Late Quaternary Sea-level History: a Speleothem Perspective

Bogdan P. Onac[1], Angel Ginés[2,3], Joaquín Ginés[2,3], Joan J. Fornós[2] & Jeffrey A. Dorale[4]

[1] *Department of Geology, University of South Florida, Tampa, USA.*
[2] *Departament de Ciències de la Terra, Universitat de les Illes Balears, Palma, Spain.*
[3] *Federació Balear d'Espeleologia, Palma, Spain.*
[4] *Department of Geoscience, University of Iowa, Trowbridge Hall, Iowa, USA.*

1. Background

Among the many impacts associated with impending climate change, those related to rapid sea-level rise are of immediate concern to society (Alley *et al*., 2005). Today, over one third of the world's population lives along low-lying coastal areas, and for these areas, future sea-level rise (even small amounts) will generate substantial societal and economic impacts (Milne *et al*., 2009). How quickly sea level rises is among the more pressing concerns, and for the coming centuries, this prediction basically remains an unresolved issue.

In the broadest sense, global sea level is an important integrative measure of the climate state of the Earth. Sea level variations involve the transfer of water between ice sheets and oceans (Figure 1, inset). The history of sea-level change contains valuable information on the possible magnitudes and rates of this transfer. Thus one approach for assessing future vulnerability to rapid sea level rise is to improve our understanding of the forcing mechanisms and responses of past events.

Sea-level history also indicates considerable spatio-temporal variations that contain information not only about climate but a number of solid-Earth processes. This is because relative sea-level change at a given site reflects not only changes in ice volume variations (eustatic variations), but also the response of the Earth to changes in surface loading in the form of surface deformation and geoid changes, or "glacial isostatic adjustment" (GIA) (Lambeck & Chappell, 2001; Mitrovica & Milne, 2002). Eustatic sea-level reconstructions require accurate models of GIA, which in turn require prescriptions of ice sheet history (including distribution, volume, and duration of former ice loads) and Earth's rheological properties (e.g., lithospheric and mantle heterogeneities, viscosity). Recent studies have pointed out that even when all of the available relative sea level data for the last 6000 years are

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incorporated in two distinct global surface load models, it is impossible to discern between homogeneous and heterogeneous GIA models (Spada *et al.*, 2006). Therefore, Milne (2009) concluded that most models are affected by errors that depend on the accuracy of each model prediction for a given site.

Because uncertainties of some type are inherent not just to models but to all of the methodologies and settings of past sea level reconstructions, there is a continued need for additional, independent sources of sea-level data that might provide unique insight and cross-checks to the existing framework of past eustatic changes in sea level. When we consider the pressing concern posed by rising sea levels to our coastal communities, there is a particular urgency for improving our understanding of past, present, and future sea-level variations.

2. Sea level reconstruction: methods and limitations

Evidence of past sea levels comes in many forms, each with certain strengths and weaknesses (Siddall *et al.*, 2007). The method that allows for a *continuous* sea-level reconstruction is based on the interpretation of $\delta^{18}O$ variations recorded by

