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Last Interglacial (*sensu lato*, ~130 to 75 ka) sea level history from cave deposits: a global standardized database

Oana A. Dumitru[1], Victor J. Polyak[2], Yemane Asmerom[2], Bogdan P. Onac[3]

[1]Biology and Paleo Environment Department, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA
[2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA
[3]School of Geosciences, University of South Florida, 4202 E. Fowler Ave., NES 107, Tampa, FL 33620, USA

Correspondence to: Oana A. Dumitru (odumitru@ldeo.columbia.edu)

Abstract. Cave deposits are powerful archives for reconstructing past sea levels as they are generally protected from weathering and erosion by their location and can be dated with U-series methods. Two main categories of cave deposits are recognized as sea level indicators: phreatic overgrowth on speleothems (POS) and submerged vadose speleothems (SVS). POS have the great advantage that they precipitate on preexisting vadose supports at a brackish water level equivalent to sea level when air-filled chambers of coastal caves are flooded by rising sea. SVS are also useful, but sea level is inferred indirectly as periods of growth provide constraints on maximum sea level positions, whereas growth hiatuses, sometimes difficult to observe, may indicate times when cave passages are submerged by sea high stands, hence they record minimum sea level elevations.

Here we describe a compilation that summarizes the current knowledge of MIS 5 (*sensu lato*) sea level captured by cave deposits. We used the framework of the World Atlas of Last Interglacial Shorelines (WALIS), a comprehensive sea level database, to provide a standardized format in order to facilitate scientific research on MIS 5 sea level. The discussion is MIS 5e-centered, but records that capture MIS 5c and 5a are also included. We present the data from 59 cave deposits (26 sea-level index points and 33 limiting points) in coastal caves located in eight different locations, and we include the spatial coverage, the samples used and their accuracy as indicators of sea level, the isotopic characteristics used to generate the U-Th chronologies, and their scientific relevance to understand past sea-level changes. The paper also emphasizes how some of these indicators are useful not only for the information they offer about the eustatic sea level, but more importantly: i) those from tectonically stable areas provide information on Earth deformation and regional ice sheet histories, thus refining the glacial isostatic adjustments models and ii) those from active regions can constrain regional tectonic uplift rates. The standardized sea-level database presented here is the first of its kind derived from cave deposits and contains all the information needed to assess former paleo relative sea level and the chronological constraints associated with them. The database is available open-access at http://doi.org/10.5281/zenodo.4313861 (Dumitru et al., 2020).

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1 Introduction

Understanding sea level changes during the last interglacial (MIS 5e; *sensu stricto* 130–116 kyr) is key to assess the behavior of ice sheets in a warmer world, hence its importance to accurately predict the future sea level rise due to ongoing anthropogenic climate change. Samples and sample sites that produce MIS 5e sea level records are often better preserved compared to earlier interglacial periods and thus, sea level evolution during this time interval is especially informative (Capron et al., 2019), and MIS 5e is considered an analog for the Holocene. Yet to date, the precise timing, duration, and amplitude of MIS 5e sea level are still being debated. The main limiting factor is finding a sea level indicator that can robustly constrain both water depth and age. Fossil corals can be dated to relatively high precision but have meter scale uncertainties in the reconstructed sea level. Other indicators such as erosional notches pinpoint sea level, but lack age control. For this reason, there is a growing demand in exploring additional sea level indicators that can complement the information derived from fossil corals, while simultaneously having robust chronology.

Relevant sea-level markers such as coral reefs (Thompson et al., 2011), flank margin caves (Mylroie et al., 2020), tidal notches (Pirazzoli and Evelpidou, 2013), and cave deposits (Richards et al., 1994; Onac et al., 2012) are unique to coastal karst environments (Van Hengstum et al., 2015). Over the past decade, there has been a growing interest in the cave deposits that represent sea, which include: phreatic overgrowths on speleothems (POS; indicative of the position of sea level still stands) and submerged vadose speleothems (SVS; suggesting maximum elevations of sea level position). A very large number of speleothem records have been reported and a comprehensive compilation by the Speleothem Isotopes Synthesis and Analysis working group was used for multiple climate reconstructions and model evaluations (Atsawawaranunt et al., 2018; Comas-Bru et al., 2020). However, the majority of these studies are mainly directed towards paleoclimate reconstructions and only a handful focused on documenting sea level changes as recorded by these deposits. The idea of using speleothems in reconstructing Quaternary sea-level changes dates back more than four decades (Ginés and Ginés, 1974; Gayscone, 1979; Harmon et al., 1981). Relative to corals, an advantage of employing speleothems as sea level markers is that the dense cave calcite is less susceptible to alteration. An additional benefit is that karst caves provide an excellent and sheltered environment in which these deposits are well preserved and protected for long periods of time against processes that disrupt or destroy other terrestrial archives.

1.1 The relationship between POS/SVS deposition and sea level changes

Phreatic overgrowths on speleothems. POS form when sea water mixes with meteoric water inside caves that are located in the close proximity to the coastline (within 300 m). The preexisting vadose speleothems become partly submerged in the resulting brackish water. The POS develop on cave walls or on speleothems only when in contact with the fluctuating water table (Ginés et al., 2012). Because the caves hosting POS are proximal to the coastline, the hydraulic gradient between them and the sea is insignificant, thus, the brackish water table in these caves is, and was in the past, coincident with sea level. As long as sea level remains at the same elevation, carbonate precipitation occurs within the tidal range at the air-water interface (Vesica et al., 2000; Fornós et al., 2002; Dorale et al., 2010; Polyak et al., 2018). Therefore, the presence of POS horizons at different elevations precisely marks the positions of paleo-water tables and consequently their associated sea level position (Fig 1c). Given the precipitation mechanism, POS arguably provide the most precise and less ambiguous indicator of the timing and the absolute elevation of the sea level position. This type of cave deposit has only been identified in a few places worldwide: Mallorca (Ginés and Ginés, 1974; Vesica et al., 2000; Tuccimei et al., 2007; Dorale et al., 2010; Polyak et al., 2018; Dumitru et al., 2019), Sardinia (Tuccimei et al., 2012), Nansei islands, Japan (Pacific Ocean; Urushibara-Yoshino, 2003), Christmas Island, Australia (Indian Ocean; Grimes, 2001), and Mexico (Jenson, 2018). Similar deposits have been recently dated from Santa Catalina Cave in Cuba (De Waele et al., 2017; 2018), and while they appear to be a type of POS, they typically are of different morphologies, such as mushroom caps and bench-like encrustations similar to cave shelfstones (called balconies) in the uppermost level of that cave (Fig. 1d). Earlier investigations of these POS suggested that their formation is highly dependent on microbial activity and a fluctuating water level (Bontognali et al., 2016).

