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**Research Article**

# Characterization of phreatic overgrowths on speleothems precipitated in the northern Adriatic during a sea-level stillstand at ca. 2.8 ka

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## Abstract

We examined a Late Holocene sea-level stillstand using phreatic overgrowths on speleothems (POS) recovered from Medvjeđa Špilja [Bear Cave] (northern Adriatic Sea) from −1.28 ± 0.15 m below present mean sea level. Different mineralogical analyses were performed to characterize the POS and better understand the mechanisms of their formation. Results reveal that the fibrous overgrowth is formed of calcite and that both the supporting soda straw and the overgrowth have very similar trace element compositions. This suggests that the drip-water and groundwater pool from which the POS formed have similar chemical compositions. Four subsamples were dated by means of uranium-series. We found that ca. 2800 years ago, the relative sea level was stable for about 300 years at a depth of approximately −1.28 ± 0.15 m below the current mean sea level. This finding roughly corresponds with the end of a relatively stable sea-level period, between 3250 and 2800 cal yr BP, previously noted in the southern Adriatic. Our research confirms the presence of POS in the Adriatic region and establishes the Medvjeđa Špilja pool as a conducive environment for calcite POS formation, which encourages further investigations at this study site.

**Keywords:** Cave deposits, U-series dating, Sea level, Holocene, Northern Adriatic, Croatia

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## INTRODUCTION

In paleo sea-level research, various indicators, including sedimentological, geomorphological, archaeological, biological, and historical sources are used and often combined (e.g., Faivre and Fouache, 2003; Faivre et al., 2013; Shennan et al., 2015). In coastal caves, hiatuses in speleothem growth signal a switch between vadose and phreatic conditions. Gascoyne et al. (1979) and Li et al. (1989) are among the first researchers who documented mineralogical changes on the surfaces of such hiatuses. Furthermore, investigations on previously submerged speleothems that contain marine biogenic overgrowths and marine boring organisms (e.g., Alessio et al., 1992, 1994; Antonioli and Oliverio, 1996) provide an additional tool to assess past sea-level positions in littoral caves (Onac et al., 2012; van Hengstum et al., 2015). The study of submerged speleothems in sea-level reconstructions has contributed significantly to the understanding of regional and global sea-level changes, especially for the western (Antonioli et al., 2002, 2004a, 2021; Bard et al., 2002; Stocchi et al., 2017) and the eastern Mediterranean basin (Surić et al., 2005, 2009; Surić and Juračić, 2010). Based on the age of marine overgrowth on speleothems, segments of the relative sea-level curve for the last 220 ka, which have been constructed for the eastern Adriatic coast (Surić and Juračić, 2010), are in general agreement with the global sea-level curve. The Early Holocene sea-level rise reached −41.5 m at ca. 9.2 ka and −10 m at ca. 7.8 ka and rose to −1.5 m by ca. 3.4 ka (Surić and Juračić, 2010).

Sea-level studies based on phreatic overgrowths on speleothems (POS) have been conducted since the early 1970s (Ginés and Ginés, 1974). Unlike the submerged speleothems and biogenic encrustations, POS allow precise sea-level reconstructions (Vesica et al., 2000; Tuccimei et al., 2010; Polyak et al., 2018; Onac et al., 2022). POS are secondary depositional structures (carbonate encrustations) that precipitate in coastal caves at the water table around pre-existing vadose speleothems in favorable geochemical conditions (Ginés et al., 1981; Fornós et al., 2002). POS grow at sea level and within the tidal range for as long as sea level remains at the same elevation (Dumitru et al., 2021) (Fig. 1). These overgrowths are composed of aragonite and/or calcite, with the latter being more common. Each POS has an exact geographic location, its elevation can be measured with high precision, its morphology provides an indicative meaning (mean sea level), and it is datable by uranium-series method. These characteristics make POS ideal sea-level index points (van de Plassche, 1986), and thus excellent markers of sea-level change with local and global significance.

In Mediterranean littoral caves (within ~300 m from the coastline), the hydraulic gradient between location and the sea

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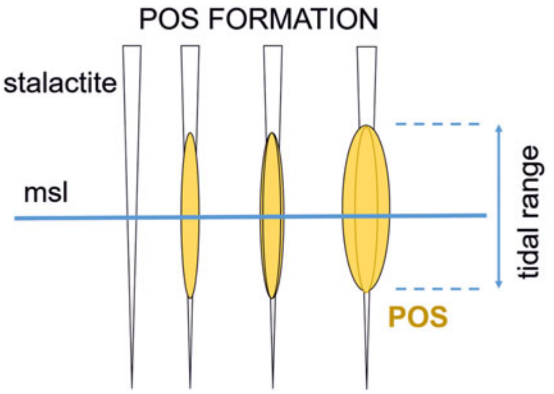

**Figure 1.** Conceptual model of phreatic overgrowths on speleothem (POS) formation (after Dumitru et al., 2021); msl = mean sea level.

is insignificant, so the cave water table is coincident with sea level, and was in the past (Dorale et al., 2010). Uranium-series (U-series) dating has shown that POS normally behave as closed systems, thus providing reliable ages (Tuccimei et al., 2006, 2011; Dorale et al., 2010). This allows precise constraint to be placed on the timing of sea-level change, assuming that sea level remained at the same elevation for ca. 300 years or more (Polyak et al., 2018; Dumitru et al., 2021).

According to Ginés et al. (2012), the first description of carbonate encrustations (later defined as POS) refers to speleothems from Coves del Drac (Mallorca) by Rodés (1925) and de Joly (1929), who assumed that their formation was related to drowning events associated with past water-table elevations. The first thorough studies of POS as sea-level indicators in littoral caves of Mallorca began in 1972 when Ginés and Ginés (1974) proposed to relate subaqueous crystallization of speleothems from Cova de sa Bassa Blanca with past Pleistocene sea stands. Besides Mallorca, POS have been used for sea-level reconstructions in Sardinia (Tuccimei et al., 2012), Japan (Miklavič et al., 2018), and Cuba (De Waele et al., 2017, 2018). POS also have been identified and described in Bermuda (Harmon et al., 1978) and Mexico (Jenson et al., 2018). So far, POS-based research has contributed greatly to the study of sea level, in particular to precisely characterize the Late Pleistocene highstands, and to improve the glacial isostatic adjustments for the western Mediterranean (Tuccimei et al., 2012; Polyak et al., 2018; Onac et al., 2022). However, some POS that formed during the Late Holocene (Tuccimei et al., 2010, 2011; Miklavič et al., 2018) and, during the last 2800 years in particular, show sea-level stability throughout that period (Onac et al., 2022).

