Characterisation of phreatic overgrowths on speleothems precipitated in the northern Adriatic during a sea-level stillstand at ~2.8 ka

ABSTRACT

We examine a Late Holocene sea-level stillstand using phreatic overgrowth on speleothems (POS) recovered from Medvjeđa špilja Cave (northern Adriatic Sea) from –1.28 ± 0.15 m below present mean sea-level. Different mineralogical analysis were performed to characterize the POS and better understand the mechanisms of their formation. Results reveals that the fibrous overgrowth is formed of calcite and that the supporting soda straw and the overgrowth have a very similar trace element composition. This suggests that the drip and groundwater pool from which the POS formed have a similar chemical make-up. Four subsamples were dated by means of uranium-series. We find that ~2800 years ago, the relative sea-level was stable for about 300 years at a depth of ~ –1.28 ± 0.15 m below the current MSL. This finding roughly corresponds with the end of a relatively stable sea-level period, between 3250 and 2800 cal BP, previously noted in the southern Adriatic. Our research attests the existence of POS in the Adriatic and demonstrated Medvjeđa špilja cave pool as an environment favorable for the precipitation of calcite POS what will allow further research at the study site.

KEYWORDS: cave deposits, U-series dating, sea-level, Holocene, northern Adriatic, Croatia

INTRODUCTION

In paleo sea-level research sedimentological, geomorphological, archaeological and biological indicators, and historical sources are used and often combined (e.g. Faivre et al., 2013; Shennan et al., 2015). In coastal caves, hiatuses in the speleothem growth signal the 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 such hiatuses' surfaces. Furthermore, investigations on once 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, 2002; Antonioli et al., 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 have been constructed for the eastern Adriatic coast (Surić and Juračić, 2010). This is in general agreement with the global sea-level curve. The early Holocene sea-level rise reached -41.5 m at ~9.2 ka and -10 m around 7.8 ka, and by ~3.4 ka, it rose to -1.5 m (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 incrustations, 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), which 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). They 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 calcite, with the latter being the most 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 have the potential to provide reliable ages, and can be used as an excellent marker 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 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 provides reliable ages (Dorale et al., 2010; Tuccimei et al., 2006, 2011). This allows precise constraint to be placed on the timing of sea-level change, assuming it remained at the same elevation for ~300 years or more (Polyak et al., 2018; Dumitru et al., 2021).

According to Ginés et al. (2012), the first description of POS refers to speleothems from Coves del Drac (Mallorca) by Rodés (1925) and 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 the subaqueous crystallizations 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 have also been identified and described in Bermuda (Harmon et al., 1978), Australia (Grimes, 2001) and Mexico (Jenson, 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; Onac et al., 2022). However, some POS have also formed during the Late Holocene (Tuccimei et al., 2010, 2011; Miklavič et al., 2018), and in particular, during the last 4000 years showing stability during that time (Onac et al., 2022).

Considering the abundance of karst forms in Croatia, including anchialine caves (Surić et al. 2010), one of the goals of 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 further combine these results with those 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 the Medvjeđa špilja Cave on the 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 carbonate rocks deposited in shallow marine environments stretching from Carboniferous to Eocene (Vlahović et al., 2005). Prevalent strata on the 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 Cave (Fig. 2b). Together with tectonics and favorable climatic conditions, 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). Karst features including caves were submerged by the Late Pleistocene-Holocene marine transgression providing a potential record for reconstructing the 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 a.s.l. (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 Božićević 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*) remnants (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. During diving prospection, the halocline is observed at a depth of ~-2 m, whereas marine conditions are fully established after ca.175 m from the entrance, i.e. from the Key Passage onward (Fig. 3). Subsequently, from that point on, all speleothems are dark-colored due to manganese coating (Miklavič et al., 2022) and pipeworms and sponges are present on the ceiling.

METHODOLOGY

Sampling and depth measurement

Suitable speleothems for sampling, were recovered after several detailed cave diving explorations of all submerged parts of the cave in March and October 2021. Sample MLp1 was found at Little Lake passage rooftop (Fig. 3a) and collected at the uppermost part of the soda straw, at the depth of -1.28 ± 0.15 m. 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 Suunto EON steel diving computer with an accuracy of ± 1% and resolution of ± 0.1 m. 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 the groundwater and open sea, as well as the tidal 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 8th and 11th. 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 record a spring tide range of 44 cm, which maximum occurred on Oct 9th 20:55, 2022 (CMHS, 2022). To account for 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 overgrowth was determined by XRD. The analysis was performed at the Department of Geology, Faculty of Natural Sciences and Engineering in Ljubljana, Slovenia using a Philips X-ray diffractometer generator PW 3830 About 1 to 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 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 (spot and line analyses) were used for chemical characterization of the afore mentioned parts of the POS. Spot analyses targeted individual crystals on both sides of the boundary, whereas line analyses crossed the boundary and were 600 to 700 μm long.

