#### Review

# The use of submerged speleothems for sea level research in the Mediterranean Sea: a new perspective using glacial- and hydro-isostatic adjustment (GIA)

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#### Abstract

The investigation of submerged speleothems for sea level studies has made significant contributions to the understanding of the global and regional sea level variations during the Middle and Late Quaternary. This has been especially the case for the Mediterranean Sea, where more than 300 submerged speleothems sampled in 32 caves have been analysed so far. Here, we present a comprehensive review of the results obtained from the study of submerged speleothems since 1978. The studied speleothems cover the last 1.4 Myr and are focused mainly on Marine Isotope Stages (MIS) 1, 2, 3, 5.1, 5.3, 5.5, 7.1, 7.2, 7.3 and 7.5. Results reveal that submerged speleothems represent extraordinary archives providing accurate information on former sea level changes. New results from a stalagmite collected at Palinuro (Campania, Italy) and characterized by marine overgrowth are also reported. The measured elevations of speleothems are affected by the local response to glacial- and hydro-isostatic adjustment (GIA), and thus might significantly deviate from the global eustatic signal. The comparison between the ages and altitude values of the Mediterranean speleothems and the flowstone from Bahamas with local GIA provides a new scenario for MIS 5 and 7 sea level reconstrutions.

Keywords: submerged speleothem, phreatic speleothem, sea level change, sea caves, GIA.

#### 1. Introduction

The study of submerged speleothems in coastal caves significantly contributed to constrain past sea level variations for the last 1.4 Myr. In particular, they have provided relevant information on the sea level for several climatically-important Marine Isotope Stages, including MIS 1, 2, 3, 5.1, 5.3, 5.5, 6.5, 7.1, 7.2, 7.3 and 7.5, especially in the Mediterranean Sea.

The importance of sea level in controlling groundwater elevation in both inland and coastal karst was first proposed by [1] but it was only in the early 1970s that the potential of using speleothems to reconstruct former sea levels was fully recognized. For example, [2] discussed Late Pleistocene sea level fluctuations based on radiocarbon (<sup>14</sup>C) and U/Th ages from a submerged stalagmite retrieved from the Ben's Hole cave in Grand Bahama Island, and [3] interpreted the origin

of the encrustations from Cova de Sa Bassa Blanca cave (Mallorca) as carbonate formations related to the Pleistocene sea-level variations.

Later on, other studies used submerged speleothems to constrain relative sea level changes, especially taking advantage of the improvement of the U-series disequilibrium dating method by mass spectrometry for precise and accurate age determination [e.g. 4–6].

These carbonate deposits are usually found in caves that are below the sea level and presently flooded and they often contain marine layers/encrustations or growth hiatuses that identify periods of highstands when the sea level reached the speleothem.

Coastal caves can be divided into two major types: sea caves and flooded caves [7]. The first type includes caves formed by marine processes, such as wave abrasion, while the second type comprises caves that developed under subaerial processes acting in dry conditions and were then submerged by the Holocene marine transgression. They can be actively forming along present-day coastlines or occur as relict sea caves on former coastlines. The formation of sea caves is mainly controlled by geological weakness, such as bedding planes, joints, and faults along sea cliffs [8]. [9] recognized a third group, called flank margin caves. These are dissolutional landforms whose genesis is due to water mixing in sealed chambers. Sea caves can develop in different salinity environments. The most common caves are anchialine ones which are defined by having a fresh to slightly brackish water lens overlying seawater [10].

The investigation of submerged spleothems retrived from coastal caves has provided considerable scientific data that contributed to precisely constrain the relative sea level variation curves. In addition to speleothems, the main markers used to reconstruct past sea level variations are: shallow-water corals, ice, lagoonal and marine cores, and archaeological remains. The Mediterranean Sea is devoid of any reef-building tropical corals since the Miocene. However, few studies have used the endemic coral species *Cladocora caespitosa* as a sea level marker [e.g. 7]. This coral species forms 3D structures comparable to tropical reefs [12] and shows a fossil record dating back to the Late Pliocene [13]. Despite the great potential of this temperate coral to reconstruct sea level variations in the Mediterranean Sea, the major drawback is the large depth range where this species lives, ranging from few meters to around 40 m, which increases the uncertainty on sea level reconstructions.

In the Mediterranean Sea, three types of submerged speleothems have been studied so far: 1) speleothems without a visible secondary concretion (rarely containing hiatuses), 2) spleothems with overgrowth(s) of marine organisms (e.g. the marine polychaete worm *Serpula massiliensis*, bryozoans and sponges), and 3) speleothems with phreatic overgrowth(s).

When rising sea level inundates a coastal cave, speleothems stop growing once submerged and several events can happen:

• A marine biogenic overgrowth, often formed by gregarious serpulid worms mixed with bryozoans and sponges [14–21] can cover the speleothem surface with thickness varying from a few millimeters to over 12 centimeters;

• Specimens of the boring mussel *Lithophaga lithophaga* can colonize the speleothem surface, creating large burrows on the submerged cave deposits [22,23];

• Mineral deposits, including halite, hematite, goethite, lepidocrite, gypsum, can precipitate on the speleothem surface or corroded layers can form by dissolution from the seawater-groundwater mixing [e.g. 4,6,13,20,21];

• A carbonate encrustation, called phreatic overgrowth on speleothem (POS), can precipitate inorganically around stalagmites or stalactites at the contact with the water table, in a brackish environment. These secondary deposition structures usually show a morphology similar to an oval ball, with the size varying in response to the local tide range [3,26–28].

Among the most important findings of speleothems retrieved from flooded marine caves worldwide and often showing hiatuses or marine overgrowth, a special attention deserve the submerged cave deposits from Bahamas [4,5,29], Bermuda [30], Yucatan Peninsula [31,32] and Cuba [33]. [34] provided an exhaustive review on the use of sea-level indicators preserved in coastal caves, including speleothems and cave sedimentary deposits.

The measured elevations of speleothems are affected by the local response to glacial- and hydro-isostatic adjustment (GIA), and thus might significantly deviate from the global eustatic signal. The contribution of GIA to local relative sea level (RSL) changes is primarily a function of the distance with respect to the ice sheets. The closer to the ice sheets, the larger the deviation from the global mean (i.e. the eustatic sea-level change) is. In near-field, ice-proximal settings, the RSL signal is opposite in sign (i.e. trend) and can be 1-2 order of magnitude larger than the eustatic. In these areas, the ice sheets configurations (i.e. areal ice thickness variation) and the spatial patterns of retreat and advance are the dominant factors. The Mediterranean Sea is at an intermediate distance w.r.t. the ice loading centers/margins, and the northern coastlines are likely to be directly affected by the ice-loading term of the Eurasian ice sheets. However, GIA is strongly modulated by the solid Earth rheological behavior, which can cause large deviations from the eustatic even at far-field regions. Here, in fact, the relevant earth rheological parameters can enhance the solid Earth response to the water-loading term (counterpart of the ice-loading term). Hence, the shape and the size of the ocean basins becomes important.

Previous studies have shown that GIA-related vertical motions might have affected the elevations of speleothems [35–37]. Different sites (Bahamas, Bermuda, Mexico, Cuba and Mediterranean Sea) show distinct relative sea-level responses to glacio- and hydro-isostatic adjustment as function of the relative distances to the continental ice sheets during MIS 2.

However, the maximum vertical variability of the MIS 5.5 maximum sea-level highstand predicted by GIA models in the Mediterranean Sea [36,38] is 2-3 m. Models were tested on field by MIS 5.5 coastal fossil deposits and fossil tidal notches. This variability largely depends on the mantle viscosity profile, and by the retreat pattern of the MIS 6 ice sheets. So far, no GIA models have been published for MIS 7 or MIS 5.1 and 5.3 in the Mediterranean Sea. GIA results for the MIS 5.1 and 5.3 along a transect between Barbados and Northern Florida have been published by [39]. The Bahamas flowstone is in a far-field position w.r.t. north American ice sheets and should be comparable to the Mediterranean sites. (see Appendix A)



Appendix A GIA in Caribbean islands and Florida (redrawn from [39]).

The number of speleothem studies for sea level reconstructions has significantly increased after the 80s, when the development of mass spectrometric techniques for the measurement of uranium and thorium isotopes has led to increases in the typical precision and accuracy of U-series ages compared to alpha-counting measurements and reduced sample size requirements [40,41]. Speleothems can usually provide more reliable records than, for instance, shallow-water corals given that their dense calcitic or aragonitic structure is less susceptible to post-depositional alteration, significantly reducing the isotope exchange with the surrounding environment.

Isotope-dilution mass spectrometry for submerged speleothem dating was first applied by [4] and [6] on a flowstone (DWBAH) recovered from 15 m below present sea level in Grand Bahama Island, which contains 5 hiathuses (Appendix B) and provided a record of the sea level over the past 280 kyrs. These studies reconstructed one of the first sea level change curve which, together with the pioneering works by [42,43] on fossil corals, has considerably contributed to the knowledge in the



Appendix B) U/Th ages vs. sampling depth of the flowstone DWBAH (redrawn from [4])

field of sea level change.

Similarly, the use of thermal ionization mass spectrometry (TIMS) and multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) for precise U/Th dating of Mediterranean speleothems greatly improved our understanding of former sea level changes.

In addition to U/Th dating, the vadose stalagmites and stalagtites and POS can also be dated by <sup>14</sup>C. However, the radiocarbon ages can be affected by the "dead carbon proportion" (DCP), which is the percentage of dead carbon incorporated in the speleothem or POS at the time of formation. The DCP is mainly the fraction of carbon within the calcium carbonate that is derived from the equilibration with the soil CO<sub>2</sub> and the radiocarbon-free "dead carbon" from the bedrock [44]. High DCP values

(e.g. > 20%), resulting from a stronger water-soil-rock interaction of the precipitating water, overestimate the radiocarbon ages and cause a large <sup>14</sup>C-U/Th age offset. In a recent study, [45] reported combined <sup>14</sup>C and U/Th measurements on vadose stalactites and POS from Mallorca and showed that the use of radiocarbon dating can be problematic when DCP values are high.