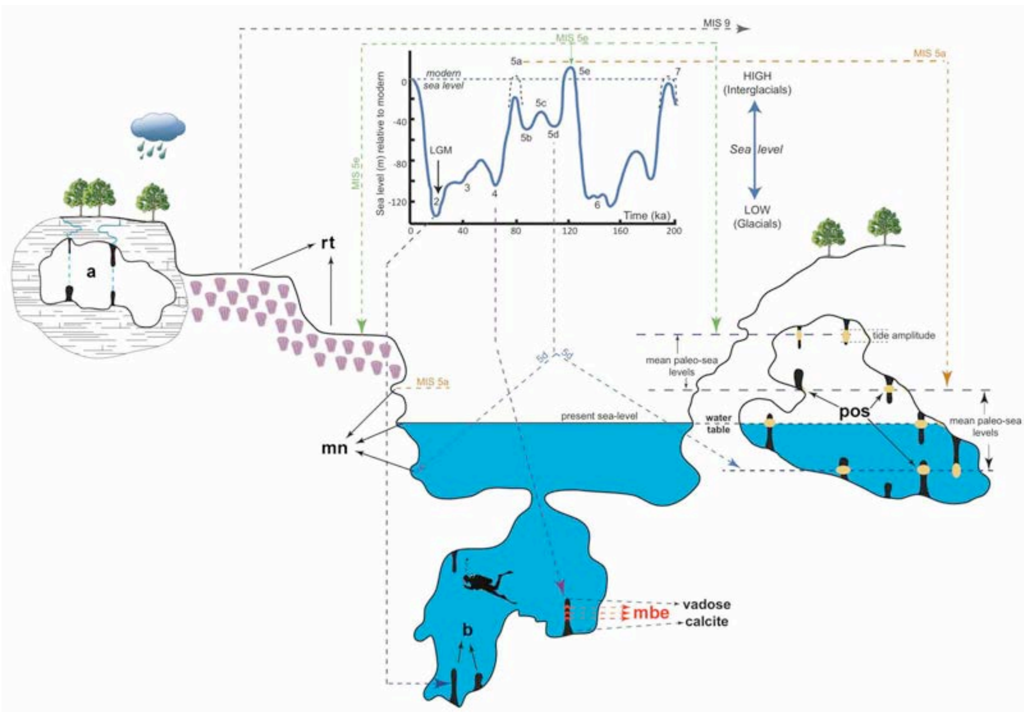

Figure 1. Composite diagram showing how speleothems form in vadose caves (a) along with various proxies used to reconstruct past sea-level stands: submerged speleothems (b); submerged speleothems with marine biogenic encrustations (mbe); phreatic overgrowths on speleothems (pos); marine notches (mn); reef terraces (rt). The glacial/interglacial sea level history (adapted from Shackleton & Opdyke, 1973 and Imbrie *et al.*, 1984) is shown in inset.

calcareous foraminifera in deep marine sediments (Shackleton, 2000; Lea *et al.*, 2002). The lighter ^{16}O isotope is preferentially evaporated from oceans and accumulates in ice sheets. As ice volume increases, seawater is progressively enriched in ^{18}O (Dansgaard *et al.*, 1984). In addition to the ocean isotopic composition, ocean water temperature is also a determining factor in the $\delta^{18}O$ value of foraminiferal calcite. These two unknown variables (ice volume and temperature) cannot be resolved explicitly without making assumptions about ice $\delta^{18}O$ and the ocean temperature structure (Shackleton, 1987), and therefore some error associated with these assumptions is inherent to this particular method of sea-level reconstruction. Furthermore, while the continuous character of deep sea $\delta^{18}O$ variations is a clear strength, the dating is not absolute, and relies on assumptions of the Milankovitch Theory of Earth's orbital forcing on global ice volume changes (Milankovitch, 1941; Shackleton & Opdyke, 1973; Hays *et al.*, 1976).

The $\delta^{18}O$ values of deep sea sediment foraminifera carbonates is an *indirect* measure of past sea level (Shackleton & Opdyke, 1973; Imbrie *et al.*, 1984; Figure 1 inset). A fundamentally different approach focuses on *direct* sea level estimates provided by markers that document the former position of sea level via either erosion (e.g., wave cut notches) or deposition (e.g., sand barriers, coral reefs, and speleothems; Figure 1). Unfortunately, most direct sea level techniques provide *discontinuous* records of sea level change.

To date, the primary evidence of a close linkage between insolation forcing, ice sheet growth, ice sheet melting, and sea level change comes from the combined application of deep-sea $\delta^{18}O$, U/Th dated fossil coral reefs, marine terraces, archaeological observations, and U/Th dated submerged speleothems (Figure 1; Broecker & van Donk, 1970; Richards *et al.*, 1994; Hays *et al.* 1976; Hearty, 1998; Shackleton, 2000; Gallup *et al.*, 2002; Edwards *et al.*, 2003; Zazo *et al.*, 2003; Antonioli *et al.*, 2004; Alley *et al.*, 2005; Thompson & Goldstein, 2005; Dutton *et al.*, 2009a; Siddall *et al.*, 2009; Anzidei *et al.*, 2011; Muhs *et al.*, 2011; Thompson *et al.*, 2011). Thus, it seems clear that a combined approach utilizing the strengths and weaknesses of the various techniques is probably the best overall approach to accurately reconstructing past sea level.