Considering the abundance of karst forms in Croatia, including anchialine caves (Surić et al., 2010), one of the goals of the SEALeveL project (HRZZ IP-2019-04-9445) was to find POS in the Adriatic that would enable more robust relative sea-level change studies and to combine these results with results from other markers. The research presented herein is based on mineralogical and U-series analyses of the first POS discovered in the Adriatic Sea. Our aim is to characterize the POS and the environment of its formation, and to define the period of relative the sea-level stability related to its growth.

## STUDY SITE

POS were found in Medvjeđa Špilja [Bear Cave] on Lošinj Island (Kvarner region, northern Adriatic; Fig. 2), which is located in the complex contact zone between Adriatic foreland, Istrian Peninsula, and the external Dinarides (Korbar, 2009; Schmid et al., 2020; van Hinsbergen et al., 2020). According to Špelić et al. (2021), this area is dominated by an alternation of structural lows and highs, mainly oriented N–S, NNW–SSE, and NW–SE (Fig. 2). A comprehensive overview of the eastern Adriatic tectonic setting is given in Korbar (2009). The area is mainly composed of Carboniferous to Eocene carbonate rocks that were deposited in shallow-marine environments (Vlahović et al., 2005). Prevalent strata on Lošinj Island are carbonate deposits of Cretaceous age, as well as Eocene foraminiferal limestone and Quaternary loess deposits (Korbar, 2009).

Formation of caves in karst is predominantly controlled by structural characteristics of the area, as is the case with Medvjeđa Špilja (Fig. 2b). Tectonics and favorable climatic conditions, along with Pliocene and Pleistocene sea-level fluctuations, caused carbonate areas to emerge, leading to the karstification of today's eastern Adriatic coast (Surić et al., 2010, 2014). During the Late Pleistocene–Holocene marine transgression, karst features such as caves became submerged. The speleothems within these caves now provide a potential record for reconstructing Quaternary relative sea-level changes.

Medvjeđa Špilja is an anchialine cave developed in Cretaceous limestone and situated in the central part of the Lošinj Island, ~55 m from the sea and 17.5 m asl (Fig. 1). The entrance to the cave is through a narrow opening formed along a vertical fissure that extends perpendicular to the coast (Malez and Božičević, 1965). The entrance leads to a bell-shaped chamber with a lake at the bottom. The rest of the cave is a mostly submerged channel with a total length of 245 m stretching along a NNE–SSW trending fissure (Jalžić, 2007) parallel to the coast (Fig. 3) The cave is linked to the sea through karstified fractures. The connection between fresh groundwater and the sea is rather direct, as often documented along the eastern Adriatic coast (Bonacci and Roje-Bonacci, 2003). Short time in-situ measurements (see Methods) revealed a tidal range of 44 cm, whereas the long-term average in the area is 48 cm (Faivre et al., 2011b). The existence of cave bear (*Ursus spelaeus*) remains (Malez et al., 1979) and collapse material in the seaward part of the cave, as observed in recent diving explorations, suggest an open horizontal connection to the coast in the past. The cave is rich in speleothems, which are mostly submerged. Salinity increases with depth. The halocline was observed at a depth of approximately −2 m during dive prospecting.

## MATERIAL AND METHODS

### Sampling and depth measurement

We conducted detailed cave diving explorations in March and October 2021, resulting in the recovery of suitable speleothems from all submerged parts of the cave. Sample MLp1 is a stalactite found at Little Lake passage rooftop (Fig. 3a) and collected in growth position at the uppermost part, at a depth of −1.28 ± 0.15 m. The speleothem is ~8 cm long, tapering from 0.5 cm at the top to ~2.0 cm at the base. This widening towards the base gives the speleothem a rounded shape, which is consistent with the morphology of POS. Its surface is light yellowish (Fig. 4). After collection, the sample was cut in half by diamond disc attached to a rotary drill mounted to a special constructed slider.

Sampling depth was measured on several occasions with the pressure depth-meter built in the Suunto EON steel diving computer, which has an accuracy of ± 1% and resolution of ± 0.1 m.