Here we provide a thorough review on the use of Mediterranean submerged speleothems to reconstruct past sea level variations, reporting literature and new data from samples retrieved in the western and central Mediterranean Sea, including the Balearic Islands, Croatia, Malta and Italy (Fig.



**Figure 1,** Overview map of the Mediterranean region showing the locations of the coastal caves discussed in this study. Specific information (latitude, longitude, sampling depths, dating method, ages) are reported in Tables 3 and 4.

#### 2. Materials and Methods

#### 2.1 General overview of the Mediterranean region

The Mediterranean Sea (MS) is a marine basin almost completely bordered by land and covers an area of about 2.5 million km<sup>2</sup>. Its geographical features were widely reviewed by [46]. The coastline extends for about 46,000 km<sup>2</sup> and approximately half of this is rocky, with plunging cliffs, sloping coasts, screes and shore platforms [47]. It can be divided into the Western and Eastern Mediterranean along an imaginary axis between the Straits of Sicily and Tunisia but a large scientific literature also identify an undefined "central Mediterranean area" [48].

The MS has a long and complex geological history that began about 250 Myr ago, following the break-up of the Pangea and the formation of the Tethys Ocean, the forerunner of the MS [49]. From a geological point of view, the Mediterranean borders the westernmost sector of the Alpine-Himalayan orogenic belt. Its geodynamic evolution was driven by the differential seafloor

spreading along the Mid-Atlantic Ridge, which led to the Alpine orogenesis [49]. It hosts wide extensional basins and migrating tectonic arcs. Vertical and horizontal movements control the geological and geomorphological history of the area. The MS includes zones of active subduction associated with volcanic activity and older zones of quiescent subduction [49]. The coastal reliefs, coupled with seismic activity generated by geodynamics, drive most erosional processes within the area. For the aforementioned reasons, rocky coastal landforms in the MS are closely connected with sea level history [48]. These coastal landforms are spread in elevation from few metres up to more than 150 m asl, due to the relevant tectonic uplift that patchily affects the basin coastline [50]. Pleistocene highstands have mainly been responsible for the formation of stepped flights of terraces along the rocky sections of the MS.

The MS is situated at the boundary between the subtropical and mid-latitudes zones and its climate is characterized by warm and dry summers and mild and rainy winters [51]. It is a semi-enclosed and highly evaporative basin that is connected with the Atlantic Ocean through the Strait of Gibraltar (sill depth ~ 300 m) and with the Black Sea through the Strait of Dardanelles (sill depth ~100 m) and the Bosphorus Strait (sill depth ~65 m). The Atlantic water that enters the Mediterranean Sea spreads throughout the entire basin and participates in the formation of intermediate and deep waters that contribute to the Mediterranean thermohaline circulation [52]. In particular, since evaporation exceeds precipitation and river runoff, the relatively fresh (salinity ~ 36.5) surface Atlantic Water entering the Mediterranean Sea across the Strait of Gibraltar at the surface becomes progressively saltier (~ 38.5) and denser during eastward advection. Evaporation and mixing together with intense cooling and strong wind-induced heat loss in specific areas in winter (Gulf of Lion, Adriatic Sea, Levantine and Aegean Seas) result in denser waters that sink via convection and form the intermediate and deep waters in the Mediterranean Sea [53,54].

Tides vary from place to place along the coasts of the Mediterranean, depending on many parameters, such as coastal geometry and bathymetry, but in general Mediterraenan tides have lower amplitudes with respect to oceanic ones. The average tidal amplitude is about 40 cm, with the exception of the remarkably large tides observed in the Gulf of Gabes (Tunisia) and in parts of the North Adriatic Sea, where they may reach amplitudes up to 1.80 m. In other areas, such as in Greece or Sicily, tides are very small, especially near the amphidromic points where the tidal range is almost non-existent. At the Strait of Gibraltar, tide increases to 1.5 m due to the influence of the Atlantic Ocean, but it quickly decreases eastwards. Weather conditions can significantly reduce or amplify the tidal amplitude, with variations up to 1 m.

#### 2.2 Numerical modelling of Glacial- and hydro-isostatic adjustment

We compute the GIA-driven RSL curves at the relevant Mediterranean sites by solving the gravitationally and rotationally self-consistent sea level equation [38,55,56] and including the relastic treatment of variable coastlines. We assume a spherically symmetric, deformable but incompressible, self-gravitating and rotating Earth model that is characterized by a Maxwel viscoelastic rheology.

We employ a four-layer model characterized by the VM2 mantle viscosity profile [57] and combined with a lithosphere thickness of 90 km (see Table 1). We also employ a three-layer model and test three mantle viscosity profiles (MVP 1-3), each combined with a lithosphere thickness of 100km (see

Table 2). The viscosity gradient of viscosity as a function of the Earth's radius increases of one order of magnitude from MVP1 to MVP3.

VM2	LT (km)	UM (x 10 <sup>21</sup> Pa·s)	LUM (x 10 <sup>21</sup> Pa·s)	TZ (x 10 <sup>21</sup> Pa·s)	LM (x 10 <sup>21</sup> Pa·s)
	90	0.67	0.44	0.46	2.53

 Table 1 Elastic lithosphere thickness and viscosity of the four-layer VM2 profile.

MVPs	LT (km)	UM (x 10 <sup>21</sup> Pa·s)	TZ (x 10 <sup>21</sup> Pa·s)	LM (x 10 <sup>21</sup> Pa·s)
MVP1	100	1	1	2
MVP2	100	0.5	0.5	5
MVP3	100	0.25	0.5	10

Table 2 Elastic lithosphere thickness and viscosity of the three-layer MVP 1-3 profiles.

We employ the following ice sheets models as forcing functions:

- ICE-5G [57], where two consecutive chronologies are combined in series to cover the last 250 ka.
- ICE-6G [58], where two consecutive chronologies are combined in series to cover the last 250 ka.
- ANICE-SELEN [38,59,60], where a ~ 2.5 m eustatic highstand occurs during MIS 5.5, mostly from the Greenland Ice Sheet melting.

# 2.3 Speleothem samples

The Mediterranean speleothems reported in this study were collected in coastal caves in the Balearic Islands and along the Croatian, Maltese and Italian coasts (Fig. 1; Table 1). The Italian samples were retrieved between 1990 and 2007, at water depths ranging between -0.3 and -48 m. Depth was determined with a digital depth gauge (typical error  $\pm 0.1$  m). Samples were collected by sawing through the base of the speleothems. For further information regarding the cave morphology, sampling method, date of sampling and the error associated to the radiocarbon and U/Th ages, the reader should refer to the original articles [4,6,14,16–24,26–28,35,61–65].

## 2.4 Speleothem from Palinuro

A ~ 10 cm stalagmite was collected in a fossil tidal notch along the carbonate coast of the Palinuro promontory in the Campania region (South Italy) at 2.1 m above the sea level. A variety of living organisms, including the crustose coralline algae *Lithophyllum*, the acorn barnacle *Chthamalus* and the limpet *Patella*, were obsersed below the tidal notch, exposed to strong wave conditions. The external surface of the speleothem was completely covered by a blackish patina that is likely the result of the precipitation of Fe-Mn oxides when the rising sea level approached the speleothem (Fig. 5 (4,7)). The top portion of the stalagmite is encrusted by a marine overgrowth that consists of several specimens of the barnacle *Chthamalus stellatus* that typically lives in the intertidal zone on high energy rocky shores and can be found above the highest tidal level [66].

#### 2.4<sup>14</sup>C and U-series dating

Three carbonate fragments were sub-sampled from the upper portion of the stalagmite from Palinuro (Fig.5 (4,7,8)) and prepare for radiometric dating. In particular, sub-sample 1 (Palinuro-1) was collected within the marine overgrowth (barnacle) and analysed for AMS-14C. The fragment was carefully cleaned using a small diamond blade to remove any visible speleothem calcite and retrive only the encrusted overgrowth. The sample was further processed and analysed for <sup>14</sup>C at the Center of Applied Physics, Dating and Diagnostics (CEDAD) Laboratory of the University of Salento, Italy, using an Accelerator Mass Spectrometer (AMS). The radiocarbon age was converted to calendar years (cal. yr BP, BP = AD 1950) using the IntCal20 calibration curve [67] and the Calib 7.10 program [68]. The ages of the other two sub-samples (Palinuro-2 and Palinuro-3) were determined through the U-series dating method at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) at Gif-sur-Yvette, France. The samples were first leached with 0.1 M HCl and then dissolved with diluted HCl and equilibrated with a mixed <sup>236</sup>U-<sup>233</sup>U-<sup>229</sup>Th spike. The uranium and thorium fractions were separated using UTEVA resin (Eichrom Technologies, USA) and analysed using a ThermoScientific Neptune<sup>Plus</sup> multi-collector inductively coupled plasma-mass spectrometer following the protocol developed at LSCE [69]. The <sup>230</sup>Th/U ages were calculated from measured atomic ratios through iterative age estimation [70], using the <sup>230</sup>Th, <sup>234</sup>U and <sup>238</sup>U decay constants of [71] and [72]. The ages were corrected for the non-radiogenic detrital <sup>230</sup>Th fraction using an initial  $^{230}$ Th/ $^{232}$ Th activity ratio of  $0.85 \pm 0.36$ , which corresponds to the mean upper crust value [73].

The U/Th ages of the DWBAH fownstone reported in [6] have been re-calculated using the most recent <sup>230</sup>Th, <sup>234</sup>U and <sup>238</sup>U decay constants of [71] and [72] and corrected for the detrital <sup>230</sup>Th fraction using a initial <sup>230</sup>Th/<sup>232</sup>Th activity ratio of  $0.8 \pm 0.8$  (Supplementary table 1), as suggested by [74] for the Bahamas speleothems. The difference between the original U/Th ages [6] and the re-calculated and corrected ages is minimal (< 3.5 kyr for ages younger than 270 kyr).