Submerged vadose speleothems. Deposits such as stalactites, stalagmites, and coralloids, form sub-aerially and their chronology indicates a time when sea level was lower than their elevation. For vadose speleothems that are subject to sea level submergence, missing growth layers that represent no speleothem deposition (hiatuses) can be correlated with a period when sea level rose and inundated the cave causing speleothem growth to cease. In the case of sea level submergence, the carbonate layer below a hiatus indicates the minimum age when the speleothem became submerged by sea-level rise. Hence, they have a ‘dipstick’ character, “switching off“ when sea-levels are above their elevation and “on” when sea level falls below them (Fig. 1b). Thus, submerged speleothems record past sea-level fluctuations by roughly indicating when the cave was air-filled or invaded by seawater (Richards et al., 1994; Moseley et al., 2013). Once the sea level falls again, if conditions are suitable, the speleothem may resume its deposition. Dating the carbonate layer immediately above each of these hiatuses provides an estimation of when the cave became air-filled again. Nevertheless, in most cases this is a very rough estimate since it may take decades or even millennia before cave conditions allow speleothems to resume their precipitation. Thus, such carbonate accumulations provide precise age constrain on the initiation of growth, but may not tell exactly when sea level dropped. Important to note also is that a prolonged pause in speleothem growth is not always caused by sea level rise; changes in hydrology and hydrochemistry above the cave, for example, undersaturation of drip water or cessation of dripping (drought or blockage of drainage path), can also lead to interruption of speleothem deposition (Onac et al., 2012). Hence, while these hiatuses can be chronologically well constrained, the vadose speleothems can only document the “moment” when a particular part of 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 (Richards et al., 1994; Surić et al., 2009). Therefore, it can be difficult interpreting the relationship between vadose speleothems growth and sea-level history. The submerged speleothem indicators can be refined by dating alternating continental and marine biogenic overgrowths (serpulid colonies) if they exist

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and are well preserved (Antonioli et al., 2004; Dutton et al., 2009), but since none of them captured the MIS 5 sea level stand, they are not discussed in this paper.

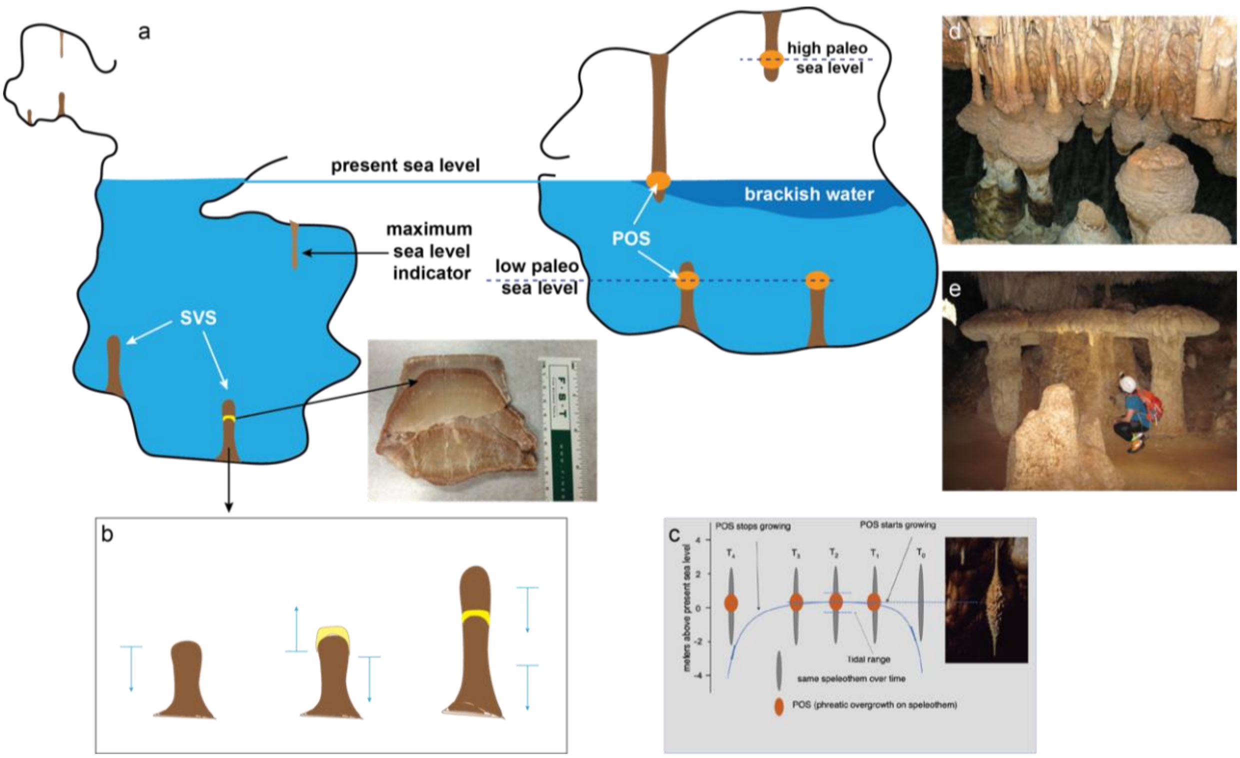

Figure 1. a) Composite diagram showing how submerged vadose speleothems (on the left) and phreatic overgrowths on speleothems (on the right) in littoral caves work as sea level indicators. b) and c) Conceptual models showing how SVS and POS form. d) POS in Cala Varques Cave, Mallorca Island. e) Mushrooms-shaped POS in Santa Catalina Cave, Cuba. All photographs by B. P. Onac.

1.2 Existing MIS 5e sea level databases and context of our work

Extensive reviews of MIS 5e sea-level indicators (coral reef and marine terraces, shore platforms, beach deposits and ridges, tidal notches, and sea caves) at global scale have been compiled by Kopp et al. (2009), Dutton and Lambeck, (2012), Pedoja et al. (2014), and Hibbert et al. (2016). A step forward was taken by Rovere et al. (2016a) who set the basis for a standardized approach to MIS 5e paleo sea-level reconstructions and interpreted the indicators in terms of the entire geological or sedimentary facies, rather than considering each of them separately. Standardized sea level databases allow for regional to global comparisons of records from disparate locations. In turn, this provides a means to disentangle spatial

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patterns and rates of sea-level change at different timescales. These curated sets of data will ultimately enhance our understanding of the mechanisms driving sea-level fluctuations, thus improving both physical models and statistical reconstructions (Khan et al., 2019).

Notwithstanding the relevance of cave deposits as sea level indicators, they have received very little attention in the existing compilations, if any at all. Currently, a dedicated cave deposits database is not available to the sea level community. In this context, the present dataset paper aims to compile existing results on cave deposits-derived sea level during the last interglacial and make them more accessible to paleoclimatology and oceanography community, with the ultimate goal to facilitate research on MIS 5 sea level. This work gathers data from previously published studies, each of which describes the samples analyzed, the isotopic characteristics used to generate the chronology, and the scientific relevance for interpreting past sea-level changes. Section 2 presents the data, including the criteria for the inclusion of each record such as spatial coverage, the elevation measurements and their uncertainties, and the U-Th methods for their absolute chronology. Section 3 discusses the interpretation of these records and highlights the valuable information they provide for eustatic sea level, but also the inputs they offer for glacial isostatic adjustment models and regional tectonic activity.