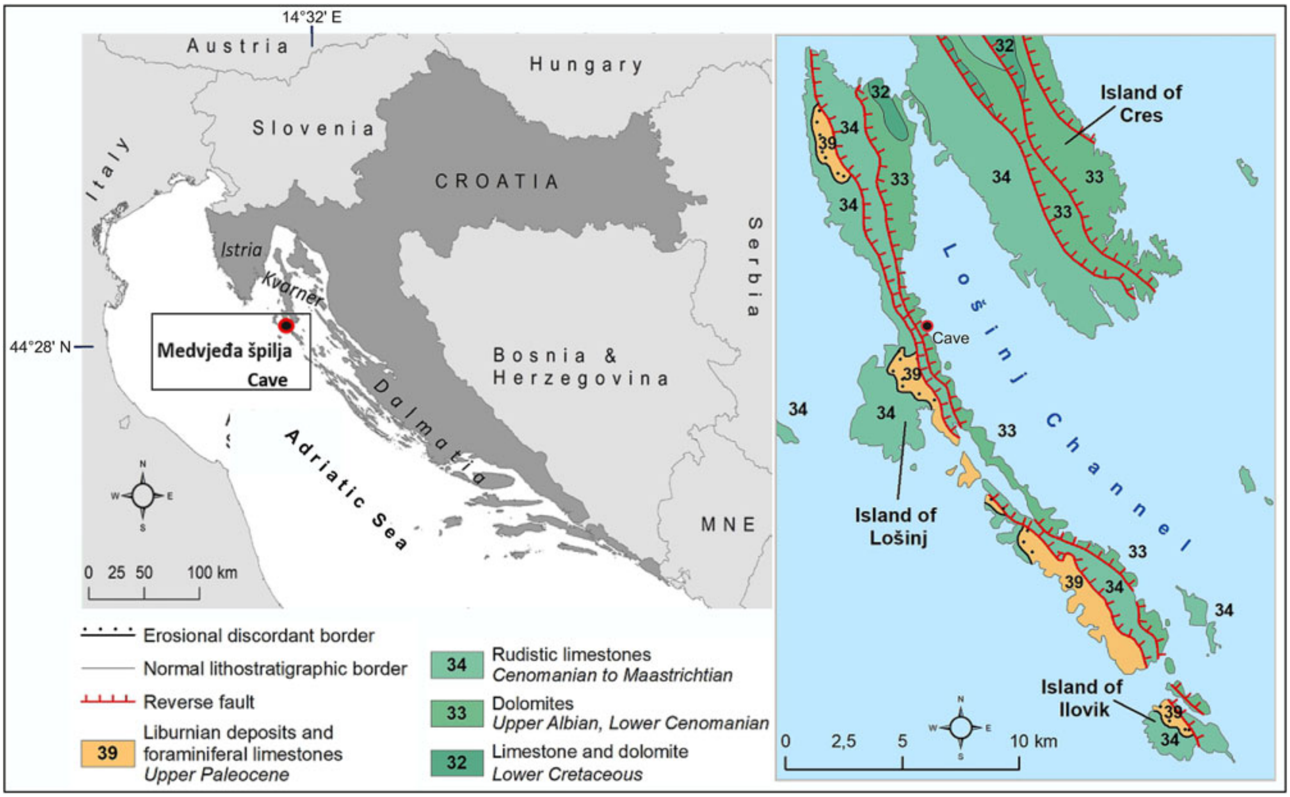

**Figure 2.** Study site and geologic setting (based on the Geological Map of the Republic of Croatia, scale 1:300 000, Croatian Geological Survey); MNE = Montenegro.

All measurements revealed the same depth. To establish the depth of measurements, the uppermost part of the soda straw was chosen as reference point. The elevation of POS paleo-levels presented here is the sum of the depth at which the sample was taken and length of the sample, referenced to the current mean sea level (MSL).

To confirm the connection between groundwater and open sea, as well as the tidally induced oscillation within the cave pool, both sea-level and groundwater-level fluctuation were recorded using a HOBO U20-001-02 TI water level logger. The device measures pressure and converts it to water elevation using the HOBOware-Pro software package with a typical accuracy of 0.3 cm (Onset, 2022). The logger was deployed during the spring tide period between October 8 and October 11. One logger was placed inside the cave in Little Lake (Fig. 3), whereas the second one was placed in the sea at same depth. A high-resolution (10-min) recording was set in order to eliminate the possibility of a false signal caused by waves. The measurements recorded a spring tide range of 44 cm, and the high tide occurred on 9 October 2022 at 20:55 (CMHS, 2022). To account for

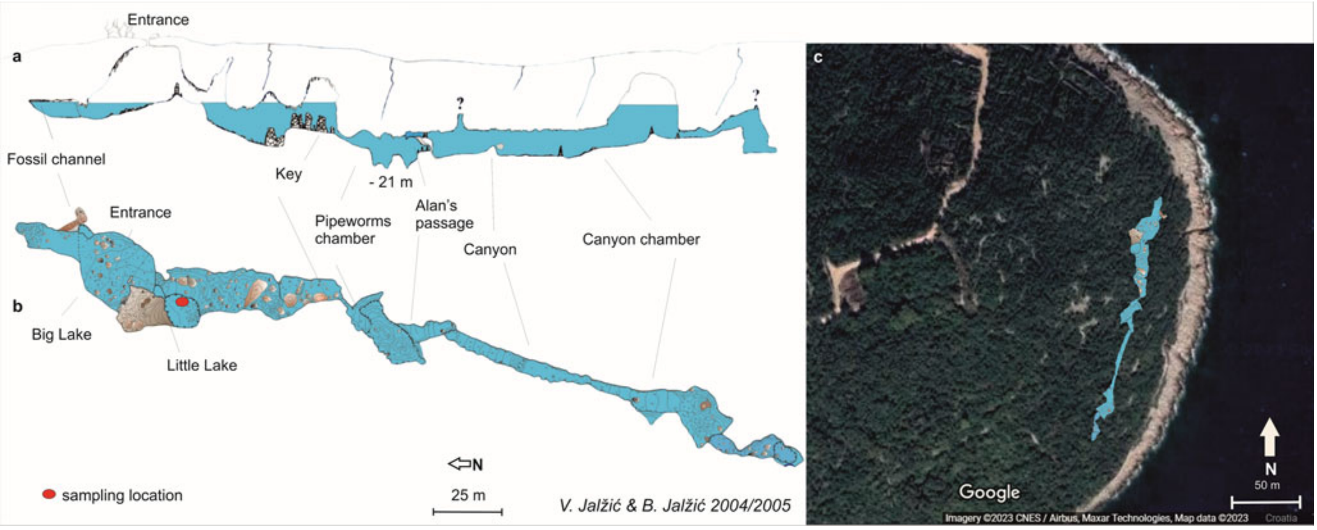

**Figure 3.** Medvjeđa Špilja (Bear Cave) longitudinal profile. (**a, b**) Cross-sectional and plan maps, (**c**) position in relation to the sea.

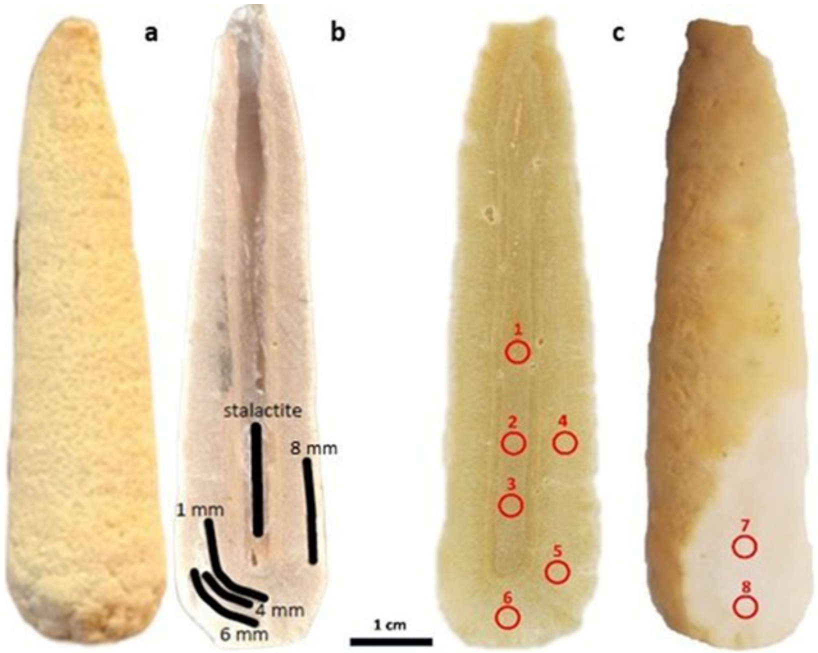

**Figure 4.** (**a, b**) External morphology and longitudinal section of phreatic overgrowth on speleothems (POS) sample MLp1, showing locations of samples for U-series dating (black marks); note the ~1-mm thick overgrowth layer immediately around the support (a pre-existing stalactite). (**c**) XRF spot analyses (red) on the halved and outer surface of the POS.

atmospheric pressure, we used data from the Croatian Meteorological and Hydrological Service Weather Station of Mali Lošinj.