#### 3. Results

Tables 3 and 4 report the relevant details of the sampling locations and the published U/Th and <sup>14</sup>C ages of the vadose speleothems, POS and marine biogenic overgrowths used for the present

Submerged cave	Coordinates (Lat °N, Long °E)	Lithology	Reference	Layer	Dating method	Time range (kyr cal BP)	Depth (m)
1-10 Mallorca, Spain	Average (10 caves)	Mesozoic to	Vesica et al. (2000)	Continental and	U/Th		
1 Cova de Cala Falcò		Miocene		POS	(TIMS)	83.9	+1.9
2 Cova de Cala Vargues		calcarenites				36.0, 83.4, 71.3, 119.9	+1.4
3 Cova des Serral						121.3	+1.5
4 Cova de Dimoni	39.49976					107.9, 112,9, 119.7	+2.5
5 Coved del Pirata	3.31629					130.4	+2.1
6 Covas de na Barxa						124.7	+2.4
7 Cova de na Mitjana						231.9, >300	+4.9, +5.8
8 Cova del Drac						>350	+3.3
2 Cova de Cala Varques	-	Miocene	Tuccimei et al. (2010)	Continental and	U/Th	1.1-2.8	
		calcarenites		POS	(MC-ICPMS)		
	-	Miocene	Dorale et al. (2010)	Continental and	U/Th	80.12-81.95 (MIS 5.1)	mean +1.4
2 Cova Varques		calcarenites		POS	(TIMS)		+1.25-1.57
4 Cova Dimoni							+1.48-1.45
1 Cova Falcò							+1.53-1.57
9 Cova des Pas de							
Vallgonera							+1.52 -1.6
1-9 Mallorca	-	Miocene	Polyak et al. (2018)	Continental and	U/Th	116.0-126.6 (MIS 5.5)	mean +2.15
		calcarenites		POS	(MC-ICPMS)		
1 Cova Falcò		Miocene	Lucia et al. (2020)	Continental	U/Th	465	+2
		calcarenites			(MC-ICPMS)	558	+2.9
						643	+2.8
						500	+3
4 Cova Dimoni						948-482	+5
10 Sa Ferradura						1084-587	+3
						1355-588	+5.5
						1205-672	+4.5
11.0	40.56462	Manager	A	Continue to I	11/21	1460-702	+3.5
Li Grotta di Nettuno,	40.56463	IVIESOZOIC	Antonioli and Mucedda (2003)	Continental	U/In (alaba sounting)	165±12 (IVIIS 6)	-52
12 Euchotel	0.10042	imestones	Alessio et al. (1994)	Continental	(alpha-counting)	E 271	1
12 Eurnotei			Alessio et al. (1994)	Continental	140	5.3/1	-1
				Continental		7.283	-1
					<sup>14</sup> C		
13 Risorgenza cala Luna,	40.22420	Mesozoic	Alessio et al. (1994)	Continental	14C	25.377 (MIS 2)	-9

Orosei gulf, Sardinia, Italy	9.62864	limestones					
14 Argentarola cave, Italy	42.4181	Upper Triassic	Antonioli et al. (2004)	Continental and	U/ <u>Th</u>	6.5-9.6	
	11.08142	dolomitic		MOVR	(TIMS)		-3.5, -21.7
14 Argentarola	42 4181	Unner Triassic	Bard et al. (2002)	Continental and	LI/Th	145 2-189 7 (MIS 6)	-18.5
Grosseto,Italy	11.08142	dolomitic	bard et al. (2002)	MOVR	(TIMS)	<201.6 (MIS 7.1)	10.5
		limestone				201.6 (MIS 7.2)	
14 Argentarola cave,	42.4181	Upper Triassic	Dutton et al. (2009a)	Continental and	U/ <u>Th</u>	201.5-189.7 (MIS 7.1)	-18, -21.7
Italy	11.08142	dolomitic		MOVR	(MC-ICPMS)	217.2-206.0 (MIS 7.3)	
ASN -18 m		limestone			(TIMS)	248.9-231.0 (MIS 7.5)	
ASE -21.7 m						35.2-48.4 (MIS 3)	
						203 3-207 1 (MIS 7 2)	
						248.9-259.0 (MIS 8)	
						183.1 (MIS 6)	
						217.2-2131.0 (MIS 7.4)	
15 Capri, Italy	40.55307	Jurassic-	Alessio et al. (1994)	Continental	<sup>14</sup> C	3.92	-3.5
	14.26406	Cretaceous					
		limestone					
16 Scaletta cave. Palinuro.	40.02373	Mesozoic	Alessio et al. (1992, 1994)	Continental and	<sup>14</sup> C	MIS 1-2	-4127
	15.27159	limestones		MOVR	-		,
			Antonioli and Oliverio (1996)	"		10.2	-48
14 Argentarola cave, Italy			Alessio et al. (1992, 1994)			MIS 1-2	16, -14, -12,
							-10, -4
17 Ustica	38.70513	Pleistocene	Alessio et al. (1994)	Continental	<sup>14</sup> C	3.8	-0.3
10 Contallamanaa	13.19478	volcanic rocks	Alessia et al. (1004)	Castisental	140	0.2	0.2
Palermo Italy	12 80470	limestones	Alessio et al. (1994)	Continental		8.3 15.0	-0.3
19 Rumena cave	12.00470	Mesozoic	Stocchi et al. (2017)	Continental	U/Th - <sup>87</sup> Sr/ <sup>86</sup> Sr	15.0	+98
Custonaci (Trapani, Italy)		dolomites		MOVR and	(MC-ICPMS)	1,4 (MIS 25-37)	
				hiathuses	. ,		
20 La Cattedrale,	37.99338	Mesozoic	Antonioli et al. (2002)	Continental,	<sup>14</sup> C	9.5	-25
Marettimo, Trapani, Italy	12.04360	limestone		MOVR and LB	U/ <u>Th</u>	25.0 (MIS 2)	
	(E )		D. 11 (20001)		(alpha-counting)	39.3 (MIS 3)	
21-25 Plemmirio caves,	Average (5 caves)	Pleistocene	Dutton et al. (2009b)	Continental and	U/Th		
Italy	15 31240	innestones		IVIOVK	(IVIC-ICPIVIS) (TIMS)		
	13.31240		1		(11415)		

21 Plemm-A						8.3	-20.2
21 Plemm-A							
21 Plemm-A						41.5-44.5 (MIS 3)	-20.2
22 Plemm-B						72.4-75.3 (MIS 5.1)	-20.2
23 Plemm-C						44.4 -52.9 (MIS 3)	-17.0
23 Plemm-C						8.8-13.0 (MIS 1)	-17
24 Mada-SC						9.2-8.4 (MIS 1)	-15.5
24 Mada SC						10.4 (MIS 1)	-36.6
25 St.Pam						41.5, 44.5 (MIS 3)	-36.6
						30.9, 43.6 (MIS 3)	-16.0
26 Gebel Ciantar cave	44.97896	Late Oligocene-	Furlani et al. (2018)	Continental and	<sup>14</sup> C	7.6, 7.7	-14.5
Malta	14.61674	Middle Miocene		MOVR			
		Globigerina					
		limestone					
27-33 Croatia	Average (7 caves)	Mesozoic	Suric et al. (2005, 2007, 2009,	Continental,	<sup>14</sup> C	MIS 1,2,3	
Eastern Adriatic	44.9389	limestones	2010) Suric and Juracic (2010)	MOVR and	U/Th	MIS 5.1, 5.5, 7.1	-1.5, -38.5
27 U vode Pit (Krk Island)	14.7218			hiathuses	(MC-ICPMS)		
Medvjeđa spilja Cave							
28 (Lošinj Island)							
29 Pit near Iški Mrtovnjak							
30 Cave in Tihovac Bay							
31 (Pag Island);							
32 Vrulja Zečica;							
33 Zmajevo uho Pit;							
<b>Flowstone Bahamas</b>	26.13029	Pleistocene	Li et al. (1989), Lundberg and	Continental and	U/Th	See Appendix E	-15
	77.17577	limestones	Ford (1994)	hiathuses	(TIMS)		

**Table** 3-Locations and geographic coordinates of the caves and speleothems reported in this study, with information on the speleothem layer(s) analysed, dating method and the time range. POS: phreatic overgrowth on speleothem; MOVR: Marine overgrowth; LB: *Lithophaga* bores; MIS: Marine Isotope Stage. For further details on the ages of samples collected from locations 27-33, refer to table 2.

review. In particular, table 3 summarizes the main results of all the studies dealing with Mediterranean submerged speleothems, which were published between 1992 and 2020: 33 caves (Figure 1, Table 3) carved on carbonate lithology that preserved vadose speleothems, POS and marine biogenic overgrowth that were used to reconstruct former sea level variations. An essential condition for the conservation of submerged speleothems is that the caves entrance are small in size so that the energy of the waves can be almost completely attenuated.

On the Adriatic coasts of Croatia, speleothems were sampled in 7 submerged caves distributed along ~ 300 km of coast (Figure 1) and dated by <sup>14</sup>C and U/Th [19,24,65,75]. Their ages range between 7 and 217 kyr (MIS 1 and MIS 7), and results are summarized in [21].

Since 1974, a pool of Spanish and international speleogists and geologists has investigated vadose speleothems and POS collected from 9 different caves located along the southern coast of Mallorca in the western Mediterranean. The phreatic speleothems were retrieved at 1.2 and 5.8 m above present sea level and their ages vary between 1 and 231.9 kyr [26,28,35,45,61,76]. The main results are reported and discussed in 2 important studies: [28] focuses on POS sampled in 5 different caves at 1.2 to 1.5 m, that precipitated within a very narrow temporal range, from 81.95  $\pm$  0.56 to 80.43  $\pm$  0.48 kyr; [35] reports the U/Th ages of 11 POS from 8 caves that enable reconstructing the relative sea level changes between 126.6  $\pm$  0.4 and 116  $\pm$  0.8 kyr.