2 Data description

The data presented here is part of the World Atlas of Last Interglacial Shorelines (WALIS, https://warmcoasts.eu/world-atlas.html), a sea-level database interface developed under the framework of the European Research Council Starting Grant "WARMCOASTS" (ERC-StG-802414), in collaboration with PALSEA (PALeo constraints on SEA level; a PAGES-INQUA working group). WALIS provides a new standardized database and aims to be the most comprehensive compilation of globally distributed (new and old) data on MIS 5 sea-level indicators. The interface allows a large range of data and metadata on relative sea level indicators and associated ages to be inserted into a mySQL database. An export tool allows downloading the data inserted by the logged user as a multi-sheet xls file. This archive is available open-access as Dumitru et al. (2020; http://doi.org/10.5281/zenodo.4313861). We summarize below the major features of the records that comprise the database in metadata fields which enable easy reuse of the time-series data. In order to ensure high quality data intended for scientific reuse, only results published in peer-reviewed literature were considered.

2.1 Criteria for records inclusion. Cave deposits used as sea level indicators have been reported from several places around the world, however, in this data paper we only present the results that capture sea level during the complete last interglacial (MIS 5; *sensu lato*, 130–75 ka). The discussion is mostly centered around MIS 5e, but also includes results on the sea level position during MIS 5c (~106–93 ka) or/and 5a (~84–78 ka; Surić et al., 2009, Dorale et al., 2010; Wainer et al., 2017). A number of POS older or younger than MIS 5 have been published from caves in Mallorca (Vesica et al., 2000; Dumitru et al., 2019; in rev.), Japan (Miklavič et al., 2018) and Mexico (Jenson, 2018), but they are not included in this paper. Similarly, SVS (some of which at much lower elevations than the ones presented here) have been identified in several submerged caves

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in the Bahamas, but their ages are far too old (Richards et al., 1994; Richards, 1995; Smart et al., 2008) or young (Spalding and Mathews, 1972; Beck et al., 2001; Hoffmann et al., 2010; Arienzo et al., 2015; 2017) to be directly relevant for MIS 5 sea level reconstruction. This database includes a total of 59 cave deposits (26 POS + 33 SVS) of varying quality for which 203 U-Th ages exist. Worth noting is that 51 out of these ages are outside the MIS 5 range, and while they are not included in the discussion of this paper, they are entered in the database for completeness.

Table 1. Sites included in data product. Location, caves name, type of cave deposits, and the corresponding references.

Location	Cave name	Type of cave deposits	Reference
	Cova de Cala Varques A		Dorale et al., 2010; Polyak et al., 2018
	Cova de Cala Varques B		
	Cova del Dimoni		
	Cova de Cala Falcó		
	Cova des Pas de Vallgornera		
Mallorca	Cova Genovesa	POS	Polyak et al., 2018
	Cova de s'Ònix		
	Coves del Pirata		
	Cova des Serral		
	Coves del Drac		
	Cova de sa Tortuga		
Sardinia	Grotta di Nettuno	POS, SVS	Tuccimei et al., 2007
Cuba	Santa Catalina Cave	POS	De Waele et al., 2017; 2018
	Government Quarry Cave		
	Bierman Quarry Cave		Harmon et al., 1978; 1981
Bermuda	Crystal Cave	SVS	
	Wilkinson Quarry Cave		Wainer et al., 2017
Yucatan Peninsula	Not mentioned	SVS	Moseley et al., 2013
Krk Island, Croatia	U Vode Pit	SVS	Surić et al., 2009
Andros Island, Bahamas	Blue Hole in South Bight	SVS	Gascoyne et al., 1979
Grand Bahama, Bahamas	Lucayan Caverns	SVS	Lundberg and Ford, 1994 Richards et al., 1994

2.2 Spatial coverage. Phreatic carbonate overgrowths on speleothems dating to MIS 5 are found in caves along the coasts of Mallorca (Vesica et al., 2000; Fornós et al., 2002; Dorale et al., 2010; Tuccimei et al., 2012; Polyak et al., 2018), northern coast of Cuba (De Waele et al., 2017; 2018), and to a lesser extent in Sardinia (Tuccimei et al., 2007). Submerged vadose speleothems were investigated from Bermuda (Harmon et al., 1978; 1981; Wainer et al 2017), Bahamas (Gayscone, 1979;

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155 Lundberg and Ford, 1994; Richards et al., 1994), Yucatan Peninsula (Moseley et al., 2013), Croatia (Surić et al., 2009), and Sardinia (Tuccimei et al., 2007). Except for the SVS from Yucatan Peninsula reported by Moseley et al. (2013) and from Bermuda (Wainer et al., 2017), studies do not report the exact cave location from where samples were collected. Hence, the latitude and longitude for the other indicators were determined using Google Earth. The geographical distribution shows all sites are located in the Northern Hemisphere within 20 and 45 ° latitude N (Fig. 2).

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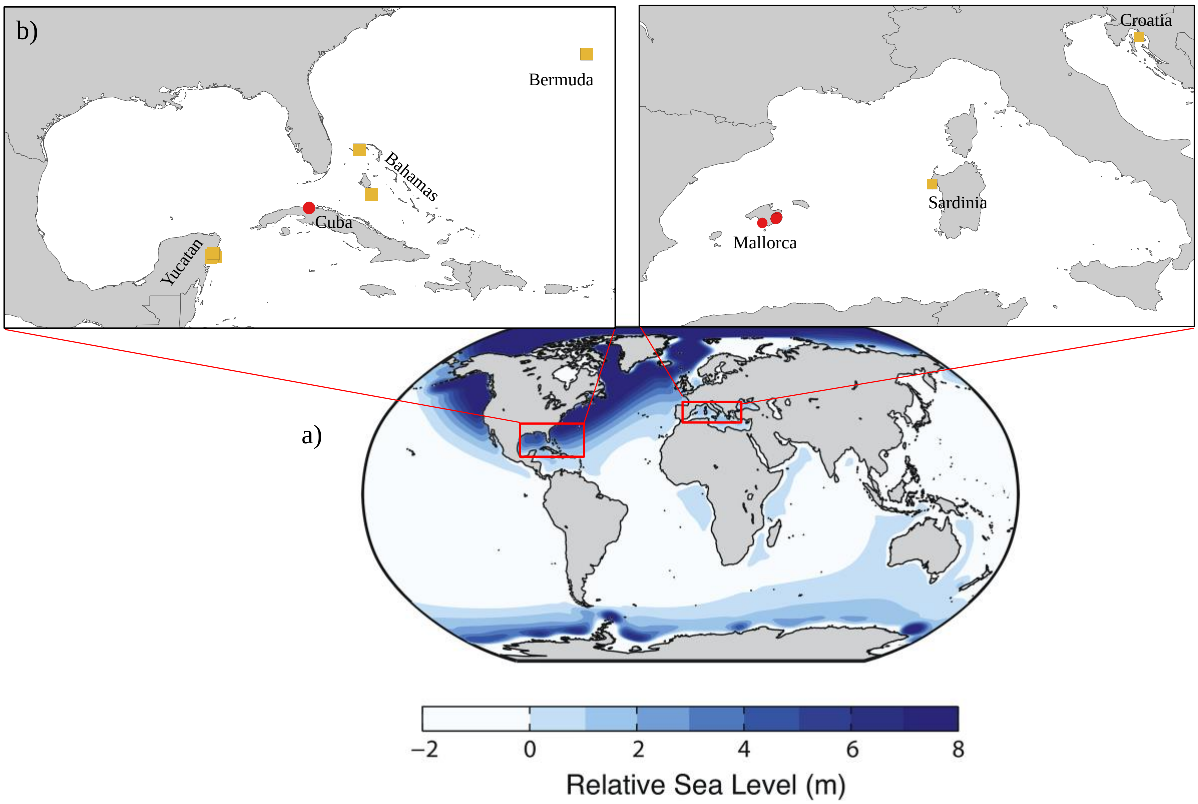