### X-ray diffraction (XRD) analysis

The mineralogy of the phreatic overgrowths was determined by XRD. The analysis was performed at the Department of Geology, Faculty of Natural Sciences and Engineering, University of Ljubljana (FNSE-UL), Slovenia, using a Philips X-ray diffractometer generator PW 3830. About 1–3 g of sample was drilled from the outer part of the POS (Fig. 4) with a dental drill and subsequently crushed in an agate mortar.

### Scanning electron microscopy–energy dispersive spectroscopy (SEM–EDS) analyses

The analyses focused on characterizing the structural and chemical differences between the supporting soda straw and overgrowth at the macroscopically visible boundary between the two units. Analyses were performed at FNSE-UL by ThermoFisher Scientific Quattro S with Schottky effect field-emission gun SEM (FEG–SEM) with an Oxford Instruments UltimMax 65 energy-dispersive spectrometer (EDS) on the polished surface of the POS longitudinal section. Structural etching (Herwegh, 2000) was used to reveal the fabric structure and helped distinguish this boundary on SEM images. Elemental mapping and spot analyses were used for chemical characterization of the aforementioned parts of the POS. Spot analyses targeted individual crystals on both sides of the boundary.

### X-ray fluorescence (XRF) analysis

XRF analysis aimed to geochemically characterize the POS and to determine if there is any difference in trace element composition between the support and the overgrowth. Special attention was paid to Mg since it was reported in previous studies to be higher in overgrowths (Vesica et al., 2000; Ginés et al., 2005; Csoma et al., 2006). MLp1 was analyzed with a Thermo Scientific Niton XL5+ XRF instrument having a 3-mm analyzing spot size at FNSE-UL. Nearly pure and partly dolomitized limestone standards (NIST-1d and NIST-88b, respectively) were used for calibration to obtain good accuracy of trace elements in a $CaCO_3$ matrix. We conducted three spot analyses on the support (#1–3), and five spot analyses on the overgrowth (#4–8; three on the cut surface [#4–6] and two on the outer surface [#7, #8] where the natural surface was abraded off by a dental drill—the resulting powder was used for XRD analysis) (Fig. 4).

### U-series dating

To obtain the deposition time of our POS, four subsamples were taken across the thickest part of the phreatic overgrowth. To document the age when the cave became submerged, the first subsample was drilled 1 mm away from the pre-existing soda straw. The second and third subsamples are located between the vadose soda straw and POS's external surface, while the last subsample comes from the outermost part of the POS (Fig. 4). The pre-existing soda straw was also dated. All subsamples were dated by means of U-series disequilibrium method on a Thermo Neptune Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) at the Department of Earth and Planetary Sciences, University of New Mexico, USA. Details on this method are available in Asmerom et al. (2006).

Since all four POS subsample dates are within a few hundred years of each other (using the often-assumed atomic ratio value of initial $^{230}Th/^{232}Th$ to be 4.4 ppm based on the bulk Earth $^{232}Th/^{238}U$ value of 3.8 [Cheng et al., 2013]), we calculated $^{232}Th/^{238}U$–$^{234}U/^{238}U$–$^{230}Th/^{238}U$ isochron age that represents a more robust overall age for the POS. The isochron was constructed using IsoplotR (Vermeesch, 2018), which yielded a measured initial $^{230}Th/^{232}Th$ atomic ratio of 9.7 ± 0.86 ppm, which is double the value traditionally used in calculating U-series ages (4.4 ± 2.2 ppm). With the measured initial $^{230}Th/^{232}Th$ atomic ratio value, we re-calculated all four POS ages (at 1, 4, 6, and

**Table 1.** Summary of the U-series measurement results for the phreatic overgrowth of speleothems sample MLp1.

| Lab. label | $^{238}$U (ng/g) | $^{232}$Th (pg/g) | $^{230}$Th/$^{232}$Th (AR) | $^{230}$Th/$^{238}$Th (AR) | $\delta^{234}U_m$ (‰) | $\delta^{234}U_i$ (‰) | Age uncorr. (yr) | Age corr. (yr) |
|---|---|---|---|---|---|---|---|---|
| **MLp-1 stalactite** | 166.6 ± 1.0 | 5533 ± 7 | 7.2 ± 0.1 | 0.0777 ± 0.0012 | 102 ± 4 | 103 ± 4 | 7895 ± 128 | 5948 ± 228 |
| **POS-MLp-1 1 mm** | 388.5 ± 2.4 | 5521 ± 7 | 7.6 ± 0.1 | 0.0340 ± 0.0006 | 104 ± 4 | 104 ± 4 | 3453 ± 65 | 2624 ± 104 |
| **POS-MLp-1 4 mm** | 388.5 ± 2.4 | 4230 ± 9 | 9.7 ± 0.2 | 0.0348 ± 0.0006 | 102 ± 2 | 103 ± 2 | 3430 ± 63 | 2760 ± 89 |
| **POS-MLp-1 6 mm** | 448.65 ± 0.9 | 5440 ± 9 | 8.9 ± 0.1 | 0.0355 ± 0.0005 | 93 ± 3 | 94 ± 3 | 3522 ± 55 | 2880 ± 90 |
| **POS-MLp-1 8 mm** | 460.5 ± 0.4 | 11051 ± 9 | 5.4 ± 0.1 | 0.0423 ± 0.0005 | 95 ± 2 | 96 ± 2 | 4222 ± 57 | 2808 ± 151 |
| **Weight average age of four POS subsamples = 2759 ± 140** | | | | | | | | |

Subsample powder sizes range from 60 to 120 mg; 1–8 mm labels reflect the distance from the stalactite outer surface. Initial $^{230}$Th/$^{232}$Th atomic ratio used to correct ages is 0.0000097 (activity ratio = 1.8) ± 10% based on a 4-point isochron. The $^{232}$Th/$^{238}$U–$^{234}$U/$^{238}$U–$^{230}$Th/$^{238}$U isochron age = 2.80 ± 0.09 yr was calculated using IsoplotR (Vermeesch, 2018). All errors are absolute 2σ. AR = activity ratio; $\delta^{234}U_m$ = measured value and $\delta^{234}U_i$ = initial value. Zero datum for all ages is AD 1950. Weight average is calculated from the four POS samples.

8 mm). The zero datum for all ages is AD 1950 and all ages are reported with absolute 2σ uncertainty (Table 1). Then we weight-averaged those ages and uncertainties to produce an overall robust time of deposition for the POS.