In Italy, the first speleothems sampled for sea level studies were retrieved from 15 submerged caves in the Tyrrhenian Sea (Figure 1) between 1992 and 1994 [14,62]. Between 2002 and 2017, a couple of studies on speleothems from the Argentarola and Custonaci caves, characterized by an alternation of continental layers, hiathuses and encrusting marine organisms (Fig. 4) allowed to constrain the sea level change during MIS 7 and the Middle Pleistocene Transition [17,23].

Finally, a submerged speleothem was sampled at -14.5 m in the southwestern coast of Malta and dated by radiocarbon. Results showed that Malta remained tectonically stable during the Holocene.

## 3.1 Croatia (2005 -2010)



**Figure 2**. Coastal caves and submerged speleothems from Croatia. (1): Map of the Adriatic Sea showing the locations of the Croatian caves [21]. (2) Stalactite P-23, with overgrowth, from Cave in Tihovac Bay (Pag Island) -23 m. 3: Stalagmite K-14 from U vode Pit (Krk Island) -14.5 m. Pink dots represent the portions of the speleothem collected for U/Th dating, yellow dots are the areas where X-ray diffraction analyses were carried by [21] to identify the hiathus between 87 kyr and 82 kyr. (4): Stalgmite K-18 from from U vode Pit (Krk Island) at -18.8 m. Pink dots represent the portions of the speleothem collected for U/Th dating, yellow dots are the areas where X-ray diffraction analyses were carried by [21] to identify the hiathus between 87 kyr and 82 kyr. (4): Stalgmite K-18 from from U vode Pit (Krk Island) at -18.8 m. Pink dots represent the portions of the speleothem collected for U/Th dating, yellow dots are the areas where X-ray diffraction analyses were carried out by [21] to identify the hiathus between 77.7 kyr and 64.5 kyr. (5): stalactite R-21 from Zmajevo uho Pit -21.1 m. Photo by M. Surić. (6): cave near Iški Mrtovnjak. Photo by M. Kvarantan.

The Adriatic coast of Croatia is a karstic coast characterized by more than 230 submarine caves that have been investigated over the last 2 decades to reconstruct former sea level changes (Figure 2, Table 4). Most of the caves (n = 126) show full marine conditions, 75 are anchialine (mostly) pits, 13 are submarine springs (vruljas), and 21 are not determined by hydrological or environmental conditions. More than 140 caves contain speleothems [77].

Location	Depth (m)	Sample	<u>Uncorr</u> . age (ka)	Corrected age (ka)
		K-14-B-50d	108.7	84.7 ± 12.3
		K-14-B-45	90.3	87.8 ± 1.3
	14.5	K-14-B-1d	82.9	$82.2 \pm 1.1$
		K-14-A-172d	93.2	87.7 ± 3.7
		K-14-A-10	95.7	90.6 ± 2.9
		K-18-S	183.1	$131.4 \pm 28.4$
		K-18-C-14L	55.7	53.8 ± 2.1
		K-18-C-14R	57.2	$55.2 \pm 1.4$
U vode Pit (Krk Island)		K-18-C-14R	52.3	$50.5 \pm 5.3$
		K-18-C-14M	54.5	52.8 ± 1.1
	18.8	K-18-C-11	58.7	58.1 ± 1.4
	10.0	K-18-C-2	65.2	$64.5 \pm 1.2$
		K-18-B-40	78.1	77.7 ± 1.4
		K-18-B-10	83.3	$82.9 \pm 0.6$
		K-18-A-95L	99.9	97.2 ± 1.4
		K-18-A-95R	93.9	90.8 ± 1.5
		K-18-A-5	94.7	93.7 ± 3.4
	1.5	L-1-2	124.9	$120.4 \pm 3.2$
		L-10-T1	33.8	$33.2 \pm 0.5$
Medvjeđa spiljaCave (Lošinj Island)	10	L-10-T1	34.2	$33.7 \pm 0.6$
	10	L-10-T2	20.6	$20.2 \pm 0.5$
		L-10-25	217.3	$216.8 \pm 10.5$
	14	M-14-T	43.6	$39.3 \pm 2.0$
		M-19-T1A	55.4	55.3 ± 1.9
Pit near Iški Mrtovniak	19	M-19-T1B	45.2	$44.8 \pm 1.0$
		M-19-T2	68.1	$68.1 \pm 0.7$
	23	М-23-Т	202.2	$201.3 \pm 5.5$
		М-23-Т	202.9	$202.0 \pm 7.4$
		Р-23-МО	53.2	$28.7 \pm 11.2$
Cave in <u>Tihovac</u> Bay	23	P-23-T1	46.9	37.3 ± 4.2
(Pag Island)	23	P-23-T2	33.3	$33.2 \pm 0.7$
		Р-23-Т3	33.1	$31.9 \pm 0.9$
		Z-41-B-40	-	-
Vrulja Zečica	41 5	Z-41-B-28	371.2	$308.1 \pm 53.8$
	11.5	Z-41-B-26	42.1	$30.2 \pm 5.2$
		Z-41-A3	40.4	$21.9 \pm 8.2$

Location	Depth (m)	Sample	<sup>14</sup> C conventional age corrected for A <sub>0</sub> (BP)	Calibrated range (cal BP) <sup>2</sup>	Calibrated age (cal BP) <sup>3</sup>
Medvjeđa spiljaCave	1.5	L-1-S	3150 ± 125	3490 - 3210	3350
(Lošinj Island)	10	L-10-S	$7015 \pm 170$	7990 – 7670	7830
<u>Vrulja Zečica</u>	41.5	Z-41-S	$9760\pm280$	9700 - 8750	9225
		B-38-P			13 950
	38.5	B-38-A	27 550 ±1600		32 200
		В-38-В	> 37 000		
	36	B-36-P			10,185
Pit in		B-36-A	25 120 ±1200		29 800
Lučice Bay (Brač		В-36-В	> 37 000		
Island)		B-34-P			9 160
	34	B-34-A	$18\;500\pm540$	22 750 - 21 250	22 000
		В-34-В	> 37 000		
	20	B-28-P			6 055
	20	B-28-A	$18\ 150\pm520$	22 350 - 20 850	21 600
Cave in Tihovac Bay	23	P-23-A	25 480 ±1230		30 300
(Pag Island)	23	Р-23-В	29 730 ±2110		34 800
Zmajava uka Dit	21.4	R-21-A	$22\ 750\pm890$		26 900
	21.4	R-21-B	$28\ 505\pm1320$		33 500

Table 4 Location, depth, sample,U\Th, corrected age of the speleothem studied in Croatia (see also Fig. 2). <sup>14</sup>C ages of speleothems L-1 and L-10 measured by a liquid scintillationcounter, and of speleothems Z-41, B-38, B-36, B-34, B-28, P-23 and R-21 measured by agas proportional counter. The youngest parts are marked with A and S, while B regards theoldest parts. <sup>14</sup>C ages are expressed as conventional <sup>14</sup>C corrected for A<sub>0</sub> = 85% andmeasured δ<sup>13</sup>C (-8‰ when not measured), and as calibrated ages.

In particular, 16 submerged speleothems were collected at depths between -41.4 and -1.5 m in 7 caves (out of 235 visited) located along the Croatian coast over a distance of ~ 300 km. The age model of these samples was constrained by 15 radiocarbon measurements and 36 U/Th analyses. Among these, the U/Th ages obtained from the stalagmites K-14 and K-18 sampled in U vode Pit (Krk Island, Figure 2) at -14.5 and -18.8 water depth deserve particular attention. Eleven U/Th ages from K-18 span a ~ 50 kyr time range, from 97 kyr (MIS 5.3) to 50 kyr (MIS 3), and identify 2 hiatuses, whereas 5 U/Th measurements from K-14 cover a ~10 kyr period, from 91 kyr to 82 kyr (MIS 5.1), with the presence of 1 hiatus marked by calcite, gypsum and halite precipitation Figures 2, (3) and (4). The deposition of speleothem K-18 ceased during MIS 3 (58–28 kyr BP) and few data are published during MIS 2 (Table 2). As for the last portion of the sea level rise (MIS 1 - Holocene) the continental layers of the speleothems L-1-5, L-10-S and Z-41-S have provided some interesting data using the radiocarbon method (Table 4): -1.5 m: 3.3 kyrs, -10 m: 7.8 kyrs and -41.5 m 9.2 kyr cal BP. The comparison with the sea level curve predicted by [78] for Croatia reveals a good agreement for the first 2 points (L-1-S and L-10-S), whereas the value for sample Z-41-S slightly deviates from what expected.

## 3.2 Italy (1992-2017)



**Figure 3 a** and **b**. First sea level change curves for the Tyrrhenian Sea (Italy) using submerged spelothems, redrawn from [14,62].

Between 1992 and 1994 [14,62] published the first relative sea level curve for the Tyrrhenian Sea during the Holocene using radiocarbon dating of samples at the contact between serpulid overgrowth and continental stalactites. The samples were retrieved at 41 and 6 m water depth at the sites of Palinuro and Argentarola and <sup>14</sup>C ages range between 26 and 3.5 kyr cal BP Figure 3a, b. The marine overgrowth observed on the Argentarola and Scaletta (Palinuro) speleothems started to encrust the speleothem surface when the rising sea level flooded the caves. The biogenic overgrowth mostly consists of white-yellow tubes precipitated by the polychaete worm *Serpula massiliensis*, and remaining of bryozoans and sponges [17]. This encrustation plays a significant role because it protects the continental portion of the speleothem from degradation, bioerosion or dissolution. The spelethems from the Argentarola and Rumena caves in Italy [17,23] represent the only cases in the world where more than one continuous deposition of continental and marine layers were observed in the same speleothem (for subsequent marine and continental highstands).

<u>Argentarola cave</u> (Grosseto, [14,16–18, 58]): Submerged speleothems were collected from -21.7 and -3.5 m and dated by <sup>14</sup>C and the U-series disequilibrium method. It was not possible to date the marine overgrowth of the higstand older than 40-50 kyr given the limit of the radiocarbon method when approaching these ages. Results obtained from speleothems of the Argentarola cave have greatly contributed to the understanding of the sea level changes and environmental conditions during MIS 7.5, 7.4, 7.3, 7.2 7.1, 6 and 5 (Figure 4).