Remarkable efforts were put into U/Th dating of fossil coral reefs, which capture the position of sea level directly and with absolute dating (Figure 1 rt). These are significant strengths, and along with the widespread nature of reefs throughout the warm regions of the world, explain why reefs have played a dominant role in Quaternary eustatic sea-level reconstructions. Yet a number of factors commonly hinder ultra-precise determination of both the height and the age of the sea level stand using fossil reefs (and reef records are highly discontinuous). Some of these factors include: 1) uncertainties of water depth above the reef (each coral species grows within a range of water depths of several meters to tens of meters; Ludwig *et al.*, 1996), 2) questions concerning the provenance of corals (i.e., in-situ or reworked; Kench *et al.*, 2009), 3) complications arising from the reef type, i.e., keep-up, catch-up, give-up (Neumann & MacIntyre, 1985), 4) lags between the timing of sea level change and the timing of reef growth (shown to be on the order of thousands of years in some cases; Hearty *et al.*, 2007), and 5) uncertainties on age estimates due to coral diagenesis (Henderson *et al.*, 1993; Edwards *et al.*, 2003). In addition to these, reef reconstructions from tectonically active areas also contain significant uncertainties related to the rates and consistency of tectonic movements.

3. Cave deposits

3.1. Speleothem: Definition and Growth

The term *speleothem* (*cave deposit* in Greek) was first coined by Moore (1952) to define secondary minerals precipitated from chemical solutions or by solidification of a fluid **after** the cave formed. The word speleothem refers to the mode of occurrence (i.e., stalactite, stalagmite, flowstone, cave raft, etc.) of a mineral and not to its composition (Hill & Forti, 1997).

In most karst regions, carbonic acid is responsible for limestone dissolution (with very few exceptions; Palmer, 2007), and results from mixing of meteoric water with atmospheric and especially soil carbon dioxide. The acidified waters trickle down along fractures, fissures, or bedding planes and dissolve limestone bedrock. Speleothems are precipitated from such bicarbonate-rich percolating waters when these waters become supersaturated with respect to calcite or aragonite upon entering a cave passage. The driving force behind speleothem growth is degassing of CO_2 in the cave atmosphere, a process that is triggered by the difference between the partial pressure of CO_2 in the cave ($10^{-2.5}$-$10^{-3.5}$ atm.) and soil ($10^{-1.5}$ atm.). This implies that speleothems like stalagmites and flowstone can only form when caves are air-filled. However, even if caves remain air-filled, certain climate and hydrologic conditions (prolong drought, permafrost/ice cover, percolation of unsaturated water, river flooding, etc.) may prevent speleothem deposition. During such periods, hiatuses (periods of no speleothem deposition) are inferred from the petrography of the speleothems by the occurrence of corrosion surfaces and/or very sharp changes in color due to the presence of thin (mm to sub-mm) brownish detrital-rich laminae.

Because deposition of speleothems is closely link to the Earth's hydrosphere, biosphere, and atmosphere, they prove to be ideal paleoclimate and paleoenvironmental archives (Richards & Dorale, 2003; Lachniet, 2009; Fairchild & Baker, 2012). To date, a large and growing speleothem science literature exists, with a strong bias toward various qualitative and quantitative Quaternary climate change reconstructions. Studies utilizing speleothems to document earthquake activity, landscape evolution, biomineralization, or ***sea-level changes*** are comparably fewer. Here we focus on the application of speleothems to sea level change.

Proxies for cave-based sea-level reconstructions include biological, mineralogical, and sometimes, archeological records. While biological and archeological archives rarely provide a direct and precise measure of past sea-level elevation and timing, they can provide indirect qualitative constraints on these indices. Speleothems used for sea-level reconstruction are of three types: 1) ordinary stalagmites and flowstones that form sub-aerially (Figure 1a) and become drowned by rising sea level (Figure 1b and 2) submerged speleothems coated by biogenic encrustations (Figure 1 mbe), and

3) phreatic overgrowths on speleothems (Figure 1 pos; Ginés *et al.*, 1981), presented in detail in the previous chapter of this book.