## RESULTS

Diving expeditions resulted in discovery of the first POS located in the Adriatic Sea. The sample MLp-1 is an 8-cm long calcite soda straw with a phreatic overgrowth (Fig. 4). The overgrowth has an uneven deposition pattern over a regularly shaped soda straw, widening towards the bottom and terminating in a rounded base (Fig. 4), a feature commonly observed in Mallorcan caves (Ginés et al., 2012). An ~1 mm thick darker overgrowth layer immediately around the pre-existing support is easily visible (Fig. 4).

### *XRD, XRF, and SEM–EDS analyses*

Calcite was the only mineral detected phase in the POS. The etched surface revealed the shapes of the crystals. The support crystals tend to be smaller and etch differently than the overgrowth crystals, which gives them a fuzzier appearance (Fig. 6a). The overgrowth crystals often show epitaxial growth on top of the soda straw support crystals (Fig. 6b), which differs from previously observed boundaries between the support and the overgrowth (Ginés et al., 2012; Miklavič et al., 2018). Zoning can be observed in both support and overgrowth crystals, although it is more common in overgrowth crystals. The ~1-mm thick, dark overgrowth layer that is easily visible with the naked eye (Fig. 4) is much more difficult to identify on SEM images. The crystals are larger and more elongated with the long crystallographic c-axis being perpendicular to the support surface away from the boundary. Macroscopically, this gives a fibrous appearance to the crystals. The results of XRF analysis indicate that the concentration of Mg in calcite is equally low in the support and the overgrowth (Fig. 5), ranging between 0.44 and 0.62 wt%. Other detected elements (Si, Al, Fe, Sr, and Ba) also were present in all sampled areas of the POS and, just as Mg, they did not show any clear trend in their distribution across the POS (Fig. 6c).

EDS elemental mapping and spot analyses showed the presence of Mg, Si, Al, Na, Cl, and S. Mg content is uniformly distributed across the POS. The occurrence of Si in clusters or associated with Al, as shown on elemental maps, indicates that these elements are related to quartz and clay particles incorporated in the POS (Fig. 6d); they are present in the support as well as the overgrowth. Na and Cl are always closely associated, suggesting the presence of halite (NaCl). They were detected along grain boundaries around a pore. In summary, the SEM–EDS analyses show there is no unequivocal difference in trace element content between the POS support and overgrowth and that the difference between the two parts of the POS is only structural.

### *U-series chronology*

U-series ages were derived from five subsamples of sample MLp1 (Fig. 4). Detailed uranium–thorium data for sample MLp1 (Fig. 4) are provided in Table 1. The soda straw stalactite, which represents growth above the water table, has an age of 5948 ± 228 yr. The stalactite grew when sea level was lower.

The U-series data for the four POS subsamples at 1, 4, 6, and 8 mm away from the stalactite (see Fig. 4) are all of similar age, if considering their error (Table 1). We used these results to produce a $^{232}$Th/$^{238}$U–$^{234}$U/$^{238}$U–$^{230}$Th/$^{238}$U isochron that yielded an age of 2795 ± 88 yr. IsoplotR offers a routine, which assumes that analytical uncertainties are not representative of the true uncertainties and applies an overdispersion term that reduces the mean square weighted deviation (MSWD) to unity (Vermeesch, 2018), with the interpretation that the larger uncertainties assigned by the program are due to geologic scatter. In our case, three of the four analyses produced an isochron age of 2852 ± 270 yr (MSWD = 9) without any assumptions. Applying the 4-point isochron-based detrital thorium correction, we use the weighted average age from the four U-series dates for the POS of 2759 ± 140 yr (Fig. 7).

## DISCUSSION

### *POS formation*

Morphology of the overgrowth depends on the tide-controlled daily groundwater level fluctuation, substrate shape, length of growth, and the degree of immersion of the substrate at the time of formation (Vesica et al., 2000). The development of

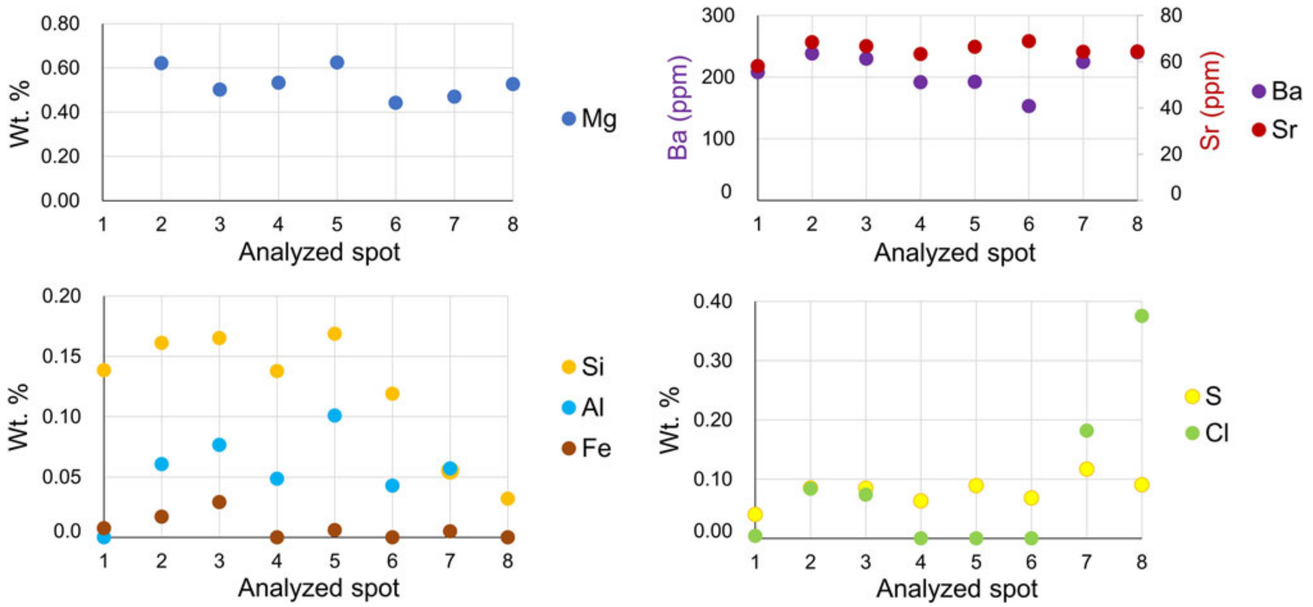

**Figure 5.** Trace element content in the analyzed spots indicated in Figure 4 (red circles).

phreatic overgrowth (MLp1) around a regularly shaped pre-existing vadose soda straw is linked to tidal fluctuations, as depicted in Figure 1. The MLp1 overgrowth (Figs. 4 and 6) grew over a pre-existing soda straw that was not long enough to capture the lowest tidal range. In such a case, POS deposition does not coincide with the full sea-level fluctuation range but likely records only the upper part of that range (Vesica et al., 2000; Ginés et al., 2012). Based on the morphology of the MLp1 overgrowth, it is apparent that the POS deposition records fluctuations between mean sea level (± 0.15 m) and the high tide, which is 24 cm above current mean sea level, given the average tidal range. We presumed that the asymmetric, almost flat-bottomed shape of the POS indicates its closeness to the mean sea level, as described in Tuccimei et al. (2010) and Ginés et al. (2012).