<u>Scaletta cave</u> (Palinuro, Salerno [14,22,62]): A speleothem was collected at -48 m, representing the deepest sample with marine overgrowth found in the MS. The sea level reached this depth at 10.2 kyr cal BP (Figure 4)..

<u>Cattedrale cave</u> (Marettimo island, Trapani [79,80]): A submerged stalactite was retrieved along an horizontal cave at -25 m. The radiocarbon age (9.4 kyr cal BP) obtained from the remaining of a fossil *Lithophaga* boring mussel that bored the continental portion of the stalactite provided of the cave submergence (Figure 4)..

<u>Rumena cave</u> (Custonaci, Trapani, [23]): A unique stalactite was collected at 98 m above sea level within a small cavity. Unlike most of the other speleothems from the Mediterranean, which are covered by serpulids, the stalactite from the Rumena cave has been encrusted by scleractinian corals Figure 4 (7,8). The cross section of the sample revealed the presence of 4 highstands (MIS 25 -37),

with the outermost coral overgrowth, which represents the final marine ingression, dated to  $1.12 \pm 0.2$  Myr through the strontium isotopes ( $^{87}$ Sr/ $^{86}$ Sr) method.

**Figure 4.** Coastal caves and submerged speleothems from Italy. 1: Sampling survey at -27 m in the Scaletta cave (Palinuro). 2: Prof. Marco Oliverio (Sapienza University) carrying in his hands the stalagmite collected at -48 m in the Scaletta cave (Palinuro). 3, 4: Argentarola cave and a large stalagmite coverd by serpulid overgrowths. 5: Stalagmite ASN collected at -18 m in the Argentarola cave. The 6 cm portion of the stalagmite covers the last 280 kyr, from MIS 8 to MIS 1 [18]. 6: Stalagmite ASL collected at -18.5 m in the Argentarola cave [17]. 7: View of the Custonaci cave. 8: Stalactite collected at +98 m in the Custonaci cave, showing 4 marine highstands [23]: 9: Stalactite collected at -53 m in the Nettuno cave. Photo by F. Antonioli.

<u>Plemmirio cave</u> (Siracusa, [63]): Submerged speleothems were collected from -15.5 and -36.6 m. The radiometric ages obtained from the U-series disequilibrium method of the speleothem calcite and <sup>14</sup>C of the encrusting serpulids range from MIS 1, 3 and 5.1.

<u>Nettuno cave</u> (Capo Caccia, [81]): A submerged speleothem was sampled at -52 m, representing the deepest speleothem collected in the MS. [82,83] reported the age of phreatic speleothems collected from the same cave which, compared with oxidation bands and tidal notches in the external portion of the cave [84], confirm the MIS 5.5 age with a local highstand at 4.2 m.

Other speleothem samples were retrieved from Stalattiti Ubriache grotta Zingaro reserve (Trapani), Grotta di Tragara Capri, Risorgenza di Cala Luna Orosei (Nuoro) and Grotta Azzurra in Ustica [14] and radiocarbon dated. Results from samples at -9 and -0.6 m depth revealed very recent speleothem formation (between 2 and 4 kyr) (Figures 4 and 5, Table 1).

All the sites described in Italy are tectonically stable with the exception of Plemmirio that is characterized by an uplift rate of 0.3 mm/yr and Rumena cave, which experienced a continuous tectonic uplift of 0.081 mm/yr for the last 1.1 Myr.



**Figure 5**. Coastal caves and submerged speleothems in Italy and Malta. 1: Stalactites sampled at -14 m in Malta. 2: Sampling survey at -41 m in the Scaletta cave (Palinuro) by F. Antonioli, L. Ferranti and M. Oliverio. 3: Oxidation bands observed at +4 m in the Nettuno cave and phreatic speleothems studied by [82]. 4 and 5: Stalagmite collected in Palinuro encrusted by specimens of the barnacle Chthamalus. Cross section of the sample showing the portions collected for 14C and U-series disequilibrium dating. 6: Cattedrale cave (Marettimo Island). 7: Growth model of the stalactite sampled in the Gebel Ciantar cave in Malta [7]. 8: Photo of the Palinuro promontory with the sampling sites of Scaletta cave and the stalagmite with the barnacle overgrowth. 9: Risogenza di Cala Luna cave. Photo by F. Antonioli.

#### 3.3 Malta

[64] studied a submerged spelothem collected at -14.5 m depth in a recently discovered submerged cave at Gebel Ciantar, Malta island Table 1, Figure 5 (1). Since the cave was mainly formed in a subaerial karst environment, the radiocarbon dating of the speleothem with serpulid encrustations Figure 5 (6) enabled reconstructing the sea level during the mid-Holocene when the cave was fully flooded. In particular, the mean radiocarbon age of 7.6 kyr perfectly aligns with the sea level curve predicted by [78] for Malta. [64] concluded that the Maltese islands were tectonically stable during the mid-Holocene, and this tectonic behaviour still persists nowadays.

#### 3.4 Mallorca (1974 -2020)



Appendix C: Tide amplitude and the POS accretion, redrawn from [27]



Figure 6. Photos of phreatic overgrowth on speleothem (POS) in Mallorca.

1: Modern POS at Cova de Cala Varques A (Manacor, Mallorca). Photo by Bogdan P. Onac. 2, 3 and 4: Modern POS at Cova des Pas de Vallgornera (Llucmajor, Mallorca). Photos by Tony Merino. 5: Subactual POS at Cova des Pas de Vallgornera (Llucmajor, Mallorca). Photo by Joaquín Ginés. 6: POS at +2.6 m in Cova des Pas de Vallgornera (Llucmajor, Mallorca), dated to MIS 5.5. Photo by Tony Merino.

The results of more than 30 years of work carried out in 10 different caves of Mallorca, all located along the southern coast of the island (Figure 1) have been published in numerous papers [26,28,35,45,61,76]. POS have been extensively studied and radiometrically dated, both modern samples formed few cm above and below the water table and fossil remains collected up to 15 m above the present sea level. Results have contributed significantly to the sea level reconstruction during MIS 5.1 and 5.5. In particular, [3] first highlight the great potential of studying POS in the caves of Mallorca and paved the way for further in-depth investigations of these distinct encrustations. [26] published the U/Th dating results of 15 POS collected between 1.4 and 5.8 m above the present sea level, spanning ages between 71 and >350 kyr; [76] identified a tilting of the southern coast of Mallorca which reconciles the different heights of speleothems dated to MIS 5.1. [45] analized 8 POS samples from Cova de Cala Varques comparing <sup>14</sup>C with U/Th ages. Result from the two dating methods generally agree but the use of radiocarbon dating can be problematic when the dead carbon proportion values are high. [28,35] reported the results of several U/Th measurements conducted on POS samples located at 1.2 to 1.5 m and at 2.2. to 3.2 m above sea level, respectively. The ages obtained by [28] fall within a narrow range, from  $81.95 \pm 0.56$  and  $80.09 \pm 0.48$ (MIS 5.1), whereas the ages calculated by [35] cover MIS 5.5, from  $126.6 \pm 0.4$  to  $116 \pm 0.8$  kyr: Finally, [61] carried out several U/Th analyses on vadose speleothems collected along the eastern coast of Mallorca at 2 m and 5.5 m above sea level. U/Th ages span a large range, from ~440 and ~1500 kyr Table 3, Figure 6. As also mentioned by the authors, the older ages (> 650 kyr), which were obtained using the  ${}^{234}U/{}^{238}U$  disequilibrium method, suffer of large uncertainties attributable mainly to the errors associate to the initial  $\delta^{234}U$  estimates needed to calculate  $\delta^{234}U$  ages.

#### 3.5 Palinuro

The U/Th dating of the vadose portion of the speleothem provided ages between  $5.49 \pm 1.65$  and  $4.46 \pm 3.74$  kyr, whereas the radiocarbon measurement of the fragment of a *Chthamalus* barnacle gave an age of 1.58 kyr cal BP (median probability). The large uncertainties of the U/Th ages, especially for the sample Palinuro-2, derive from the high detrital Th contamination ( $^{230}$ Th/ $^{232}$ Th < 2).



**Figure 7.** Sea level rise curve since 8 kyr cal BP for Palinuro. Blue/orange squares: U/Th ages of the continental portion of the stalagmite; Blue dot: <sup>14</sup>C age of the barnacle overgrowth. See also Figure 5

Sample_Code	AMS- <sup>14</sup> C													
	<sup>14</sup> C-age (yrs BP)	<sup>14</sup> C-age (yrs BP) Median probability (yrs BP) Calibrate age (yrs BP, 2σ range)												
Palinuro-1	1686 ±45	1580		1513-1646										
	U-series dating													
	<sup>238</sup> U (µg/g)	<sup>232</sup> Th (ng/g)	$\delta^{234}U_m$	(‰)	( <sup>230</sup> Th/	<sup>238</sup> U) <sub>act</sub>	( <sup>230</sup> Th/	<sup>232</sup> Th) <sub>act</sub>	Age	(ka)	δ <sup>234</sup>	U <sub>(0) corr</sub>	Age	<sub>rr</sub> (kyr)*
Palinuro-2	0.336 ±0.003	104.72 ±0.11	81.5	±0.7	0.12697	±0.00066	1.24	±0.01	13.62	±0.08	82.6	±0.7	4.46	±3.74
Palinuro-3	0.148 ±0.001	19.14 ±0.01	54.1	±2.0	0.08615	±0.00348	2.03	±0.08	9.31	±0.41	54.9	±2.0	5.49	±1.65

**Table 5**. Results of the <sup>14</sup>C and U/Th dating of the vadose speleothem (Palinuro-2 and Palinuro-3) and marine overgrowth (Palinuro-1) from Palinuro. <sup>238</sup>U and <sup>232</sup>Th concentrations were determined using the enriched <sup>236</sup>U and <sup>229</sup>Th isotopes, respectively.  $\delta^{234}U_m = \{[(^{234}U/^{238}U)_{sample}/(^{234}U/^{238}U)_{eq}]-1\} \times 1000$ , where  $(^{234}U/^{238}U)_{sample}$  is the measured atomic ratio and  $(^{234}U/^{238}U)_{eq}$  is the atomic ratio at secular equilibrium.  $\delta^{234}U_{(0)}$  corr is the initial value and is calculated by the equation:  $\delta^{234}U_{(0)} = \delta^{234}U_m \exp(\lambda_{234}t)$ , where t is the corrected age in years and  $\lambda_{234}$  is the decay constant for <sup>234</sup>U. \* Ages corrected for detrital <sup>230</sup>Th using an inital <sup>230</sup>Th/<sup>232</sup>Th activity ratio of 0.85 ± 0.36 [73].

