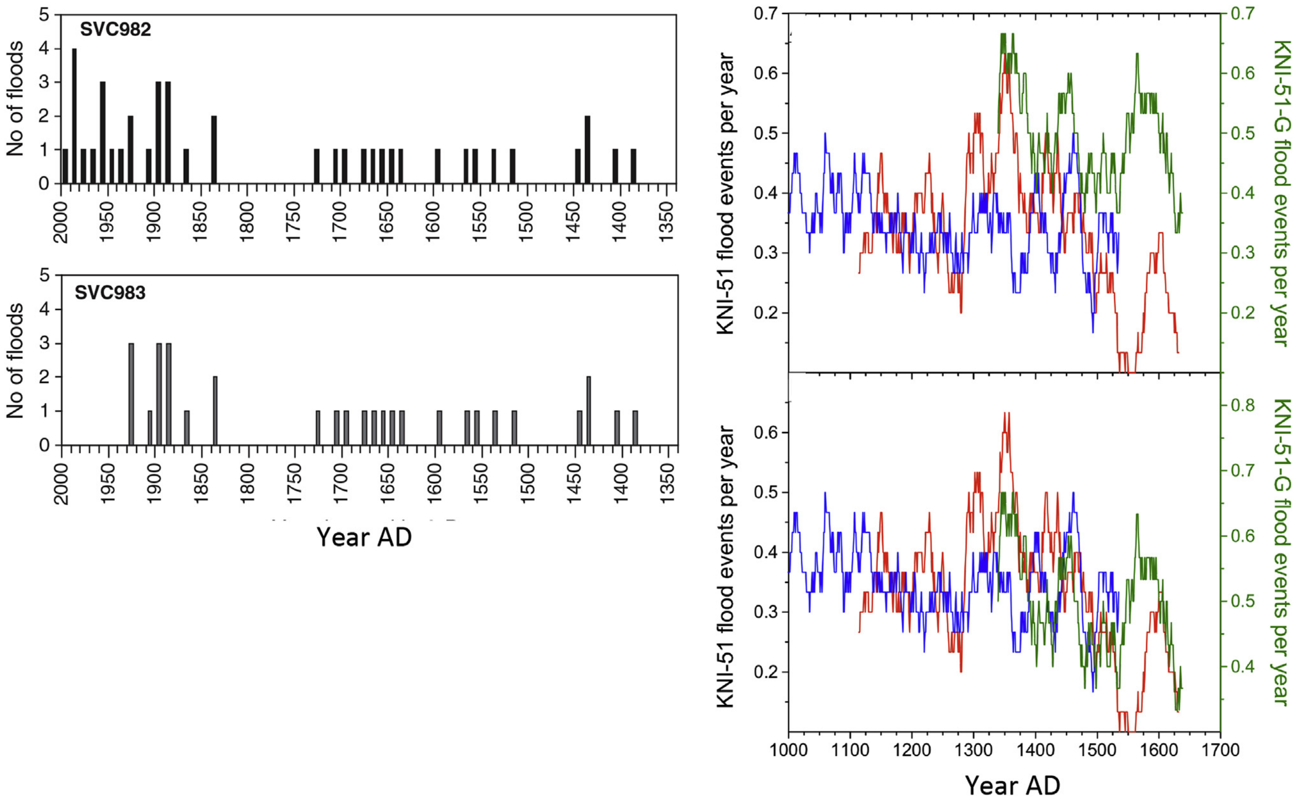

Fig. 8. (Left) Flood events reconstructed using geochemical and petrographic analysis of two stalagmites (top: SVC982; bottom: SVC983) from a Midwestern cave. Events are apportioned into 10-year bins. Note high degree of consistency between the two samples (from Dasgupta et al., 2010). Image used by permission of EPSL. (Right) Top: Cave flood time series from three coeval stalagmites (each shown as a different color) from a tropical Australian cave. Data presented as 30 year running means. While each of the three samples contains a similar structure, stalagmite KNI-51-G stalagmite (shown in green) is characterized by flood recurrence rates that exceed those of the other two stalagmites (shown in red and blue). All samples were broken and down when collected. One possible explanation for this discrepancy involves KNI-51-G having grown at a lower elevation in the cave and thus at a level that experienced more shorter recurrence interval floods. Bottom: KNI-51-G flood time series plotted on separate (righthand) y-axis with adjusted scale showing similar trends among all three stalagmites. From Denniston et al. (2015). Image used by permission of the Proceedings of the United States National Academy of Sciences.