XRD analysis of MLp1 shows that the fibrous overgrowth is made of calcite. Such overgrowths are also known from Mallorca, although the majority of the POS with fibrous crystals on this island are aragonite (Ginés et al., 2012). The calcite overgrowths on Mallorca, however, showed higher Mg concentrations than the calcitic support, which was attributed to the Mg-richer brackish water from which the overgrowth calcite precipitated (Vesica et al., 2000; Ginés et al., 2005; Csoma et al., 2006). The absence of any distinct difference in trace element content between the support and the overgrowth in MLp1, as revealed by XRF and SEM-EDS analyses, therefore indicates that the drip water and pool water from which the calcite precipitated must have had a similar composition. In other words, the topmost layer of the cave pool water column was probably pure fresh groundwater unmixed with marine water. The often-observed epitaxial growth of the crystals in POS over the supporting soda straw (Fig. 6b) indicates a transitional phase in which the crystals were growing in alternating conditions (i.e., as support [while emerged during low tide] and overgrowth [when submerged during high tide] crystals). This may in turn explain the occurrence of the distinct dark overgrowth layer observed with the naked eye around the support (Fig. 4). This layer might have formed during this transitional period.

### *Time of deposition and regional relative sea-level context*

Studies on Holocene relative sea-level changes in the northern Adriatic have a long history. This research began with the first evidence of submerged archaeological structures, as documented by Gnirs (1908) and Degrassi (1955). Subsequent investigations in Istria, including work by Antonioli et al. (2007), Faivre et al. (2011a), and Florido et al. (2011), have provided detailed insights into the last 1600 yr of relative sea-level changes in this region (Faivre et al., 2019) (Fig. 8). Recent high-resolution relative sea-level studies have further enriched our understanding of this complex phenomenon (Faivre et al., 2019; Kaniewski et al., 2021). New paleoenvironmental reconstructions are now available from Cres Island covering the Late Pleistocene and Holocene (Brunović et al., 2019, 2020) and from the more distant island of Pag (Ilijanić et al., 2022). However, data during the period of POS formation reported here are sparse. Thus, POS can provide new evidence, which can supplement and improve existing data.

Previous studies of speleothem deposition in Medvjeđa Špilja, as well as in other Croatian coastal caves (e.g., Surić et al., 2007; Surić and Juračić, 2010), revealed hiatuses in submerged stalagmites that can be used in studies of relative sea-level change. According to those records, ca. 7000 yr ago, sea level was ∼10 m lower than present, while ca. 3350 yr ago sea level rose to around −1.5 m (Surić et al., 2007). Speleothem L-1 of Surić et al. (2007) is a stalactite that had broken off from the roof and was found in an upside-down position. Detailed analysis revealed that calcite deposition continued in the new position, in the form of needle-like deposits, around a previously deposited stalactite, indicating alternating freshwater/brackish conditions. Consequently, Surić et al. (2007) and Surić and Juračić (2010) proposed that the sea level ca. 3350 years cal yr BP had not yet reached −1.5 m.

The supporting soda straw in the MLp1 sample is 5948 ± 228 years old, indicating vadose conditions during its formation. The four ages of the POS are slightly reversed, but within their errors they are essentially the same. Brackish water has to remain stable for a length of time to become saturated with enough calcite for