The following discussion is intended to clarify some confusion regarding those vadose speleothems that contain carbonate overgrowths. There is a clear distinction between marine biogenic encrustations (see subchapter 3.2.2 below) and phreatic overgrowths on speleothems (see chapter 3 in this volume and subchapter 3.3 below). Keeping both terms under a general heading of "*marine overgrowths on speleothems*" (Ford & Williams, 2007) is misleading because biogenic encrustations are indeed marine in origin, whereas the POS are only forming in brackish water at and a few centimeters below present or a former sea level being exposed to minor tidal oscillations that are reflected in a particular morphology (Figure 2).

Figure 2.
POS in Cova des Pas de Vallgornera. The thickest part of the encrustation corresponds to the mean sea level, whereas the gradually decreasing up-ward and downward overgrowth reflects the tidal fluctuation.

Furthermore, POS should not be misidentified with the shelfstone, which is common in vadose caves as flat deposits attached to cave walls or speleothems in confined passages where the percolation water forms pools (Hill & Forti, 1997). These speleothems do record the past or present pool level via a number of distinct shelfstone horizons (mm to cm one below each other) but morphologically are very different from the POS (Figure 3a and 3b). We therefore suggest that when discussing these unique speleothem-based proxies for reconstructing sea levels to make a clear difference between the ***marine biogenic encrustations*** (Figure 4) and the ***phreatic overgrowths on speleothems***.

3.2. Submerged speleothems

In an air-filled cave formed on a carbonate island, a variety of speleothems would commonly being precipitated as discussed above (Figure 1a). If sea-level rises and completely floods the cave, the growth of speleothem ceases. While submerged, speleothems may be preserved intact, or, a number of chemical and biological processes may affect the external and internal structure of the submerged speleothems, providing great visual templates for detecting growth hiatuses, which in turn help in deciphering sea-level changes. These features (sometimes very complex in nature at both macro- and microscopic scale) are highlighted by the 1) presence of corroded layers caused by dissolution at the halocline (Li *et al.*, 1989; Surić *et al.*, 2009), 2) existence of biogenic encrustations (Antonioli *et al.*, 2001; Figure 4), or 3) deposition of seawater precipitated minerals (e.g., halite, gypsum; Surić *et al.*, 2009).

The timing of initiation and cessation of speleothems growth is relatively easy to resolve applying U/Th measurements on carbonate material extracted from the

Figure 3. A (left): Multiple shelfstone levels in Lechuguilla Cave (Photo: A. Palmer). B (right): Present-day phreatic overgrowths on speleothems in Cova des Pas de Vallgornera, Mallorca.