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 is paid to Mg since it was reported to be higher in overgrowths in previous studies (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. Nearly pure and partly dolomitized limestone standards (NIST-1d and NIST-88b, respectively) were used for calibration to obtain a good accuracy of trace elements in a $CaCO_3$ matrix. We conducted three spot analyses on the support (#1-3), and five 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 are located between the vadose soda straw and POS's external surface, whilst the last subsample comes from the outermost part of POS (Fig. 4). The preexisting soda straw was also dated. All subsamples were dated by means of U-series disequilibrium method 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).

To determine a more robust time of deposition for our POS we measured an isochron age based on all four samples. We interpret that because 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)), that a $^{232}Th/^{238}U$-$^{234}U/^{238}U$-$^{230}Th/^{238}U$ isochron age can be calculated that would represent 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, 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 (1 mm, 4 mm, 6 mm and 8 mm), each reported in years BP with absolute 2-sigma uncertainty (Table 1), and weight-average 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 phreatic overgrowth (Fig. 4). The overgrowth is unequally deposited over a regularly shaped soda straw, enlarging downwards and ending with a rounded bottom (Fig. 4) as is 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 is the only mineral detected phase in the POS. The etched surface revealed the shape of the crystals. The support crystals tend to be smaller and etch differently than the overgrowth crystals giving 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, 2018). Zoning can be observed in both support and overgrowth crystals, although in overgrowth crystals it is more common. The ca. 1 mm thick dark overgrowth layer 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 axis (*c*) 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 is equally low in the support and the overgrowth (Fig. 5) ranging between 44 and 62%. Other detected elements Si, Al, Fe, Sr and Ba, were also 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 (line and spot analyses) showed the presence of Mg, Si, Al, Na, Cl, and S. Mg content has uniform distribution 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 data and ages were derived from five subsample powders of sample MLp1 (Fig. 4) which are provided in Table 1.. The soda straw stalactite, which represents growth above the water table, has an age of 5948 ± 228 years before present (yr BP). 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) produce a $^{232}Th/^{238}U$-$^{234}U/^{238}U$-$^{230}Th/^{238}U$ isochron that yielded an age of 2795 ± 88 years BP. IsoplotR offers a routine we used that assumes analytical uncertainties are not representative of the true uncertainties and applies an overdispersion term that reduces the 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 produce an isochron age of 2852 ± 270 years BP (MSWD = 9) without any assumptions. Applying the 4-pt isochron-based detrital thorium correction, we use the weighted average age from the four U-series dates for the POS of 2759 ± 140 years BP (Fig. 7).

DISCUSSION

POS formation

The morphology of the overgrowth depends on the tide-controlled daily groundwater level fluctuation ("cave tide"), substrate shape, length of growth, and the degree of immersion of the substrate at the time of formation (Vesica et al., 2000). The phreatic overgrowth (MLp1) that unequally developed around a regularly shaped pre-existing vadose soda straw is related to tidal fluctuations, as shown in Figure 1. The MLp1 overgrowth (Fig. 4 and 6) grew over a pre-existing soda straw that was not long enough to capture the lowest tidal range. In such 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 the fluctuations between the mean sea level (± 0.15 m) and the high tide, which is 24 cm above current MSL given the average tidal range. We presume that the asymmetric, almost flat-bottomed shape of the POS indicates its closeness to the MSL, as described in Tuccimei et al. (2010) and Ginés et al. (2012).

The 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 elements content between the support and the overgrowth in MLp1, as revealed by XRF and SEM-EDS analyses, therefore indicates that the drip and pool water from which the calcite precipitated, must have had a similar composition. In other words, the top-most 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 crystals (when submerged during high tide). 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 of Holocene relative sea-level (RSL) changes in the northern Adriatic have a long history, starting with the first evidence of submerged archaeological structures (e.g. Gnirs, 1908; Degrassi, 1955), followed by investigations in Istria (e.g. Antonioli et al., 2007; Faivre et al., 2011a; Florido et al., 2011), where the RSL changes can be precisely followed from 1.6 ka (Figure 7) (Faivre et al., 2019), and up to recent high-resolution RSL studies (Faivre et al., 2019; Kaniewski et al., 2021). New paleoenvironmental reconstructions are now available from Cres Island covering the Late Pleistocene and Holocene periods (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 Cave, as well as in other Croatian coastal caves (e.g. Surić et al., 2007; Surić and Juračić, 2010) revealed hiatuses in submerged stalagmites which can be used in studies of relative sea-level change. According to those records, ~7000 yrs ago sea-level was ~10 m lower than present, while around 3350 yrs ago sea-level rose to around –1.5 m (Surić et al. 2007). Speleothem L-1 of Surić et al. (2007) is a stalactite broken off from the roof and found in 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 ~3350 years BP had not yet reached –1.5 m.