Figure 2. a) Global map showing the predicted RSL near the end (119 ka) of the modelled MIS 5e (see figure 2 of paper: https://doi.org/10.1016/j.quascirev.2017.06.013, Dendy et al. (2017)) to highlight the potential of the samples' sites to record the behaviour of the forebulge during ice-sheet loading and unloading. b) Sites where POS were documented and sampled are
165 **indicated by red circles and where SVS were sampled are indicated by the yellow squares.**

2.3 Elevation measurements and their uncertainties. The sample elevation is the vertical distance between the indicator and a vertical datum (i.e., a 'zero' reference frame, representing modern mean sea level) and is a fundamental property measured in the field. Several tools with different uncertainties have been used to measure the elevation of the cave deposits: barometric altimeter (± 0.1 m; Moseley et al., 2013), metered tape or rod (± 0.5 m; Harmon et al., 1978), inclinometer (±
170 0.05 m; Dorale et al., 2010). The uncertainties of Mallorcan POS elevation, even though some of the samples are collected

from the same cave, vary depending on the instrument used (e.g., ± 0.1 m in Tuccimei et al. (2007) and Polyak et al. (2018); ± 0.05 m in Dorale et al. (2010)). The POS belt from Cuba occur within 0.4 m, more or less corresponding to the average tidal range measured in the city of Matanzas (< 25 km from the cave site). In some cases, information regarding elevation measurements and their uncertainties are not reported because the papers are not strictly sea level studies, but indirectly provide sea level information, or that precise measurements are not so relevant because the uncertainties related to local tectonics are much larger (Surić et al., 2009).

2.4 Samples. In the WALIS database, each sample is assigned a *Sample ID* that is composed of the first two letters of the main author' last name, followed by the year of publication and a number code given to each speleothem individually (Table 2). The *Analysis ID* complements the Sample ID by including a distinct number for when two or more ages are reported for the same speleothem. Finally, the *Reported ID* is the sample code offered by the authors in the original paper.

Table 2. Example to show how samples are coded in the WALIS database.

Sample ID	Analysis ID	Reported ID
DO10-001	DO10-001-001	CCVA-1
DO10-002	DO10-002-001	CCVA-2
DO10-003	DO10-003-001	CDD-1
DO10-004	DO10-004-001	CDD-2
DO10-005	DO10-005-001	CCVB
DO10-006	DO10-006-001	CCF-1
DO10-007	DO10-007-001	CCF-2
DO10-008	DO10-008-001	CPV-1
DO10-009	DO10-009-001	CPV-2
DO10-009	DO10-009-002	CPV-B8
DO10-010	DO10-010-001	CPV-B6
DO10-010	DO10-010-002	CPV-B9

A variety of different cave deposits are reported to have recorded past sea levels. Stalagmites grow from the floor upward in caves, stalactites (dripstones) hang from the ceilings, and flowstones are sheetlike deposits that form on walls and floors. The POS analyzed by Dorale et al. (2010) and Polyak et al. (2018) have different size, shape, and morphology, depending on the vadose support and on the extent of their immersion in the brackish pool (Ginés et al., 2012). They are generally small enough to collect in-situ, and larger POS can be cored in place. The Cuban POS investigated by De Waele et al. (2017; 2018) in Santa Catalina Cave are rare composite mushroom-shaped speleothems with caps reaching diameters > 1 m and balconies present along the walls. In this case, the authors analyzed samples from mushroom stalk or cap, balcony, and other

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associated speleothems. Most of the vadose speleothems investigated as sea-level indicators are stalagmites, but results from flowstones and stalactites have been reported as well. Since SVS can only accrete when above sea level, they should be sampled when in growth position (not broken) to robustly indicate relative sea level below their elevation (Harmon et al., 1978; Moseley et al., 2013).

2.5 Sample mineralogy. The mineralogy affects the reliability of individual dates (i.e., samples from recrystallized calcite could have been subjected to uranium loss, which is an important factor that impacts U-Th ages (Lachniet et al., 2012; Bajo et al., 2016)). Given that speleothems are less likely subjected to alteration and diagenesis when compared with organic precipitation of corals, an elaborate sample pre-screening is not critical. Thus, only some of the studies compiled here report the mineral assemblage of the samples by X-ray diffraction (Surić et al., 2009; De Waele et al., 2018). However, we cannot exclude the possibility that screening was performed, but not reported. To allow recognition of diagenetic fabrics and to make the best selection of samples for successful dating, De Waele et al. (2017), for example, complemented the screening method with petrographic investigations (thin sections) and imaging using scanning electron microscopy. While not always necessary, including information on mineral assemblage, and diagenetic and crystalline descriptions are useful.

2.6 U-series methods. Accurate geochronology is essential to these studies. Dutton et al. (2017) provide a template of what should be reported for U-series data for geochronology and timescale assessment in the earth sciences that is very applicable to speleothem sea-level work as well. As was found for coral-based sea-level work, the speleothem U-series results reported often contain insufficient information to completely assess the data collected. This ultimately limits the value of the data since often times it is not possible to assess or recalculate a date using the information provided. While it may not be practical to recalculate dates from older data, what is more important is to have data and methods so that decisions can be made to request or recollect samples of interest. We include in the database the U-series method used (alpha, thermal ionization mass-spectrometry (TIMS), multi-collector inductively coupled plasma mass spectrometry (MC-ICP MS)), the decay constants used, and the measured isotopic characteristics of the sample, all of which are required to recalculate U-Th ages and to assess their robustness. Generally, analyses of standards with the samples enhance the reliability of results reported. Advances in technologies since the mid 1980s have notably increased the analytical precision and lowered age uncertainties, thereby allowing for dating of progressively smaller sample-sizes, which permits better sampling along single growth layers (thicker samples will integrate material of different ages). The development of TIMS and then MC-ICP MS in measuring U-series isotopes constituted a major step forward from the alpha spectrometric method. The majority of the records compiled here were dated using MC-ICP MS, and only few used or reported alpha spectrometry (Harmon et al., 1978; 1981; Gascoyne et al., 1979; Vesica et al., 2000; Tuccimei et al., 2007) or TIMS (Lundberg and Ford, 1994; Tuccimei et al., 2007; Dorale et al., 2010).