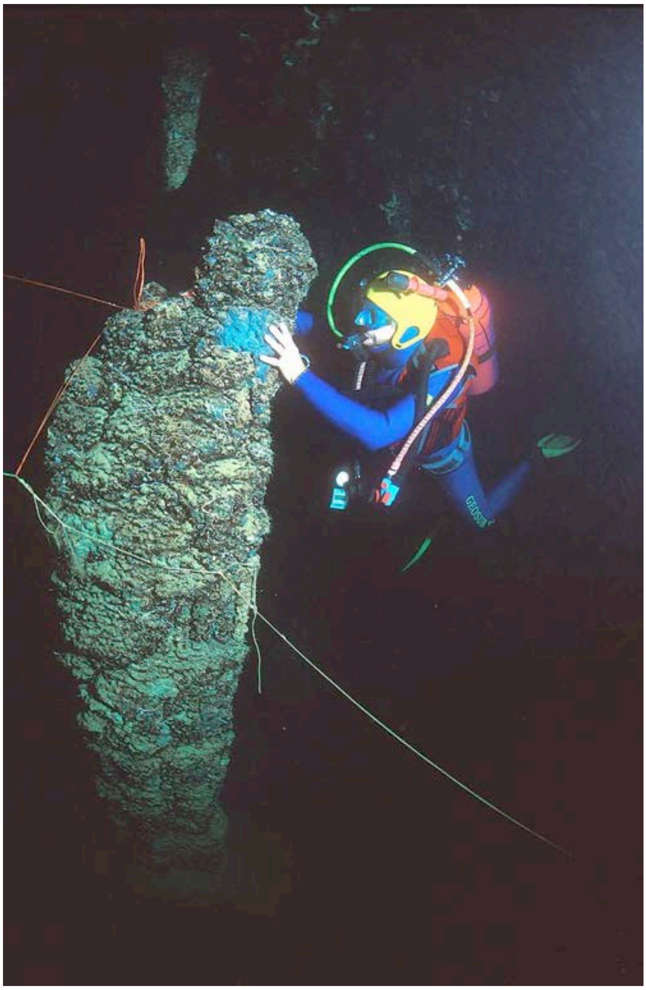

Figure 4.
Submerged speleothem showing marine biogenic encrustations (Argentarola Cave, Italy; Photo: F. Antonioli).

bottom and top of a speleothem. The obtained ages will roughly indicate when thecave was air-filled and then invaded by seawater (Li *et al.*, 1989; Richards *et al.*, 1994). Nevertheless, the precise elevation of the sea level stand will remain unknown unless additional information (e.g., marine organisms that colonizes very narrow habitats below sea surface) becomes available. After a preliminary study published by Spalding & Mathews (1972) on a submerged stalagmite from Ben's Hole (Grand Bahama Island), the idea of using such speleothems in reconstructing Quaternary sea-levels made headlines in journals such as Science and Nature (Gascoyne *et al.*, 1979; Harmon *et al.*, 1981; Li *et al.*, 1989; Richards *et al.*, 1994).

3.2.1. Submerged speleothems with or without growth hiatuses

The development of thermal ionization mass-spectrometry in measuring U-series isotopes (Edwards *et al.*, 1987) constituted a huge step forward from the α-spectrometric methods of the day. Employing this new technique and using samples of at least one order of magnitude smaller, Li *et al.* (1989) and Richards *et al.* (1994)

deciphered the changes in sea level over 280 ka and pinpointed the maximum sea level for the Last Glacial period in the Bahamas, respectively.

If corroded hiatuses exist along a given speleothem, their ages need to be constrained by U/Th technique, below and above them (Li *et al.*, 1989; Lundberg & Ford, 1994; Hodge *et al.*, 2008; Surić *et al.*, 2009). However, we have to keep in mind that even in a coastal cave setting, this particular type of hiatus (if not accompanied by burrows, biogenic encrustations, seawater precipitated minerals, etc.) is not always caused by sea-level fluctuation. Changes in hydrology and hydrochemistry above the cave may also result in either a temporary or permanent cessation of speleothems deposition. If one can safely document the hiatus is sea-level related, the carbonate layer underneath the hiatus indicates the minimum age for the timing of the rise in sea level that caused cessation of speleothem deposition by drowning. The growth of speleothems may resume at any time after the sea-level falls. Therefore, dating the newest carbonate layer immediately above each of these hiatuses provides a first-order estimation of when the cave became air-filled again, however it may take decades or millennia before specific climatic, land surface, and cave hydrology conditions allow the speleothems to commence their growth. Thus, such carbonate accumulations provide a relatively imprecise age constraint on the initiation of growth after sea level regression. In summary, while U/Th dating works very well to constrain the ages of these hiatuses, the method, really only documents the "moment" when a particular elevation within the cave became flooded or air-filled, not precisely when and where the water level was actually located throughout the bulk of the rise-fall cycle (Lundberg & Ford, 1994; Richards *et al.*, 1994; Surić *et al.*, 2009). Particularly in the case of sea level drop, the "moment" may be significantly compromised by unknown lags between the timing of sub-aerial exposure and the initiation of speleothem deposition. Therefore, caution is needed in interpreting the relationship between speleothem growth and sea-level history (Smart *et al.*, 1998; Dutton *et al.*, 2009a).