#### 3.6 Predicted RSL curves

The predicted RSL curves for ICE-5G, ICE-6G and ANICE-SELEN and VM2 mantle viscosity profile (grey curves in Fig. 8 a-c) show an increase of variability, in the Mediterranean, with respect to the eustatic when moving from the interglacials (i.e. MIS 5.5) through the interstadials (i.e. MIS 5.1-5.3 and MIS 3) and glacials (i.e. LGM).

The relatively limited regional RSL variability during the interglacials, is characterized by a maximum deviation from the eustatic of ~2.5 m for the three ice sheets models (Fig. 8 a-c), confirming previous findings [36,38,85].

This also supports the results of [39] for Bahamas, where the RSL gradient as a function of latitude vanishes during the MIS 5.5. Our predict RSL curves for Bahamas (red curves in Fig. 8 a-c) fall within the Mediterranean response, thus confirming that Bahamas is an intermediate-field site (w.r.t. north American ice sheets), and similarly to the northern Mediterranean sites (w.r.t. Fennoscandia and Eurasian ice sheets).

The predicted maximum highstand during the MIS 5.5 in Bahamas is delayed with respect to the eustatic. For both ICE-5G and ICE-6G, the MIS 5.5 peak occurs at the end of the MIS 5.5 and exceeds the eustatic value. For ANICE-SELEN, instead, the delayed maximum peak is lower than the eustatic.

The predicted RSL variability during the interstadials shows up as deviation from eustasy of the order of ~15 m and ~25 m for MIS 5.1-5.3 and MIS 3, respectively. This confirms previous findings for Bahamas [37,38], and shows that the ice-loading term causes strong regional RSL gradients also in the Mediterranean Sea.

Also at Bahamas, the deviation from the eustatic increases towards the interstadials and glacials [39], implying its dependency on the fluctuations of the north American ice sheets.

At Bahamas, the predicted RSL curves are above the eustatic for both ICE-5G and ICE-6G. On the other hand, ANICE-SELEN results in lower than eustatic curve. The predictions at the Mediterranean sites are distributed around the eustatic values.



**Figure 8** Cumulative predicted RSL curves for ICE-5G (a,d), ICE-6G (b,e) and ANICE-SELEN (c,f) ice sheets models in combination with different mantle viscosity profiles. The grey curves are for each site within the Mediterranean Sea, the red curves are for Bahamas and the black curves represent the eustatic (w.r.t. present-day ocean function) for each ice sheets model.

The cumulative predictions in the Mediterranean for three ice sheets models and mantle viscosity profiles (MVP1-3) are characterized by a larger variability (grey curves in Fig. 8 d-f). Again, the variability increases towards the interstadials and glacials, implying the viscosity gradient is a significant factor in the regional RSL variability in the Mediterranean Sea. The predicted variability at Bahamas is significantly larger than in the Mediterranean (red, green and blue curves in Fig. 8 d-f) and fully bounds the predictions at the Mediterranean sites. Increasing the viscosity gradient, i.e. moving from MVP 1 to MVP 3, results in an upward shift of the RSL curves between MIS 5.5 and LGM. The predicted total RSL glacial-interglacial excursions (glacial-interglacial) for MVP 1are larger than for MVP3, indicating that a larger viscosity gradient (and a larger viscosity value for the lower mantle) results in a significant delay of the solid Earth response. This can be appreciated during the MIS 5.5, when the maximum peak of transgression appears at the end of the interglacial and during the Holocene (i.e. steeper RSL rise curves).



**Figure 9** Predicted RSL curves for ICE-5G (red curves), ICE-6G (green curves) and ANICE-SELEN (blue curves) ice sheets models in combination with MVP 1-3 mantle viscosity profiles (solid, dashed and dotted, respectively) at each site and with respect to the measured elevations. a, predicted RSL curves at MIS 5.1 at Bahamas and with respect to the elevation of the flowstone. b, predicted RSL curves at MIS 5.1 at Mallorca. c, predicted RSL curves at MIS 5.1 in Croatia and elevation of the speleothemes. d, predicted RSL curves at MIS 5.1 at Argentarola and elevation of the speleotheme. e, predicted RSL curves at MIS 5.1 at Argentarola and elevation of the speleothemes. f, predicted RSL curves at MIS 7.1 – 7.2 at Argentarola and elevation of the speleothemes.

## 4. Discussions

The use of submerged speleothems provided remarkable results for the sea level change history during the Holocene and for the long-term sea level change reconstruction during the Late Pleistocene, in particular for MIS 1, 7.1, 7.2, 7.3 and 7.5 highstands (Argentarola stalagmites), MIS 5.1 highstand (Croatia and Mallorca), MIS 5.5 highstand (Mallorca) and MIS 6.5 highstand (Nettuno cave in Italy) (Tables 1, 2). Unfortunately, marine overgrowth layers encrusting Italian or Croatian speleothems with ages beyond the radiocarbon dating range (i.e. > 40-50 kyr) cannot be analysed by the U-series disequilibrium method due to diagenetic overprints that cause exchange of uranium [86].

## 4.1 Palinuro speleothem

For the interpretation of the <sup>14</sup>C and U/Th results obtained from the Palinuro sample, a study of the tidal area was conducted along the promontory of Palinuro over a distance of ~3 km from the sampling site. The survey revealed the presence of a fossil tidal notch, below which we found specimens of the crustose coralline algae *Lithophyllum*, the acorn barnacle *Chthamalus* and the limpet *Patella*. Based on [78], the sea level was 4.4 m, 3.3 m and 0.73 m lower that the present level at 5.5 kyr, 4.5 kyr and 1.6 kyr, respectively (Table 3, Figure 7). Therefore, the barnacles started to colonize the stalagmite at 1.6 kyr when the rising sea reached a level that exposed the sample to strong wave conditions, favourable to the barnacle growth. However, no living barnacles were observed during the sampling of the stalagmite and this might be due to changes of the environmental conditions since the deposition of the fossil barnacles.

#### 4.2 Speleothems from Italy



Figure 10  $\delta^{18}$ O series of the marine layer of ASI (-18.5, MIS 5.5), compared with ODP 975 (Central Mediterranean sea), redrown from [16]

U/Th dating and geochemical analyses of the speleothem samples from the Argentarola cave provided detailed information on the timing, duration and position of sea level highstands during MIS 7.1, 7.2, 7.3, 7.4 and 7.5 [17,18]. Based on the  $\delta^{18}$ O results obtained from the serpulid overgrowth on a stalagmite collected at -18.5 m from the same cave (Figure 4 (6)) and the correlation with foraminifera  $\delta^{18}$ O values from the Mediterranean ODP site 975 [87], [16] identified as MIS 5 the timing of the marine overgrowth deposition, without any visible interruption from MIS 5.1 to MIS 5.5 (Figure 9). It is worth mentioning that the timing of the MIS 7.3 and 7.2 highstands identified by U/Th dating on the speleothem agrees with the global sea level curve reconstructed by [88]. In the Nettuno cave, the deepest speleothem sampled in the Mediterranean at -52 m was dated by the

alpha-counting U-series method (see Table 1 Figure 4), which provided an age of  $165 \pm 12$  kyr, corresponding to MIS 6.5 and in agreement with [88].

Finally, as regard the speleothem Plemm A (Table 3) in the Plemmirio cave [62] collected the sample at -20.2 which is corrected to -35.3 m when considering the tectonic uplift (0.2 mm/yr, [62])

# 4.3 Speleothems from Croatia

The speleothems retrieved along the Croatian coast and studied by [20,21,24,65,75,89,90] greatly contributed to the sea level reconstruction from 1.5 kyr to 220 kyr (Figure 11). In particular, high-precision U/Th. dating of the speleothems K-14 and K-18 sampled at -18.8 m and -14.5 m in the U vode Pit cave (Krk Island) provided significant data to constrain the relative sea level curve during MIS 5.1 highstand. Regarding the presence of 2 hiatuses in the K-18 stalagmite, on the basis of the lack of XRD analyzes that invoked the presence of a hiatus between 90.8 ka and 82.9 ka, in correspondence with a change in color, we suppose that only the second hiatus is present between 77.7 ka and 64.5 kyr Fig. 3.



Fig 11 Sea level curve for Croatian Speleothem redrown from [21]

The ~13-18 m difference between the elevation of the two speleothems (-18.8 m and -14.5 m) with the ice-volume-equivalent global sea level curve by [91] has been justified by [21] invoking a long-term regional tectonic uplift with an average rate of 0.15-0.25 mm/yr during the last 75-85 kyr. However, the vertical tectonic movements along the Croatian coast are still a matter of debate. For example, [90] suggested a generalized downlift in Istria and uplift along the southern cost of Croatia. [7] investigated the carbonate coast stretching from Trieste to southern Croatia and showed that the tidal notch is always submerged between 1.8 and 0.5 m below mean sea level. Furthermore, archaeological studies along the Croatian coast revealed the presence of Roman remains (2 kyr BP), including pier and fishtanks, at ~1.5-1.8 m below sea level as a result of tectonic subsidence or coseismic downlift [92,93]. Finally, none of the fossil outcrops related to the MIS 5.5 highstand that are usually found at ~6 m a.s.l. in tectonically stable regions [36,94] have been observed so far in the north-eastern Adriatic Sea. Therefore, we hypothesize that most of this area is affected by tectonic subsidence (a minimum of 6 m since MIS 5.5), with possibly local uplift movements [21]. Accordingly, we decided to correct the elevation of the stalagmites K-14 and K-18 by 4 m, to -10.4 and -14.7 m, respectively, assuming a constant subsidence of 0.048 mm/yr for the last 80 kyr.