We also included in the database the initial $^{230}Th/^{232}Th$ ratios and the decay constants, when these are provided by the authors. The correction for the effect of detrital thorium concentration incorporated at the time of speleothem deposition is

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extremely important for age calculation and is sensitive in samples that contain very little uranium or an abundance of detrital thorium. Hellstrom (2006) suggested that a ratio of $^{230}Th/^{232}Th$ larger than 300 can be considered as an indicator of clean samples not requiring correction for detrital thorium. The decay constants for ^{234}U and ^{230}Th used to calculate the U-Th ages have been updated and improved over time (Jaffey et al., 1971; Edwards et al., 1987; Cheng et al., 2000; 2013). Most recent papers used the ^{234}U and ^{230}Th decay constants of Cheng et al. (2000; 2013), and in some papers, especially in the older ones, these values are not provided. It is not likely that published U-Th dates will be corrected and reported, but rather that assessment of materials and their U-Th dates might be used to make decisions on the need to obtain those samples through request or recollect samples from the same outcrop or site.

The datum for modern reference state of ages reported is either BP (or AD 1950) or not mentioned. This is usually not considered significant because the errors on MIS 5e ages are generally > 500 years. However, with the improvements made using MC-ICP MS (Cheng et al. 2013), age errors are now possible to ± 100 years, making how the age is reported (i.e., BP) more important. Another reference commonly used now is yr b2k (years before AD 2000).

3 Discussions

The elevation of a sea level proxy indicator is not always coincident with the elevation of the relative sea level (RSL) at the time the indicator formed, but rather is correlated to, via a quantifiable relationship. This is defined by the indicative meaning, a concept that needs to be considered when calculating the elevation of paleo relative sea level (van de Plassche, 1986; Shennan, 2015; Hibbert et al., 2016; Rovere et al., 2016a). To define the position of past sea level over space and time, the sea level indicators need to provide information on the geographic positioning, elevation with respect to a contemporary tidal datum, age of formation, and the indicative meaning (Shennan, 2015; Khan et al., 2019). Most records of MIS 5 sea level have come from coral reefs, but the interpretation is hampered by the challenges of finding pristine and well-preserved corals and to the uncertainties related to the water depths above the corals. For cave deposits, indicating the past sea level position in space and time depends on their type: i) POS have the ability to define the discrete position (Fig. 3), hence, they are considered sea level index points, whereas ii) SVS provide only an upper bound, and they are called limiting points (Fig. 4).

3.1 POS define reliable positions of RSL

POS precipitation was tentatively associated with past sea level stands almost five decades ago (Ginés and Ginés, 1974), but due to advancements in the U-Th dating, only recently have studies demonstrated their suitability as meaningful sea-level index points (Vesica et al., 2000; Dorale et al., 2010; Tuccimei et al., 2012; Polyak et al., 2018; Dumitru et al., 2019). The most important benefit of using POS as sea level indicators is their clear relationship to sea level. For example, the indicative range accounts for the vertical extent over which an entire POS forms, and the reference water level corresponds to their thickest part, which is the midpoint of the indicative range and the mean sea level. Hence, they provide a unique opportunity to further enhance our knowledge on MIS 5 sea level history, as presented below.

Obtaining 43 new U-series dates on POS from cave sites along the southern and eastern coasts of Mallorca, Polyak et al. (2018) reported an accurate timing of MIS 5e sea-level history, with absolute errors of their U-Th ages better than ± 500 years. The external elevation error within each cave is reported as ± 0.25 m and between all of the caves used in their study is reported to be ± 0.75 m. Their results show that relative sea-level in Mallorca was ~2.15 ± 0.75 meters above present level (mapsl) between 126.6 ± 0.4 and 116 ± 0.8 ka, although centennial-scale excursions cannot be excluded due to some small gaps in the POS record (Polyak et al., 2018). Similar encrustations were found in Grotta di Nettuno, Capo Caccia area (NW Sardinia, Italy), ~500 km east of Mallorca, but only one episode of high sea stand at 4.3 mapsl was documented (Tuccimei et al., 2012). Polyak et al. (2018) attributed this discrepancy in RSL between Sardinia and Mallorca to minor differences in GIA and/or tectonic movement between the two sites. Given the high age uncertainties obtained using alpha counting and TIMS (see Figure 3), it would be worth revisiting the chronology from Grotta di Nettuno and complement it with more samples. Two POS-derived MIS 5e data from Mallorca were also reported by Dorale et al. (2010) at 2.6 mapsl in Cova des Pas de Vallgornera at 116.2 and 120.6 ka, respectively. Using younger POS from the same and other caves, Dorale et al. (2010) also showed that RSL in the western Mediterranean was at ~1 mapsl during MIS 5a (~81 ka), challenging the prevailing view of lower MIS 5a sea-level position. POS are hence reliable and accurate indicators able to better resolve RSL during MIS 5.

Over 200 large POS, out of which 24 were recently dated, occur in a limited altitudinal range of ~40 cm in Santa Catalina Cave on the northern Cuban coast suggesting a sea level high stand that flooded the cave at 16 mapsl during MIS 5e (De Waele et al., 2017). The authors suggest that the oldest age (126 ka, sample SC2.6a) is the most likely to reflect the chronology of the sea-level stand. They interpret the younger ages which show much higher initial uranium activity ratios, to reflect recrystallization processes. After sea level dropped, the coastal area underwent a slow uplift, bringing the POS to 16 mapsl (De Waele et al., 2017; 2018). Additionally, these 24 POS contributed to the reconstruction of the speleogenetic stages and the local coastal uplift, while also providing information on the sea-level variations during the last ~400 ka.

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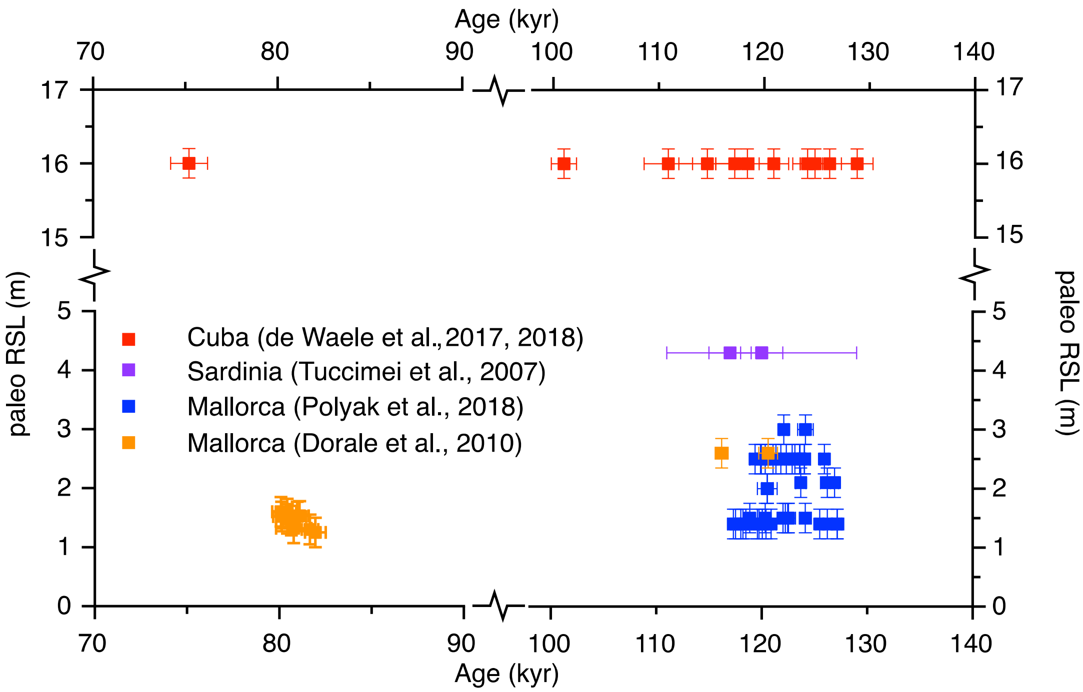