3.2.2. Submerged speleothems coated by/containing biogenic encrustations (± burrows)

Submerged speleothems that contain biogenic overgrowth crusts (e.g., serpulid worm secreted calcite) and/or preserve fragments of various boring organism shells refine the basic submerged speleothem technique. The first workers to explore this field was a team led by Gascoyne who documented a MIS 6 sea level low stand (at least 42 m below present level) between 160 and 139 ka based on five stalagmites recovered from a blue hole just east of Andros Island (Gascoyne *et al.*, 1979). Later, Alessio *et al.* (1992, 1996), generated a sea-level curve over the past 40 ka by radiocarbon dating marine biogenic carbonates precipitated on submerged speleothems from the central Tyrrhenian region of Italy. Antonioli & Oliverio (1996) recovered a stalagmite from a depth of -48 m in the Scaletta-Punta Iacco cave system (Capo Palinuro, Italy) that not only was bored by the date shell *Lithophaga litophaga*, but at several locations the shells were actually sealed-in by the subsequently formed calcite. Considered an early colonizer of bare limestone (mainly in the low tide zone, but never below -20 m), this species indicates the time of marine transgression and hence inundation and submergence of the cave. Precise radiocarbon or U-series dating on such shells may provide supplementary data to help reconstruct local sea-level changes.

Figure 5.
Speleothem ASI from Argentarola Cave (Italy). For details see the text (Photo: F. Antonioli).

To date, the most detailed studies on stalagmites that show sequences of sub-aerial precipitated calcite (i.e., times of low sea-level stands) and marine biogenic overgrowths (serpulid colonies; corresponding to periods of highstands) were carried out by Bard *et al.* (2002) and Antonioli *et al.* (2004). Their work is based on a number of speleothems recovered from Argentarola Cave (Italy) from depths between -3.5 and -21.7 m below present sea-level. Particularly important was stalagmite ASI (Figure 5), which displayed five marine and four terrestrial calcite layers that allowed the authors to generate the history of sea-level changes over the past 215-ka. From the very same cave, using two additional submerged speleothems, Dutton *et al.* (2009a) documented three sea-level highstands between 245 and 190 ka (MIS 7).

Similar studies (some combining submerged speleothems with archeological markers) have been undertaken on the western Mediterranean (Ginés *et al.*, 1975), Tyrrhenian Sea (Antonioli *et al.*, 2001), Ionian Sea (Scicchitano *et al.*, 2008; Dutton *et al.*, 2009a, b), and on the eastern seaboard of the Adriatic Sea (Surić *et al.*, 2005, 2009).

Apart from their implications in reconstructing sea-level oscillations over various parts of the Quaternary, the submerged speleothems also provided tectonic uplift rates for many regions within the Mediterranean basin. Last but not least, the compilation of a large submerged speleothem-based sea-level dataset helps inform the glacio-hydro-isostatic models.

One advantage of using submerged stalagmites is that they allow estimation of past low sea level stands (lower than today) in both interglacial and glacial periods. Such information is critical especially in tectonically stable regions (Bahamas, part of the Mediterranean Basin) where evidence (marine and/or reef terraces) is not exposed above sea level the way it is in uplifting coastline regions (e.g., Huon, Barbados, Haiti).

3.3. Phreatic Overgrowths on Speleothems (POS)

Because this topic is abundantly discussed in the previous chapter of this book, only a brief presentation is given here. The coastal caves of Mallorca provide an extraordinary setting for capturing past sea-level changes. Along its eastern and southern coast, the interaction between freshwater and seawater produces a geochemical environment that allows caves and speleothems to develop in a unique manner (Mylroie & Carew, 1990; Ginés, 1995) when compared to caves formed in more common inland settings (Palmer, 2007). Most of these caves are highly decorated with vadose speleothems that formed in early Quaternary time when the caves were air-filled chambers. Throughout the Middle and Late Pleistocene, the caves were repeatedly flooded by glacio-eustatic sea level oscillations. The water level of each flooding event left a clear mark as a distinct encrustation of calcite or aragonite over existing speleothems and along cave walls (Figure 1 pos). Experienced cave divers also noticed the presence of unusual bulky speleothems at different depths within most of the flooded caves along Mallorca's coastlines. Thus far, several well-defined carbonate overgrowth horizons above and below the present-day sea level (corresponding to older sea-level high and low stands) have been recognized (Figure 1). These ancient encrusted speleothems are considered ideal sea-level indicators in terms of both age and elevation.