The supporting soda straw in the MLp1 sample is 5948 ± 228 yrs old, indicating vadose condition 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 calcite enough for deposition that would be recognized as a POS (Polyak et al. 2018). Therefore, we estimate that around 2759 ± 140 yrs BP sea-level was relatively stable for about 300 years at –1.28 m ± 0.15 m below current MSL. Based on our new findings of POS deposition, we can also presume that needle-like deposits of L-1 described by Surić and Juračić (2010) represent POS 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 refers to 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 like 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). Accordingly, it is considered that eastern Adriatic tidal notches formed during two main periods (Late Antique Little Ice Age and Little Ice Age) of relative sea-level stability, similarly with 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 component connected to the Northern Hemisphere global mean cooling attested e.g. by Mann et al. (2008), Ljungqvist (2010), PAGES 2k Consortium (2013), and Neukom et al. (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 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 Cave (formed around 2800 yr BP) 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 all over the Mediterranean, including the SPD-1 stalagmite from the island of Dugi otok which showed that the entire period between ∼3.3 and 2.7 ka was dry, interrupted by short wet events, and that wetter conditions followed only after 2.7 ka (Lončar et al., 2019). On the eastern Adriatic coast, particularly prominent dry conditions were also observed in lake sediments from Albania and Montenegro (Zanchetta et al., 2012) which occurred at around 3300 cal BP.

This dry period can be also associated with the cooling phase in the Aegean Sea, around 3300 cal BP as well (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 BP (Kaniewski et al., 2010; Langgut et al., 2015; Kagan 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 to the 3.2 ka event characterized by cooling of –0.38 ± 0.19°C, over ~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 corresponds well to the nearby composite 5000 years 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 around ~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.

CONCLUSION

Speleothem-based research on Pleistocene and Holocene relative sea-level changes along the eastern Adriatic relied up to now only on biogenic encrustations, hiatuses and mineralogical changes documented on submerged speleothems. Our research in the Medvjeđa špilja Cave (Lošinj Island, northern Adriatic) reveals that the cave hosts a pool environment favorable for POS precipitation during sea-level stillstand conditions. Performed mineralogical analyses confirmed that speleothem MLp-1 has a typical morphology of a phreatic overgrowth over a speleothem (POS) which makes it the first POS found in the Adriatic. XRD analysis showed that the fibrous overgrowth is formed of calcite, while both, XRF and SEM-EDS analysis 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 the support (calcite soda straw) formed and the upper water column in the cave pool (from which the overgrowth precipitated), had the same chemical composition. Based on uranium-series dating, we conclude that ~2800 years ago the relative sea-level must have remained stable for ~ 300 years at a depth of ~ –1.28 ± 0.15 m below the current MSL. We also observed that conditions of RSL change at the eastern coast of Lošinj island seem to be generally close to trends observed along the coastal Istria pointing to general subsidence at the study area of around 0.46 mm /yr during the Late Holocene. Further research of POS at this study site will enable gathering more SLIPs which will enable the development of longer and more precise curves of relative sea-level change in the northern Adriatic.

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Figure 3. Medvjeđa špilja Cave longitudinal profile, plan map and position in relation to the sea.

Figure 4. Morphology and longitudinal section of the MLp1 with POS deposits and subsampling spots for U-series dating (black dots) and XRF analysed spots (red) on the cut and outer surface where the surface was sampled for XRD analysis. Note the ~1 mm thick overgrowth layer immediately around the support (a pre-existing soda straw).

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

Figure 6 (a) Analysed area of the POS by SEM. The picture to the left shows the lower part of the POS (compare with Fig. 3) with marks approximately delimitating boundaries between the support (dark overgrowth layer) and the overgrowth (dashed red lines) and the area of the SEM image shown on the right side. Note the fuzzier etched surface and smaller crystals of the support compared to the overgrowth. (b) The boundary between the support and the overgrowth with visible epitaxial crystal overgrowth (inset picture in the upper right corner). (c) EDS spot analysis along the support-overgrowth (the 1 mm dark layer) boundary (above) and the Mg content in these spots. Note the crystal zoning around the sampling spot #3. (d) EDS elemental map showing a uniform distribution of Mg across all three types of calcite, and localized concentration of Si and Al. The colour on each of the elemental maps represents the element labeled on top of them (i.e. Mg - blue; Si - orange; Al - cyan)

Figure 7. The $^{232}Th/^{238}U$-$^{234}U/^{238}U$-$^{230}Th/^{238}U$ isochron age and weighted mean diagram of POS subsamples (#2 - 5 in Fig. 4)

Figure 8. POS 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)