Figure. 3. Paleo RSL position recorded by POS. Except for Tuccimei et al. (2007), all U-Th ages are corrected for detrital Th.

3.2 SVS growth intervals - implications for sea level upper bound estimates

SVS from submerged caves in tectonically stable areas provide an additional source of sea level data, as their growth stops when rising sea levels flood the caves (Richards et al., 1994). The timing of initiation and cessation of speleothem growth is fairly easy to resolve applying U-Th measurements on carbonate material extracted from the bottom and top of a growth hiatus. The obtained ages will roughly indicate when the cave was air-filled and then invaded by water (Li et al., 1989; Richards et al., 1994). One advantage of using SVS is that they allow estimation of past low sea level stands (lower than today) in both interglacial and glacial periods. Such information is especially critical in tectonically stable regions, e.g., Bahamas and parts of the Mediterranean Basin, where changes in sea level can be directly associated with changes in ice-sheet volume, which is challenging to do for sea level indicators found on the uplifting coastline regions (e.g., Huon, Barbados, Haiti).

Submerged speleothems form Bermuda provide strong sea level evidence and contribute notably to deciphering the stands during MIS 5. The growth deposition of stalactites, stalagmites, and flowstones with low ^{232}Th content found in Bermudan caves indicates that sea level stood at ~4 to 6 m higher than present at ~125 ka, it fell below −6.5 m by 120 ka, and it stabilized for a short time at approximately 8 m below present at ~114 ka (Harmon et al., 1978). A few years later, a study by Harmon et al. (1981) using ages from submerged speleothems and aeolianites showed that sea level at ~105 and ~85 ka was

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between −15 and −20 m and was at least −15 m below present level at ~95 ka. The recent study of a submerged stalactite from Wilkinson Quarry Cave, northern Bermuda indicates hiatuses starting at 137 ± 5, 106 ± 6, 84.3 ± 1.5, and 79.9 ± 0.9 ka. These new results provide important constraints suggesting that local sea level might have peaked above ~1.5 m during MIS 5e, 5c, and 5a, representing a scenario that was previously unclear (Wainer et al., 2017). They also indicate a double highstand at MIS 5a, and while in agreement with other studies from tectonically active regions (Surić et al., 2009), given the tectonic stability of Bermuda, they interpret the results as indicating that this is a global feature associated with changes in ice-sheet volume, and not a tectonic movement.

A large number of speleothems were collected from the Bahamian caves from different elevations as mentioned earlier in Section 2.1, but very few of them captured sea level stands during MIS 5. Li et al. (1989) first presented ages on a flowstone collected from −15 m below modern sea level in Lucayan Caverns, Grand Bahama Island and documented hiatuses at a few different intervals including at 133−110 kyr and 100−97 kyr. These ages were substantially improved by an order of magnitude using TIMS method and thus, sea level during MIS 5a was constrained to be below −8.5 m (Lundberg and Ford, 1994) and between −15 m and −18 m, as suggested by Richards et al. (1994). The latter study also precisely constrained the termination of MIS 5a by determining the age of a sample that started growth at 79.7 ± 1.8 kyr. More recently, Richards et al. (2012) revisited these estimates and applied the correction for non-Bulk Earth initial $^{230}Th/^{232}Th$ contamination using the isochron method on samples of stalagmites from the same settings (Richards and Dorale, 2003). Stalagmites from a blue hole east of Andros Island were also sampled and dated for sea level application. The first set of ages showed that some of the samples deposited during MIS 5; however, they were found to be out of stratigraphic order possibly due to incorporation of minor amounts of marine deposits surrounding the central core (Gascoyne et al., 1979). The authors eliminated the age-biasing marine deposits by progressive acid leaching of crushed samples and analyzed the cleaned calcite crystals and the new results showed higher ages documenting a MIS 6 sea level low stand (at least 42 m below present level) between 160 and 139 ka (Gascoyne et al., 1979).

Subaerial growth periods of speleothems from Yucatan Peninsula provide precise and reliable maximum constraints for relative sea levels during MIS 5 that contribute to our understanding of sea level in the western North Atlantic-Caribbean region (Moseley et al., 2013). The authors show that following the MIS 5e highstand, RSL dropped below −4.9 m by 117.7 ± 1.4 ka. They also provide maximum sea level stands during MIS 5 c and 5a: i) MIS 5c sea level high stand occurred after 107.7 ± 0.9 ka reaching above −11 m, but not as high as −4.9 m and ended by 108.2 ± 4.9 ka and ii) sea level peaked during MIS 5a after 87.6 ± 0.6 ka at an elevation higher than −9.9 m. Following MIS 5a peak, sea level dropped below −14.6 m by 86.6 ± 6.4 ka and the speleothem continued to grow throughout the remainder of MIS 5. In addition to the information provided on the maximum RSL, when speleothems with precise ages are used in conjunction with data from other local sea level indicators, they can also offer robust chronologies for the timing of the relative sea-level fall at the last interglacial termination (Moseley et al., 2013).

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Constraints on the maximum RSL during MIS 5a in the eastern Mediterranean basin are provided by Surić et al. (2009) who dated two submerged stalagmites from the U Vode Pit on the Krk Island, in the eastern Adriatic Sea. Their double high stand MIS 5a sea level scenario is supported by layers of halite and gypsum associated with hiatuses in speleothem growth probably caused by seawater inundation during sea-level highstands. The timing of possible marine incursions was determined by dating the layers below and above these growth hiatuses.