## 4.4 Speleothems from Mallorca

A large number of precise U and Th isotope measurements have been performed on submerged speleothems sampled from 10 coastal caves on the island of Mallorca. Data published by [35] agree with previous studies reporting MIS 5.5 fossil deposits in Mallorca [95,96]. These deposits contain the Tyrrhenian Senegalese fauna assemblage that was analysed by the amino-acid dating technique [95] and remainings of the coral *Cladocora caespitosa* that were dated by U/Th [96].

The elevation of MIS 5.1 POS samples studied by [28] in Mallorca still represents a scientific debate.

The reconstructions obtained by [88] and [97] indicate that sea level during MIS 5.1 was 21.2 m and 26.7 m below present sea level, respectively. However, the global sea level curves do not take into account the local tectonic and GIA. Based on the U/Th results of [96] on the fossil corals from Mallorca, we can rule out the presence of MIS 5.1 coral deposits in the Island.

In Sardinia, the presence of fossil tidal notches, attributed to MIS 5.5, was reported by [66] in the Orosei Gulf, a tectonically stable coastal area in Italy. The fossil tidal notches in this area show a lateral continuity of tens of kilometers, while there is no evidence of younger fossil tidal notches at lower altitudes.

In other regions worldwide, like in the Carribean Sea, observational data of MIS 5.1 deposits from submerged speleothems seem to disagree with the finding of POS samples located at ~1.4 m a.s.l. in Mallorca and dated at ~81 kyr BP. The U/Th results for the DWBAH flowstone recovered from 15 m below present sea level in Grand Bahama Island clearly indicate that during MIS 5.1 the sea level did not rise as high as -15 to -10 m [6].

Discrepancies on the elevations of different sea level markers, ranging from -20 m to +5 m, are found along a latitudinal transect on tectonically stable areas for the coasts of Haiti, Bermuda, Bahamas, South Carolina, and Florida. However, these apparent inconsistencies are reconciled when taking into account the isostatic response of the Earth to the North American ice sheets melting during the last glacial cycle [39]

Results from the MIS 5.1 POS samples in Mallorca agree with:

• The finding of some deposits from the same age between +2 and +1.5 m near Gibraltar [98]; but disagree with:

- All the eustatic curves (in particular [75] and [85]);
- The U/Th ages reported by [84] for Mallorca;
- The speleothem from Plemmirio located at -20.2 m [62];
- The speleothems K-18 and K-14 from Croatia at -18.8 m and -14.5 m;
- The DWBAH flowstone from Bahamas at -15 m;
- The morphology of the MIS 5.5 tidal notches (Antonioli et al., 2018) and the lack of younger tidal notches;

• The mushroom-like landforms with tidal notches at -25 m found at Tavolara island (Sardinia) and interpreted by [36] as being MIS 5.1 in age;

• The results of glacial and hydro-isostatic adjustment (GIA) of the Mediterranean sea (See Figures 8, 9).

We decided to compare the vertical position of most of the submerged speleothems described in this review with the DWBAH flowstone [4,6] (Fig. 15, 16 and 17). This exceptional flowstone contain 5 hiatuses identified by the deposition of a thin layer of red or yellow mud (Fig. 12), and was extensively dated by the U-series disequilibrium method, providing precise ages that unravealed for the first time the history of sea level variations from ~300 kyr to ~30 kyr. The hiatuses mark the

marine highstands as follow: H1 between 231 kyr and 237 kyr (MIS 7.5), H2 between 213 kyr and 220 kyr (MIS 7.3), H3 between 112 kyr and 127 (MIS 5.5); H4 between 94 kyr and 105 kyrs (MIS 5.3); H5 at 34 kyr (Figure 12). DWBAH flowstone elevation and the original U/Th ages were corrected for a tectonic subsidence of about 1 m for 50 kyr [4] and for the detrital <sup>230</sup>Th component (see Materials and Methods and Appendix D).



Figure 12 The DWBAH flowstone, sampled at -15 m in the Grand Bahama Island (courtesy Joyce Lundberg)

Based on the correction for the subsidence, the DWBAH flowstone started to form ~300 kyr ago at -10 m and ceased growing ~39 kyr ago. The flowstone is presently located at -15 m. Similarly, the elevation of the two speleothems sampled in the Plemmirio cave in Sicily (Table 3) was corrected from 20.2 m b.s.l. and 35.3 m b.s.l. to 22.7 m b.s.l. and 38.2 m b.s.l. considering an uplift rate of ~0.2 mm/yr, as evaluated by [63].

In Croatia, the elevation of the stalagmites K-14 and K-18 was corrected considering a subsidence of ~ 4 m in 81 kyr. The correction derives from the fact that MIS 5.5 at 6 m a.s.l., or at higher elevations, has been never found in Croatia. This means that MIS 5.5 is below the present-day sea level and 4 m is extrapolated from a subsidence of the coast of at least 6 m in 125 kyr, corresponding to MIS 5.5. The elevation of the other speleothems considered in the present review (i.e. Argentarola cave, Mallorca, Malta and Sardinia) was not corrected for uplift or subsidence owing to the tectonic stability of these areas.

### 4.5 GIA-modulated RSL curves

The GIA modulated regional RSL variability in the Mediterranean is minimal during the Interglacials (~2.5 at MIS 5.5) but increases during the Interstadials (~15 m at MIS 5.1-5.3), thus complicating the task of finding the correct eustatic value (grey curves in Fig. 8). In fact, the GIA signal is strongly dependent on the solid Earth rheological profile, which is itself an unknown. In particular, the viscosity gradient and the lower mantle viscosity are important parameters in the Mediterranean Sea, as well as at Bahamas. The predictions at Bahamas are characterized by a larger mantle-driven variability around the eustatic than in the Mediterranean sites during MIS 5.1-5.2 (Fig. 8 d-f). In particular, for each ice sheets model, increasing the vertical viscosity gradient (i.e. moving

from MVP 1 to MVP 3) results in a vertical upwards shift of the RSL curves of ~ 25 m (Figure 9 a and Figure 14). At Mallorca, on the other hand, the predictions for each ice sheets model are very close to each other (Fig. 9 b), implying that the local signal is almost eustatic between MIS 5.1 and MIS 5.3, and the role of the mantle viscosity profile is negligible (see also Figure 16). The MIS 5.1-5.3 RSL variability increases slightly in the other Mediterranean sites and is larger for ANICE-SELEN (blue curves in Fig. 9 c-e; see also Fig. 14).

When compared to the observations, the predictions are generally significantly lower, with the MVP 3 scenarios reducing the vertical gap between model predictions and observation (Fig. 9 a-f). At Bahamas, for each ice sheets model, the MVP 3 profile shifts the RSL curve upwards and closer to the observed transgression at the MIS 5.3. This implies that a slightly higher eustatic (hence smaller ice sheets volume) might be necessary to explain the observed submersion. The observed +1.5 m sea level at Mallorca at 81 ka, on the other hand, stands out as a clear outlier and cannot be reconciled with the current ice-sheets and earth rheological models. Predictions at Croatia, Plemmirio and Argentarola (Figure 9 c-e) are in agreement with the observed vertical limits. However, the models cannot exceed the -20 m limit at 81 ka in Argentarola, thus implying that a further melting of ice sheets is required.



**Figure 13** Predicted MIS 5.1-5.3 RSL curves at Bahamas and at the relevant Mediterranean sites for ANICE-SELEN and MVP 3 mantle viscosity profile. The black curve shows the eustatic

The predicted MIS 5.1 regional RSL variability, according to ANICE-SELEN and MVP 3, is characterized by higher-than-eustatic values towards East-North East and around the continental margins (Fig. 17). On the other hand, the predicted values are lower than eustatic at the center of the basins towards South East (where the ocean loading term dominates). Interestingly, Plemmirio and Mallorca are very close to the eustatic (Fig. 17).



## Figure

**14** Predicted RSL elevation in the Mediterranean Sea during MIS 5.1 according to ANICE-SELEN and MVP 3 mantle viscosity profile. The pink dots indicate the location of the sites. The black isoline corresponds to the eustatic (-38.5 m).

Predictions based on ANICE-SELEN and MVP 1-3 are in satisfactory agreement with the MIS 7.1-7.2 observations at Argentarola (Fig. 9 f).



#### 5. Conclusions

**Figure 15** Elevations and radiometric ages (<sup>14</sup>C and U/Th) of the Mediterranean speleothems and marine overgrowths discussed in the present study and comparison with the DWBAH flowstone. <u>Argentarola (Italy)</u>, -18.5, [17]; -18, -21.7, [18]; <u>Plemmirio (Italy)</u>, -23 m, [63]; Grotta di <u>Nettuno (Italy)</u>, -53 m, [81]; <u>U vode Pit (Krk Island, Croatia)</u>, Stalagmite K-14 (-14.5 m) and K-18 (-18.8 m), [24]; POS from Mallorca (Spain), +1.5 m, [28,35]; Malta, [64]; DWBAH <u>Flowstone (Bahamas)</u>, -15 m, [6]. Black line: global sea level curve built by [88]



**Figure 16.** Zoom 1 of figure 15 Green line: DWBAH flowstone [6]; pink line: Stalagmite ASI (-18.5) from Argentarola cave [18]. Black line Speloethems K14 and K18. Yellow and blu line : Mallora POS; Fine lack line: global sea level curve reconstructed by [88]



**Figure 17.** Zoom 2 of figure 15. Green line: DWBAH flowstone [6]; orange line: Stalagmite ASN (-18 m) from Argentarola cave [17], and stalagmite ASI (-18.5) from Argentarola cave [18]. Black line: global sea level curve reconstructed by [88]. Dark blue line: sea level drown with observed data.