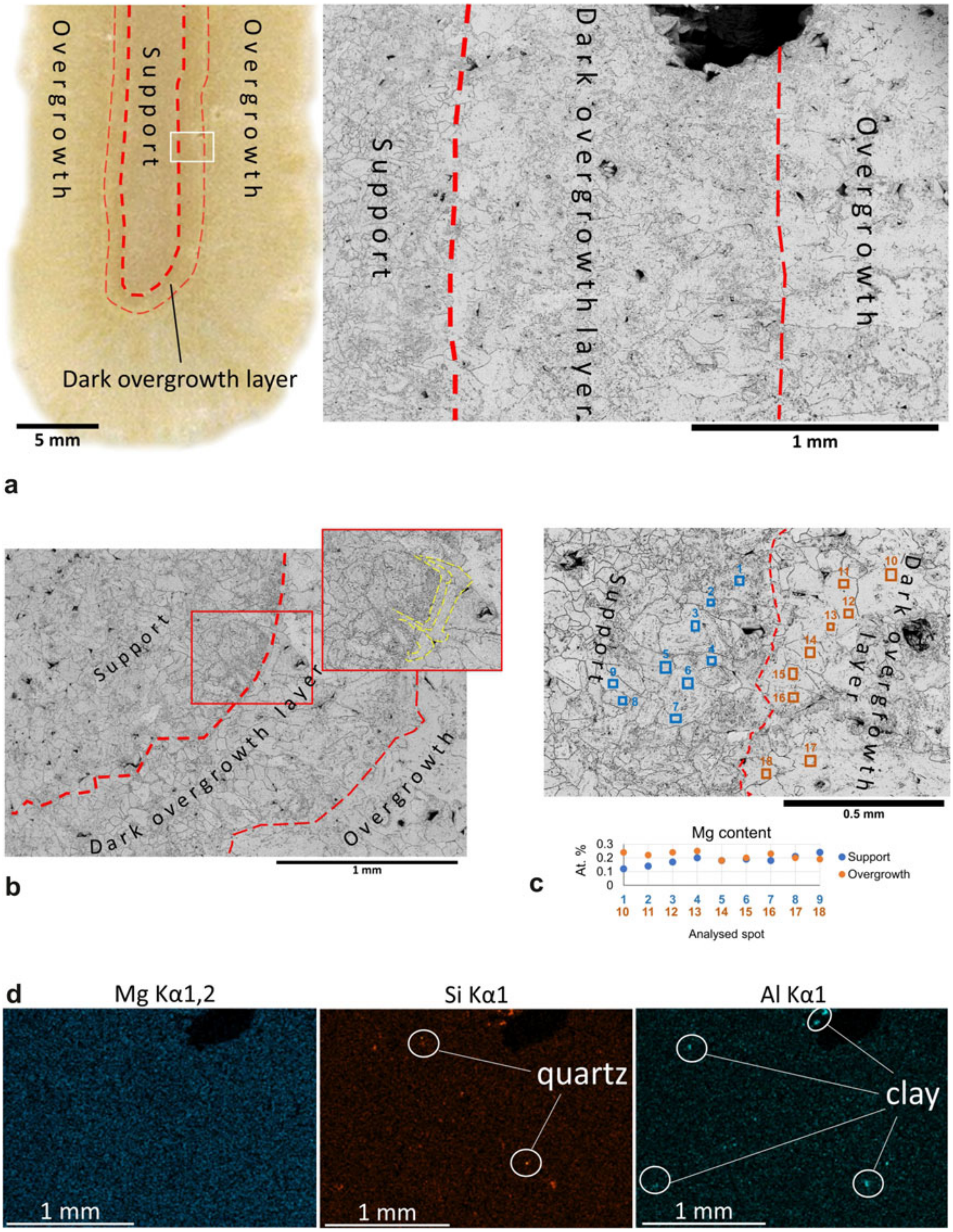

**Figure 6.** (**a**) The three parts of the POS as seen macroscopically (left) and under SEM (rigth; the area is indicated by white rectangle on the macroscopic picture). (**b**) The boundary between the support and the overgrowth with visible epitaxial crystal overgrowth in the inset picture. (**c**). SEM image showing the boundary (red dashed line) between the support and the dark overgrowth layer, and the EDS spot analysis at the support–overgrowth boundary (1 mm dark layer), showing Mg content. Observe the crystal zoning near spot #3. (**d**) EDS elemental map of the area shown in (a) showing a uniform distribution of Mg in the calcite across all three layers, and localized concentration of Si and Al.

deposition that would be recognized as a POS (Polyak et al., 2018). Therefore, we estimate that around 2759 ± 140 yr sea level was relatively stable for about 300 years at −1.28 m ± 0.15 m below current mean sea level. Based on our new findings of POS deposition, we also presume that the needle-like deposits of L-1 described by Surić and Juračić (2010) represent POS that formed within the tidal range.

According to isotopic records of eastern Adriatic speleothems, the Holocene is characterized by many and sudden environmental changes, whereas the Late Holocene primarily is characterized by

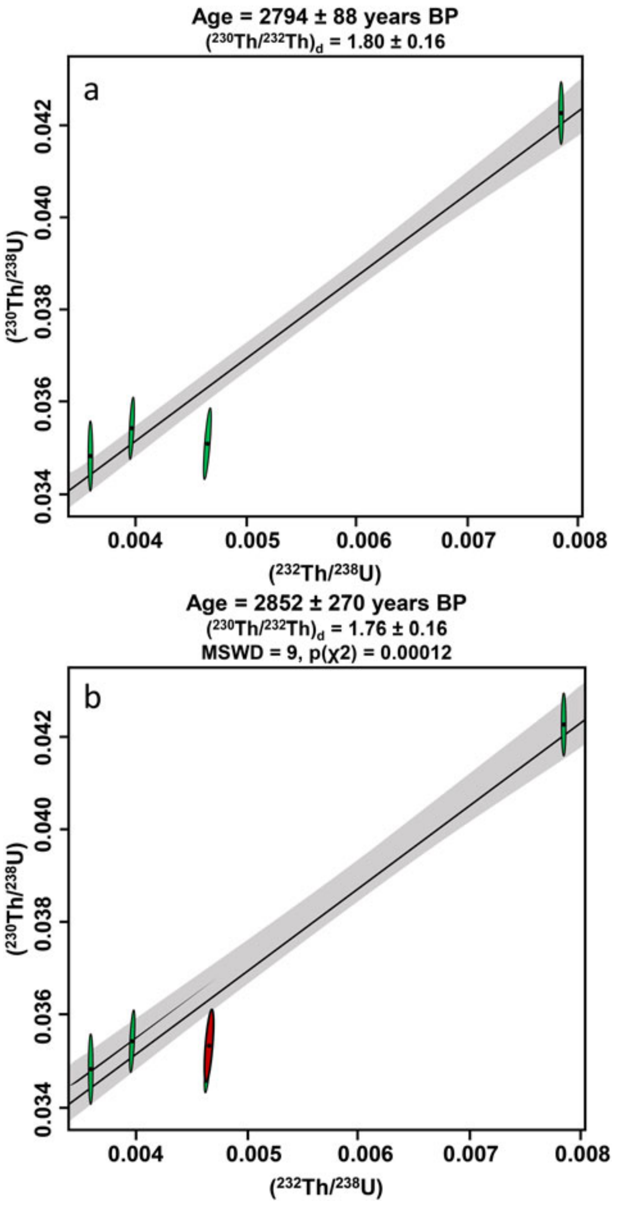

**Figure 7.** The $^{232}$Th/$^{238}$U–$^{234}$U/$^{238}$U–$^{230}$Th/$^{238}$U isochron age for the phreatic overgrowth of samples MLp1. (**a**) The over dispersion routine provided in IsoplotR (Vermeesch, 2018) produces an age and 2σ absolute uncertainty of 2794 ± 88 years. (**b**) The isochron produced from three of the four subsamples yields an age of 2852 ± 270 years.

drier conditions (Surić et al., 2021), which were occasionally interrupted by wet stages (Lončar et al., 2017, 2019). Periods of relative sea-level stability have been documented along the eastern Adriatic coast using different RSL markers such as tidal notches (e.g., Fouache et al., 2000; Antonioli et al., 2004b; Benac et al., 2004; Marriner et al., 2014) and algal rims (e.g., Faivre et al., 2019, 2021a, b). Eastern Adriatic tidal notches are interpreted to have formed during two main periods (Late Antique Little Ice Age and Little Ice Age) of relative sea-level stability, similar to findings in other parts in the eastern (e.g., Boulton and Stewart, 2015), central (e.g., Faivre et al., 2013, 2021b), and western Mediterranean (e.g., Vacchi et al., 2022). The northern Adriatic notches formed during the Late Antique Little Ice Age (Faivre et al., 2019), whereas central Adriatic notches formed during the Little Ice Age, about 500 years ago (Faivre et al., 2013, Faivre and Butorac, 2018). These periods of relative sea-level stability have also been observed in the southern Adriatic (Faivre et al., 2021a, b). Such intervals could be related to periods of drop in global mean sea level connected to the Northern Hemisphere global mean cooling noted by Mann et al. (2008), Ljungqvist (2010), and PAGES 2k Consortium (2013, 2019), which offset the glacial isostatic adjustment effects (Faivre et al., 2023).