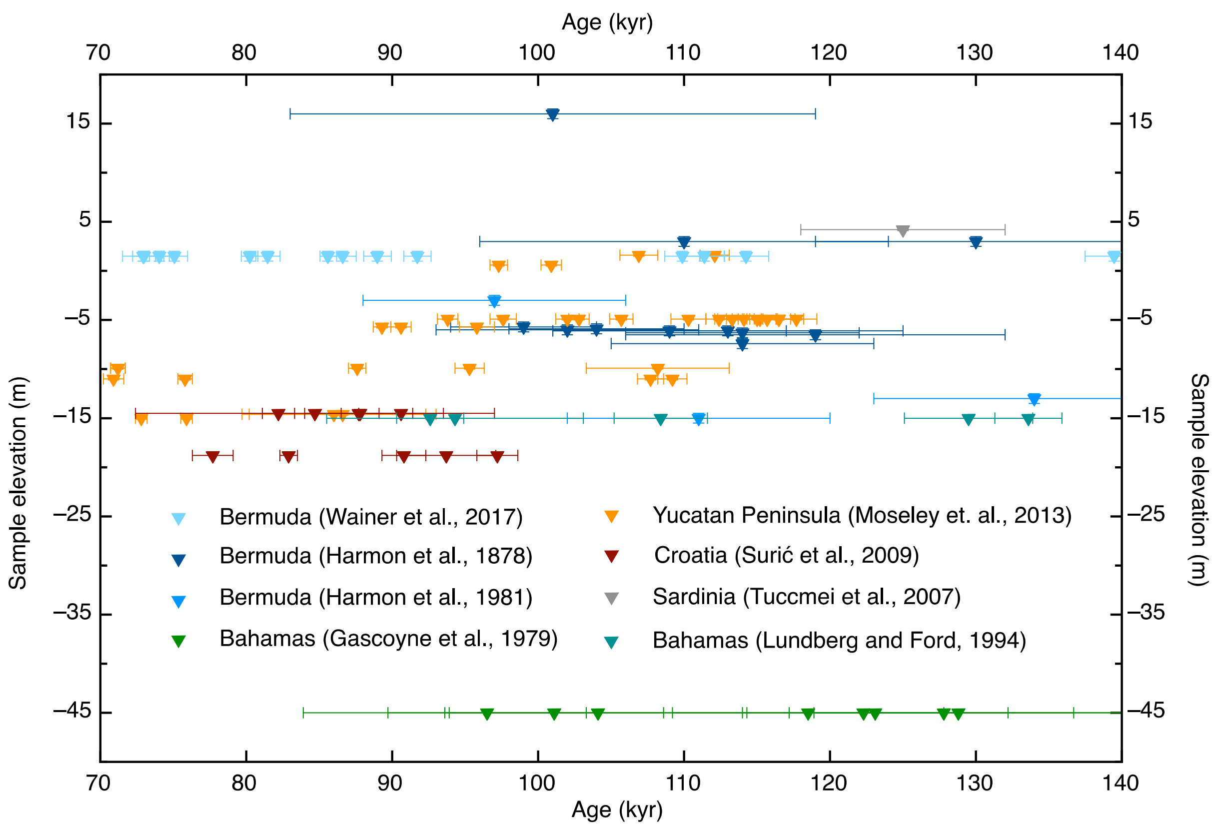

Figure 4. SVS elevation indicating maximum positions of RSL during the time of their deposition. Note that none of the data are corrected for GIA or long-term deformation.

3.3 POS- and SVS-derived sea level provides inputs for glacial isostatic adjustment models

The recorded elevations of sea level indicators reflect a combination of local changes in sea level of a region due to glacial isostatic adjustment (GIA) that causes land uplift or subsidence, displacing the local sea-level datum relative to the global mean (Rovere et al., 2016b). Thus, a significant part of the spatial variation in the MIS 5 sea-level record is due to the diverse response of coastlines to GIA, depending on the extent of continental or insular shelves, the distance from former ice sheets, and other variables (Dutton and Lambeck, 2012; Creveling et al., 2015; Dendy et al., 2017). Consequently, interpreting local sea-level markers first involves understanding and correcting for the ongoing effects of GIA. Numerical models generally estimate GIA with assumptions about the thickness, distribution, extension, and duration of former ice loads as well as the viscoelastic properties of Earth (Mitrovica and Milne, 2003; Austermann et al., 2017). The cave deposits from locations such as Mallorca, Bermuda, Bahamas, and Yucatan Peninsula provide an additional and independent source of sea level data, which have the potential to provide valuable information about the deformation parameters of the Earth and about the distribution of past ice sheets. Their distance from large pre-existing ice sheets and relatively stable passive margin tectonic setting is what makes them ideal locations.

The high-resolution POS-derived sea level record from Mallorca was corrected to estimate the ice-equivalent sea level by using nine different GIA models (Polyak et al., 2018). The authors preferred model showed that in Mallorca sea level peaked early in the MIS 5e at 5 mapsl due to the proximity to the forebulge of the former the penultimate glacial maximum (PGM) Eurasian Ice Sheet and then gradually decreased and stabilized by 122 ka at 2.15 ± 0.75 m, until the highstand termination at 116 ka. None of their models support the hypothesis of a second highstand during MIS 5e, and their results show no evidence for rapid sea-level fluctuations larger than 1 m. They also suggested that the corrected sea level is more sensitive to the size and distribution of the Northern Hemisphere PGM ice sheets than to the one-dimensional Earth model used for other predictions. This record allowed the authors to test both the sensitivity of MIS 5e sea level stand predicted by GIA models to PGM ice distribution and the timing of deglaciation (Polyak et al., 2018).

Bermuda is strongly affected by the glacial forebulge that forms due to the presence of the Laurentide Ice Sheet during glacial periods (Harmon et al., 1981; 1978; Wainer et al., 2017), hence sea level markers from this location have the potential to capture the response of the forebulge to glacial loading and can be seen as gauges. Based on U-Th ages of SVS from Wilkinson Quarry Cave, Bermuda, Wainer et al. (2017) showed that RSL was higher than 1.5 ± 0.5 m during MIS 5e, MIS 5c, and MIS 5a. The results also suggest a double RSL peak during MIS 5a, indicating rapid sea level variation associated with changes in ice-sheet volume. Testing GIA models against these new constraints, the results reinforce the presence of a smaller Laurentide Ice Sheet during late MIS 5 and a restricted range of Earth viscosity values, with higher values of lower-mantle viscosity compared to those used in some GIA models (e.g., Creveling et al., 2017). Wainer et al. (2017) confirm that it is possible to explain a wide range of MIS 5c-a relative sea levels observed across the Western North Atlantic–Caribbean in GIA models, but only with a limited range of mantle deformation constants.

The Bahamas Archipelago spans the south-eastern edge of the peripheral bulge of the ancient Laurentide ice complex, and hence this is a region that captures gradients in the GIA prediction. The majority of existing local MIS 5 sea level estimates in the Bahamas are reconstructed using corals (Chen et al., 1991; Thompson et al., 2011; Skrivanek et al., 2018; Muhs et al., 2020). While these records demonstrate the potential of this area for sea level reconstruction, despite the data abundance, the precision of the inferred water depth and also the open-system U-series behavior of some corals, cast uncertainty on existing estimates of relative sea level. Undoubtedly, the uncertainties behind GIA corrections and the models that investigators adopted for this, also decrease the accuracy of the reconstructed sea level. None of the Bahamian cave deposits reported so far (Gascoyne et al., 1979; Lundberg and Ford, 1994; Richards et al 1994) address these corrections, but observations indicate the abundance of this type of sea level indicator and their potential to provide additional data to help decipher the duration and amplitude of last interglacial sea-level in this region.