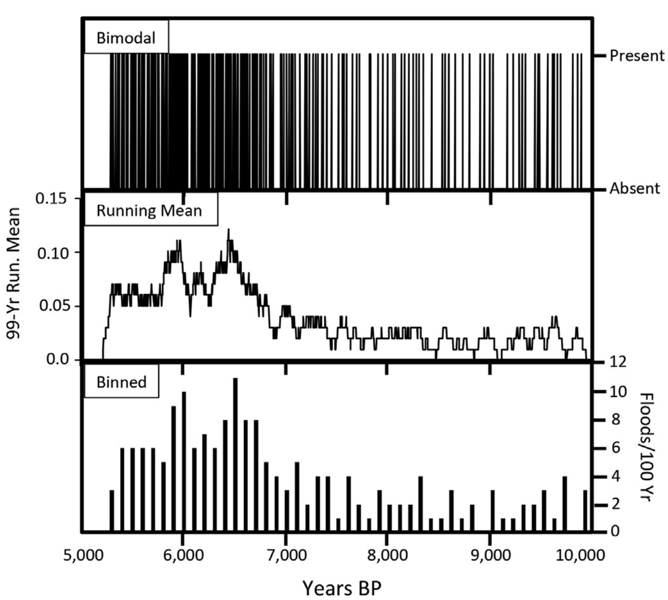

Fig. 9. Methods for visual representation of stalagmite flood layer time series. Data from stalagmite BES-117, Cape Range, Western Australia (An, 2014) based on ages obtained using growth models derived from multiple U/Th dates (Denniston et al., 2013). (Top Panel) Mud layer occurrences plotted using the presence/absence method. Mud layers were identified using reflected light microscopy on a polished but not thin sectioned portion of the sample. (Middle Panel) Same mud layer data as in second panel but presented as 99-year running mean; values shown as flood events/year. (Bottom Panel) Same as third panel but mud layers are fractionated into 100-year-long bins.

7. Summary

Adequately defining the context of historical flooding requires reconstruction of flood events over centuries or millennia using natural archives. Detrital layers in speleothems represent an important but little exploited paleoflood proxy that can be independently dated with U-Th methods and/or laminae counts. Flood layers in speleothems are identified through a number of petrographic and geochemical methods, ideally at annual resolution. Their replication from multiple speleothem records is required, however, to assess any biases in deposition or preservation. Ideally, the interpretation of robust palaeoflood time-series will be supported by multi-year cave monitoring regimens, which also help define samples well positioned to record moderate to low frequency events. Because stalagmite-based paleoflood reconstructions have not been thoroughly tested, attempts should be made to calibrate them against observational weather data and to integrate them with more traditional paleoflood records. Therefore, we encourage researchers working on “classical” speleothem records to share information about detrital layers. These results can form important contributions to the new but rapidly expanding paleoflood databases such as the one constructed by the PAGES Floods Working Group.

We suggest the following methodologies be considered for speleothem-based paleoflood reconstructions:

- Detailed documentation of the cave network and its geomorphological evolution is required to put the samples into context;

- Efforts should be made to identify any recent changes in land use, cave sedimentation, etc. that could have impacted cave hydrology;
- A multi-year cave monitoring program should be used to quantify thresholds for flooding prior to sample selection;
- Active stalagmites may provide useful information to calibrate historical flood activity against instrumental records of precipitation;
- For cave conservation purposes, broken and down stalagmites are preferred but only if their original growth position can be definitively identified;
- In order to allow for replication, multiple stalagmites should be analyzed from the same area and elevation of the cave;
- Consideration should be made regarding the growth position of stalagmites relative to the annual flood horizon. Stalagmites deposited close to the water level may suffer from excess detritus that complicates U-Th dating;
- As calcite deposition may have been discontinuous, it is useful to obtain U-Th dates on material cored from the base of selected stalagmites in order to increase the likelihood of collecting a suitable sample;
- In order to account for biases in preservation of flood detritus across a stalagmite's growth surface, stalagmites should be examined in multiple areas across the growth surface (both macroscopically and in thin section) and in multiple planes oriented parallel to the primary growth axis, either using parallel cuts to produce a slab or by making cuts at right angles to one other;
- Unless stalagmite growth rates are extremely high and detrital layers abnormally thick, the identification of flood layers should involve a combination of thin section petrography and chemical analysis. Metals with low solubilities in surface waters (e.g., Al) may help to identify detrital layers, but care must be taken to consider also particles transported from the land surface to the cave via fracture flow.
- U-Th dating of detritus-rich stalagmites should involve a multi-method approach to determine initial $^{230}Th/^{232}Th$ ratios. Suitable methods include isochrons, dating of zero-age calcite, stratigraphic constraints, and/or dripwater analysis. The possibility of multiple sources of Th, each with its own distinct isotopic ratio, should be considered and, wherever possible, tested, in order to obtain the most precise and accurate dates possible. Relying solely on lamina counting without U-Th dating is problematic and may not produce accurate chronologies.
- Flood time series may be presented as bimodal data or as running means. Selection of the degree of time averaging should be based, in part, on the errors on the U-Th dates, the ambiguity associated with identifying individual flood layers, and the research questions being addressed;
- Following publication, flood data should be made available to the public, including through the PAGES Floods Working Group database.

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