A period of relative sea-level stability during the Late Bronze Age and the transition to the Iron Age between 3250 and 2800 cal yr BP was already documented in the southern Adriatic based on the presence of algal rims on Lopud Island (Faivre et al., 2021a). Thus, POS data from the Medvjeđa Špilja (formed around 2.8 ka) provide possible indications of RSL stability in the northern Adriatic Sea at the end of this period. Dry conditions during that period were inferred from different proxies throughout the Mediterranean, including the SPD-1 stalagmite from the island of Dugi otok. SPD-1 shows that the entire period between ca. 3.3 and 2.7 ka was dry, although it was interrupted by short wet events, and true wetter conditions only followed after 2.7 ka (Lončar et al., 2019). Particularly prominent dry conditions around ca. 3300 cal yr BP were also observed in lake sediments from Albania and Montenegro (Zanchetta et al., 2012).

This dry period can also be associated with the cooling phase in the Aegean Sea, also around 3300 cal BP (Rohling et al., 2002), and with the severe long-term drought in the Eastern Mediterranean, which dramatically affected agriculture and triggered societal collapse in the Late Bronze and Iron ages, generally between 3150–2800 cal yr BP (Kaniewski et al., 2010; Kagan et al., 2015; Langgut et al., 2015). Overall, the formation of our POS could be roughly related to the end of the longest Holocene cooling phase in the Mediterranean associated with the 3.2-ka event characterized by cooling of −0.38 ± 0.19°C, over ca. 320 years (Marriner et al., 2022).

The above studies directly indicate that relative sea-level change during the Late Holocene was not linear and provide evidence for the existence of periods of relative sea-level stability that are likely related to climate conditions (Faivre et al., 2023). Overall, our new results from Mali Lošinj Island POS correspond well to the nearby 5000-yr composite relative sea-level curve from Istria (Faivre et al., 2011a, 2019; Kaniewski et al., 2021), suggesting a similar trend of subsidence in Istria and along the eastern coast of Lošinj during last 2800 years of ∼0.46 mm/yr (Fig. 8). The general agreement of the results obtained from POS with previous local and regional results from the Adriatic and the eastern Mediterranean confirm POS as a reliable sea-level indicator.

## CONCLUSIONS

Speleothem-based research into Pleistocene and Holocene relative sea-level changes along the eastern Adriatic has traditionally focused on biogenic encrustations, identified hiatuses, and mineralogical shifts within submerged speleothems. Our research in the Medvjeđa Špilja (Lošinj Island, northern Adriatic) reveals that the cave hosts a pool environment favorable for phreatic overgrowths on speleothems (POS) precipitation during sea-level stillstand conditions. Mineralogical analysis confirmed that speleothem MLp-1 is made up of calcite and has a typical morphology of POS, which makes it the first POS found in the Adriatic. The XRF and SEM–EDS analyses showed that there is no difference in trace element composition between the support and the overgrowth. Obtained results suggests that the drip water from which

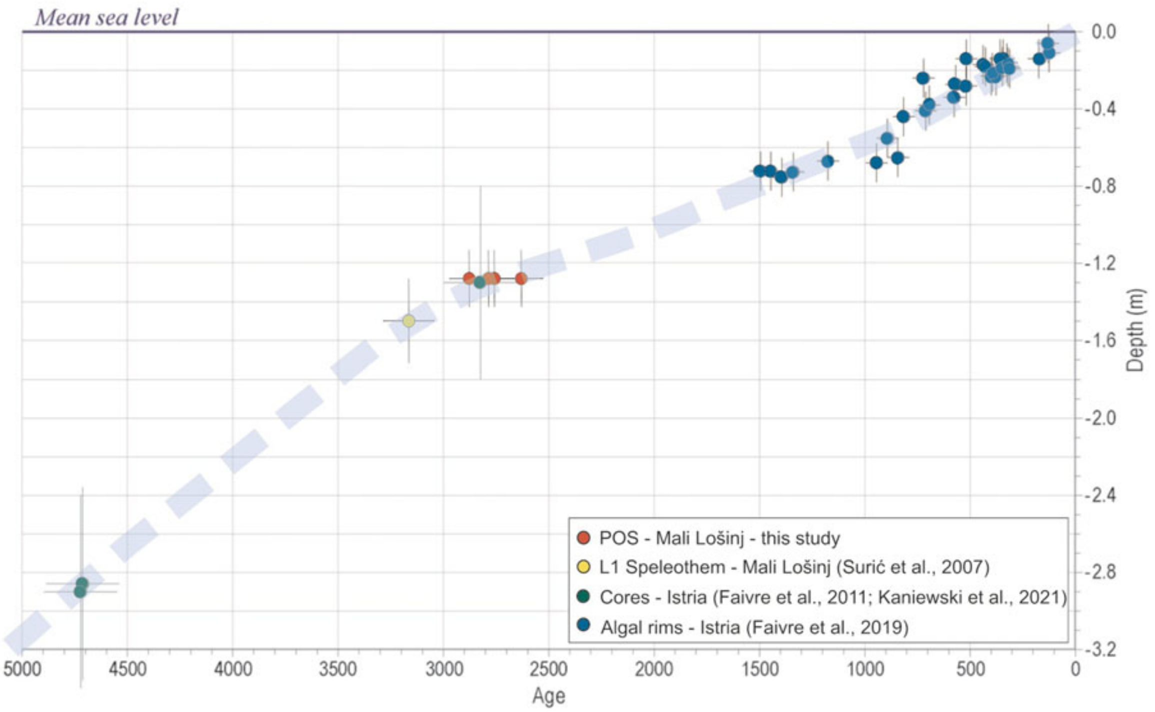

**Figure 8.** Phreatic overgrowth sample MLp1 and speleothem L-1 superimposed on the relative sea-level curve for the northern Adriatic Sea constructed for Istria (Faivre et al., 2011a, 2019).

the support (calcite soda straw) formed and the upper part of the water column in the cave pool (from which the overgrowth precipitated) had the same chemical composition. Based on uranium-series dating, we conclude that the relative sea level at ca. 2.8 ka must have remained stable for ca. 300 years at a depth of approximately −1.28 ± 0.15 m below the current MSL. Patterns of relative sea-level changes along the eastern coast of Lošinj Island align with trends seen along the Istrian coast. This suggests a general subsidence rate of ~0.46 mm/yr during the Late Holocene in the study area. Further research of POS at this study site will enable recording more sea-level index points, which will enable the development of longer and more precise curves of relative sea-level change in the northern Adriatic.

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