The use of submerged speleothems significantly contributed to reconstruct the short-term (Holocene) and long-term (Middle and mostly Late Pleistocene) sea level changes in the Mediterranean. Even though there are still some open questions, the different groups that have been working on the speleothems from Mallorca, Croatia and Italy since many years, have carried out an extensive and valuable work, which significantly contributed to improve our knowledge on the sea level changes during the Mid- and Late Pleistocene.

The present review reports the elevations and radiometric ages (<sup>14</sup>C and U/Th) of the published submerged speleothems in the Mediterranean. Elevation data are corrected for local tectonics (uplift or subsidence) and compared with results from the DWBAH flowstone in Grand Bahama Island.

<u>Holocene</u>: Most of the data on the Holocene sea level curve in the Mediterranean result from the investigation of continental portions of submerged speleothems, marine overgrowth (serpulids) and *Lithophaga* boring mussel in samples collected in Italy and Croatia;

<u>MIS 3</u>: The K-14 stalagmite from Croatia shows that sea level during MIS 3 never reached 15 m b.s.l. Sea level during MIS 3 was lower than 21.7 m in Argentarola, lower than 25 m in Marettimo and lower than 45 m in Sicily. However, this latter value was corrected for vertical tectonics.

<u>MIS 5.1</u>: Samples of phreatic overgrowth on speleothem (POS) collected at 1.5 a.s.l. show an U/Th age of ~81 kyr. However, other speleothem samples from Croatia (K-14 and K-18) and Sicily (Plemm A), collected at lower elevation (-14.5, -18.8 and -20.2, respectively) do not show evidence of growth interruption (hiathus) during MIS 1. [28] estimated a duration of 2.5 kyr for MIS 5.1;

<u>MIS 5.3</u>: The sea level highstand corresponding to MIS 5.3 reconstructed by the DWBAH flowstone is higher compared to the global sea level curve from [88];

<u>MIS 5.5</u>: POS samples in Mallorca record a relative sea level at  $2.15 \pm 0.75$  m [35]. However, other fossil evidences suggest sea level between 7 m and 8 m a.s.l. [36]; [35] reported a duration of 11 kyr for MIS 5.5, from 116 kyr and 127 kyr;

MIS 6.5: The deepest stalagmite collected so far in the MS from the Nettuno cave (Sardinia) at -52 m and dated to ~ 165 kyr [81] suggests that the sea level was lower than the elevation of the submerged sample;

<u>MIS 7.1</u>: Three speleothems from the Argentarola cave (Figure 13) clearly show a serpulid layer between MIS 6 and MIS 7.2 [17,18]. The sea level was therefore higher than 18 m b.s.l.. Based on the results from the DWBAH flowstone, lacking a hiathus at 197 kyr [6], the sea level was lower than 12 m b.s.l., in agreement with the global sea level [88]. The duration of the sea level highstand was between 201.5 kyr and 198.7 kyr [18];

<u>MIS 7.2</u>: The highstand is represented in the Argentarola cave. The sea level stillstand between 18.5 m b.s.l. and 21 m b.s.l. is quite similar to the global curve that reaches 27 m b.s.l.;

<u>MIS 7.3</u>: Based on the results from the stalagmites of the Argentarola cave (Fig. 13), the sea level was slighty lower than 18 m b.s.l. In fact, speleothems record the presence of the sea at 21.3 m and 18.5 m b.s.l. Therefore, resuts from Mediterranean speleothems reduce the elevation of the MIS 7.3 highstand, reconstructed from the global sea level curve [88]. However, the DWBAH flowstone shows a hiathus during MIS 7.3, which seems to be older than the marine layers from the Argentarola stalagmites. The duration of the sea level highstand was between 217.2 kyr and 201.6 kyr [18];

<u>MIS 7.5</u>: The results from the stalagmites of the Argentarola cave and DWBAH flowstone indicate that the sea level was between 18 m and 12 m b.s.l., in agreement again with the global sea level curve [88]. The duration of the sea level highstand was between 248.9 kyr and 231.0 kyr [18].

Some GIA models have been published for the Mediterranean basin [35,36,38]. The latter two models were tested in the field with the comparison of coastal fossil deposits aged MIS 5.5 and fossil tidal notches of the same age. The maximum reported differences for the entire Mediterranean basin for MIS 5.5 are less than 2.5 m in elevation. This value is consistent with the predicted GIA-driven RSL variability within the Mediterranean basin during the MIS 5.5.

Here we show, for the first time, that the regional RSL variability increases during Interstadials MIS 5.1-5.3 and Glacials (MIS 2), most likely as a consequence of the ice-loading-induced spatial RSL gradients. However, because the GIA signal also depends on Earth rheology, this further complicates the search for the eustatic constraints in the Mediterranean Basin.

Overall, we argue that the observations call for a revised eustatic (i.e. ice sheets volume) during MIS 5.1-5.3 and MIS 7.1-3. In particular, we speculate that a reduction of ice sheets volume, hence an increase of the eustatic, is needed during MIS 5.1-5.3. This is consistent with the recent findings of [99], which are based on a novel ice sheet modelling technique.

In particular for MIS 5.1, based on the elevations below sea level observed in the ASI stalagmite (Figure 13, Table 3) between the well dated continental layers of MIS 6 and MIS 3 at -18 m [16,17] and the altitude of the Bahamian flowstone [35] at -13.5 m, which is considered mid-field like the Mediterranean, see Figures 8 an 9, and therefore comparable with the Mediterranean speleothems described in figures 15, 16, 17 it is possible to hypothesize an eustatic altitude of MIS 5.1 of approximately -16 meters (average between 18.5 and 13.5). According to Figure 14 the Mallorca site is located around this eustatic altitude while the Croatian site (samples K-14 and K-18, Table 4) would be raised for isostatic reasons of about 7 meters, all that in agreement with [99], and the novel ice sheet modelling technique described.

However, we also argue that the high value observed in Mallorca (1.5 m above m.s.l.) cannot be reconciled with GIA and would require a drastic reduction of ice sheets volume, which is not required at other sites.

Sample	U conc.	<sup>234</sup> U/ <sup>238</sup> U	<sup>230</sup> Th/ <sup>234</sup> U	<sup>230</sup> Th/ <sup>232</sup> Th	Age uncorrected	<b>-2</b> σ	2σ	Age re-calculated	Age corrected
	(ppm)	Act.	Act.	Act.	(kyr)	(kyr)	(kyr)	(kyr)	(kyr)
1	0.14	1.07	0.85	200	196.9	7	7	197.9	197.6
2	0.13	1.07	0.82	362	177	9.4	11.1	180.2	180.0
4	0.12	1.06	0.79	1499	164.1	10	11.7	165.6	165.6
5	0.13	1.06	0.81	682	177	10	10.5	175.7	175.6
6	0.14	1.06	0.8	562	168.2	4.1	4.1	170.5	170.4
7	0.15	1.06	0.58	849	94.3	8.2	8.8	93.6	93.5
8/9	00.13	1.06	0.7	2202	129.5	4.4	4.4	129.0	128.9
10	0.13	1.06	0.74	1466	144.1	9.4	10.5	143.8	143.8
10r	0.13	1.06	0.73	1635	138.9	10	10.5	139.9	139.9
11	0.21	1.07	0.84	67	188.7	5.3	4.7	191.7	190.7
12	0.28	1.07	0.72	64	133.6	2.3	2.3	135.7	134.8
13	0.16	1.06	0.58	196	92.6	2.6	2.3	93.6	93.3
14	0.15	1.06	0.48	1459	70.6	3.8	4.1	70.8	70.7
14r	0.15	1.06	0.45	1395	64.5	4.4	4.4	64.8	64.7
15	0.19	1.06	0.45	1250	64.2	1.2	1.2	64.8	64.7
16	0.15	1.06	0.45	1236	64	5.3	5.6	64.8	64.7
17	0.08	1.02	0.38	799	51	5	5.1	52.0	52.0
18	0.12	1.05	0.3	237	39.1	1.4	1.4	38.8	38.7
F	0.16	1.06	0.74	1864	143	3.5	2.9	143.8	143.8
G	0.18	1.06	0.75	2484	145.9	4.7	4.7	147.8	147.8
н	0.2	1.06	0.75	2642	149	4.1	4.7	147.8	147.8
1	0.2	1.06	0.73	2461	140	5.9	5.3	139.9	139.9
Ν	0.21	1.06	0.89	228	226.2	8.2	8.2	228.5	228.2
Р	0.26	1.05	0.9	1567	241.4	7	7	239.3	239.3
Q	0.34	1.06	0.9	854	236.7	11.7	14.1	237.3	237.2
Qr	0.34	1.05	0.93	963	269.5	21.1	25.8	271.6	271.5
R	0.38	1.05	0.97	133	328.1	18.8	23.4	337.5	337.0
A1	0.09	1.05	0.86	1285	208.6	22.3	28.1	207.0	206.9
T1	0.14	1.06	0.9	1573	239.1	19.9	23.4	237.3	237.3
T2	0.14	1.06	0.89	1215	225	11.7	15.2	228.5	228.5
Τ4	0.22	1.06	0.89	173	225	7	5.9	228.5	228.1
T4r	0.21	1.06	0.88	223	222.7	9.4	8.2	220.4	220.1
B1	0.22	1.06	0.9	769	240.2	9.3	10.5	237.3	237.2
B2	0.16	1.05	0.93	186	274.2	9.4	9.4	271.6	271.2
Y	0.25	1.04	0.64	278	108.4	2.9	3.2	110.4	110.2

Appendix D Flowstone ages **[6]** that we corrected for the detrital <sup>230</sup>Th component.

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## Supplementary Materials:

# Author Contributions:

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# Appendix

Appendix A GIA in Caribbean islands and Florida (redrawn from [39])

Appendix B: U/Th ages vs. sampling depth of the flowstone DWBAH (redrawn from [4])

Appendix C: Tide amplitude and the POS accretion, redrawn from [27] Appendix D Flowstone ages [6] that we corrected for the detrital <sup>230</sup>Th component.