Similar encrustations form at present in a low-amplitude, tide-controlled microenvironment, at or a few centimeters below and above the water table where CO_2 escapes the brackish water causing precipitation of calcite and/or aragonite (Figure 5; Tuccimei *et al.*, 2010). All caves hosting these encrusted speleothems are within a short horizontal distance of the coast; thus, the water table of the caves is, and was in the past, coincident with sea level. The very narrow environment in which the encrustations form coincides with the "*mineral sea-level*". Hence the vertical accuracy achieved is better than 10 cm and their respective time of formation can be determined by U/Th dating, with unprecedented resolution and time control, over the past two glacial/interglacial cycles.

Speleothems that possess these types of carbonate overgrowths (or similar) are widespread, with most of the investigated sites being located in Mallorca (Ginés & Ginés, 1995; Vesica *et al.*, 2000; Fornós *et al.*, 2002; Dorale *et al.*, 2010; Tuccimei *et al.*, 2006, 2010, 2011) and to a lesser extent in Sardinia (Tuccimei *et al.*, 2007), Bermuda

(Harmon *et al.*, 1978), Nansei islands, Japan (Pacific Ocean; Urushibara-Yoshino, 2003), and Christmas Island, Australia (Indian Ocean; Grimes, 2001).

Particular types of POS are those that on either one occasion or repeatedly were exposed to the meteoric-marine mixing zone; these are excellent indicators of paleoclimate and sea-level changes (Harmon *et al.*, 1978; Csoma *et al.*, 2006). Geochemical and petrographical studies on such carbonates have shown that the alternation of vadose and phreatic precipitates mirrors changes from meteoric-vadose to meteoric-marine mixing zone environments. Specifically, during glacial stages when sea-level was below the present one, vadose conditions prevailed. The most common carbonate mineral precipitated during this phase was calcite (columnar, prismatic, or bladed). Throughout interglacial stages when caves were partly flooded, new carbonate material coated the vadose support at the water-air interface. Both calcite and aragonite (acicular, bladed, and prismatic) were deposited from the brackish water pooling in the cave. Isotopic and fluid inclusion salinity analyses allowed Csoma *et al.* (2006) to suggest that although both minerals are associated with sea-level high stands, calcite precipitated during periods of more meteoric recharge, whereas aragonite formed under conditions of lower rainfall. Therefore, studying the mineralogy and geochemistry of vadose and phreatic speleothems could provide local climatic insight tied to past sea-level stands. A better understanding of calcite and aragonite precipitation in the freshwater/seawater mixing zone (i.e., controlling factors such are CO_2 degassing, salinity, CO_3^{2-} supply, saturation index, etc.) is crucial if these speleothems are to be used in either paleoclimate or sea-level reconstructions.

The advantages of using POS for reconstructing sea level are straightforward and powerful: within a single cavity one can document several sea level stands and provide a test of the tectonic stability of the area by comparing their elevation against well-known markers, such is MIS 5e. Furthermore, the past sea level high stands are well preserved in POS as the cave environment protects them from processes that disrupt or remove other terrestrial archives.

4. Conclusions

Compared to any of the methods discussed above, the phreatic overgrowth mechanism arguably provides a more precise and less ambiguous indicator of the timing and the absolute elevation of the sea level position, as illustrated in the previous chapter of this book by Ginés *et al.* (2012).

Presently, most of the sea-level fluctuations encoded in cave-based records are from the northern hemisphere and cover MIS 7 through 1. Littoral caves at low- and mid-latitudes offer a means of addressing the temporal and spatial sea-level data gaps in other proxies. Investigations in the North Atlantic and Mediterranean Basin show that cave-based proxy records provide an opportunity to independently date sea-level changes without using the deep sea isotope record and associated orbital tuning techniques. These studies are important tools in the documentation of rapid sea-level events that may have occurred in response to large hemispheric temperature variations, and to better quantify the rate of sea-level change at various Terminations and within interglacial or glacial stages.

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