Moseley et al. (2013) used SVS growth periods to constrain maximum elevations of relative sea level, which are in agreement with GIA models for the near to intermediate region of the former North American ice sheet. Based on GIA modeling, Lambeck et al. (2012) classified Yucatan Peninsula as a near-field site in the western North Atlantic–Caribbean region located on the deformational bulge; thus, its MIS 5 sea level indicators are affected by significant GIA effects. Moseley et al. (2013) provide additional constraints on the timing of sea level fall following the MIS 5e highstand and on sea levels peaks during MIS 5a and 5c, indicating that a second MIS 5a highstand did not reach as high as the first in the Yucatan. The authors highlight the challenges of comparing sea-level records from the Yucatan Peninsula with data even from other field sites in the western North Atlantic–Caribbean region due to the complexity of estimating the GIA effects. They also emphasize the need for improved estimates of the MIS 5 sea level highstand in the Yucatan in order to better constrain the sea level history that can be used in predictive GIA modeling studies.

Altogether, both POS and SVS provide powerful constraints for future GIA models and also help refining ice-sheet histories and Earth properties. The geological data can test the GIA models, which will lead to an improvement of the modeled MIS 5 sea-level elevations for a large number of localities around the world.

3.4 POS- and SVS-derived sea level register tectonic uplift rates

Long-term deformation (uplift or subsidence) can substantially affect the cave deposits-derived sea level results. Assessing POS ages and their elevation and knowing their clear relation to sea level, proved to be a useful tool in estimating past tectonic evolution of the regional coastal karst landscape (Fornós et al., 2002; De Waele et al., 2018; Polyak et al., 2018).

Using U-Th data from Vesica et al. (2000), Fornós et al. (2002) suggested some tectonic tilting (increasing elevations northwards) in the eastern part of Mallorca based on POS horizons dated at MIS 5e, 5c and 5a. They estimated an average minimum velocity of the tilting of ~0.02 mm/year in the southern part with respect to the north. However, more recent higher-resolution U-Th results with better analytical precision and also more accurate elevation measurements provide evidence for tectonic stability of the region from MIS 9 to the present (Dorale et al. 2010; Polyak et al. 2018). This evidence is based on the presence of multiple highstands within the same cave indicated by different POS horizons, which suggest that RSL remained within the vertical extent of the cave over time (1.1 mapsl during MIS 9; 2.15 mapsl during MIS 5e, and 1.42 maspl during MIS 5a; Dorale et al., 2010; Polyak et al., 2019). The same authors showed also the stability of Mallorca during the Late Holocene by comparing POS from Mallorca and Sardinia. A more recent study has confirmed the tectonic stability of the island based on the observed elevation of six Pliocene POS and estimated a median uplift rate at this site of 2.0 m/Myr (0.6 – 4.4 m/Myr; Dumitru et al., 2019).

POS sampled from Cuba reveal Upper Pleistocene-Holocene coastal uplift rates at Matanzas between 0.05 and 0.10 mm/year (De Waele et al., 2017), one order of magnitude lower than those reported previously based on geodetic measurements along various parts of the Cuban coastline (Iturralde-Vinent, 2003). These results confirm the lower uplift rates of the western part of Cuba compared with the eastern sectors and argue that uplift rates are site-specific (De Waele et al., 2017). De Waele et al. (2018) further show that coastal uplift of Cuba has varied widely over the last 600-400 ka, with no uplift or even periods of slow subsidence that characterized the MIS 11 - MIS 5e time frame. Data also allowed to place these stages in a broader regional context of uplift and sea-level variations during the last ~400 ka.

The SVS collected from Croatia indicate MIS 5a sea-level stand of at least −14 m (Surić et al., 2009), however, the authors acknowledge that these results would most likely need to be corrected for long-term regional tectonic uplift of 0.15–0.25 mm/year with episodical subsidence events generated by collision of Adria microplate with Eurasia Plate (Surić et al., 2009). If other model evidence is assumed, these results can put constraints on temporal uplift.

4 Concluding remarks and future directions

This dataset paper represents the first compilation of cave deposits-derived sea level history for the last interglacial during MIS 5. The purpose of this work is to contextualize the interpretation of cave deposit records in a framework that would facilitate the MIS 5 sea level research community to use the worldwide database. Littoral caves offer a means of addressing the temporal and spatial sea-level data gaps in other proxies, by hosting deposits which provide an opportunity to independently date records of past sea-level changes. The phreatic overgrowth mechanism that deposits calcite/aragonite at sea level arguably provides the most precise and less ambiguous indicator of RSL timing and elevation. Cave deposits from locations such as Mallorca, Bermuda, Bahamas, and Yucatan Peninsula are particularly useful, not only for the information they provide about the eustatic sea level but more importantly for the powerful constraints for future GIA models to help refine ice-sheet loads and Earth properties. These records of sea level from low-lying islands and continental coasts could benefit other research related to water resources availability, sea level rise, saltwater intrusions, etc.

Our contribution to the WALIS database should be seen as a highlighting point on the relevance of cave deposits for sea level studies. In this compiled database on MIS 5 sea level, we list the areas where these sea level indicators are located and identify future research priorities. One research direction could be exploring for additional POS levels from Sardinia, which in conjunction with the extensive POS data from Mallorca would provide relevant information for better GIA and tectonic context for the western Mediterranean basin. Another direction could be sampling and dating the stalagmites identified at elevations much lower than present in caves from the Bahamas and Bermuda; their chronologies can contribute to an improved record of low sea level stands during the Pleistocene. Of equal priority is to re-analyze the samples that have been dated by means of alpha spectrometry, using the more advanced facilities in order to increase the precision of the ages. Of great importance is exploring new locations for additional POS or SVS along continental and island carbonate coastlines that would complement the already existing records.

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In order to collectively improve the utility of U-series data and to build a more valuable dataset that will have more longevity and use within the discipline, we encourage researchers publishing new sea level studies based on cave deposits to follow the recommendations offered by Dutton et al. (2017) in reporting their data. These authors specify the required data to enable calculation and, if needed, re-calculation of the same ages using different parameters and also, to facilitate the interpretation in the context of other studies. These recommendations will increase the usefulness of this type of analytical results in the U-series geochronology community (Dutton et al., 2017).

5 Data availability

The cave deposits database is available as open access and periodically updated as needed, at the following link: http://doi.org/10.5281/zenodo.4313861 (Dumitru et al., 2020). The description of each field in the database can be found at: https://doi.org/10.5281/zenodo.3961544 (Rovere et al., 2020). More information on the World Atlas of Last Interglacial Shorelines can be found at: https://warmcoasts.eu/world-atlas.html. Users of our database are encouraged to cite the original sources alongside with our database and this article.

Author contributions

O.A.D. compiled the data, drafted, and wrote the manuscript with input from B.P.O., V.P., and Y.A. BPO contributed to designing the figures and V.P and Y.A. provided expert review of U-series data.

Competing interests

The authors declare that they have no conflict of interest.

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