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Coastal cave characteristics and speleothems as indicators of sea-level change in the eastern Adriatic

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Abstract

So far, the exploration of coastal and submerged karst caves in Croatia has provided significant insights into the complex interplay between geological, hydrological, and biological processes. This study gives an overview of coastal caves and submerged speleothems in the eastern Adriatic as natural archives for reconstructing past sea-level changes. The research focuses on the distribution and characteristics of completely or partially submerged caves, together with the recent cave-diving discoveries and collected speleothems. Detailed analyses, including U-series dating and mineralogical assessments, reveal that certain caves were shaped during periods of lower sea levels, with the oldest speleothems dating back over 500,000 years. The discovery of Phreatic Overgrowths on Speleothems (POS) in the Adriatic has placed Croatia among the few regions globally contributing to POS based sea-level research, being the 6th location identified and researched worldwide. This finding provides an important tool for reconstructing relative sea levels in the Adriatic, marking significant progress in both speleological and sea-level studies. Variations in cave distribution, morphology, and speleothem formation emphasize the need for ongoing exploration and conservation of these fragile ecosystems. As the impacts of climate change become increasingly evident, coastal karst caves in Croatia will continue to serve as archives for understanding Earth's past and predicting future environmental changes. Future research should expand knowledge of these systems, refine cave-diving sampling techniques, and develop strategies for their sustainable management and conservation.

Resum

L'exploració de les coves càrstiques costaneres i submergides a Croàcia ha proporcionat una visió significativa de la complexa interacció entre els processos geològics, hidrològics i biològics. Aquest estudi ofereix una visió general de les coves litorals i els espeleotemes submergits a l'Adriàtic oriental com a arxius naturals per a reconstruir els canvis pretèrits del nivell de la mar. La investigació se centra en la distribució i les característiques de les coves submergides total o parcialment, així com en els recents descobriments fets amb l'espeleobusseig a les coves i els espeleotemes recollits. Les anàlisis detallades, incloses les datacions mitjançant les sèries de l'urani i les avaluacions mineralògiques, revelen que determinades coves es van formar durant períodes de nivells del mar més baixos, amb els espeleotemes més antics datats que es remunten a més de 500.000 anys. El descobriment de sobrecreixements freàtics en espeleotemes (POS) a l'Adriàtic ha situat Croàcia entre les poques regions del món que contribueixen a la investigació del nivell del mar basada en els POS, essent la sisena ubicació identificada i investigada a tot el món. Aquesta troballa proporciona una eina important per reconstruir els nivells relatius de la mar a l'Adriàtic, i representa un progrés significatiu tant en els estudis espeleològics com en les investigacions sobre el nivell de la mar. Les variacions en la distribució de les coves, la seva morfologia, així com la formació dels espeleotemes, emfatitzen la necessitat d'exploració i conservació contínua d'aquests fràgils ecosistemes. A mesura que els impactes del canvi climàtic es facin cada cop més evidents, les coves càrstiques costaneres de Croàcia continuaran servint com a arxius per entendre el passat de la Terra i predir els futurs canvis ambientals. La investigació futura hauria d'ampliar el coneixement d'aquests sistemes, perfeccionar les tècniques de mostreig de busseig en coves i desenvolupar estratègies per a la seva gestió i conservació sostenibles.

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Introduction

Croatian coastline is one of Europe's most geologically complex and significant regions, largely due to its karst topography. Speleogenesis in Croatian karst regions is driven by tectonically fractured limestone and dolomite (KUHTA & BAKŠIĆ, 2001; GARAŠIĆ, 2021; MIŠUR et al., 2021; STROJ et al., 2024) with hydrogeological factors facilitating rock dissolution and erosion, particularly in high-activity areas (GARAŠIĆ, 2021). Karstification varies across regions, influenced by tectonic activity, leading to diverse karst forms (BOGNAR et al., 2012). As part of the external Dinaric Karst

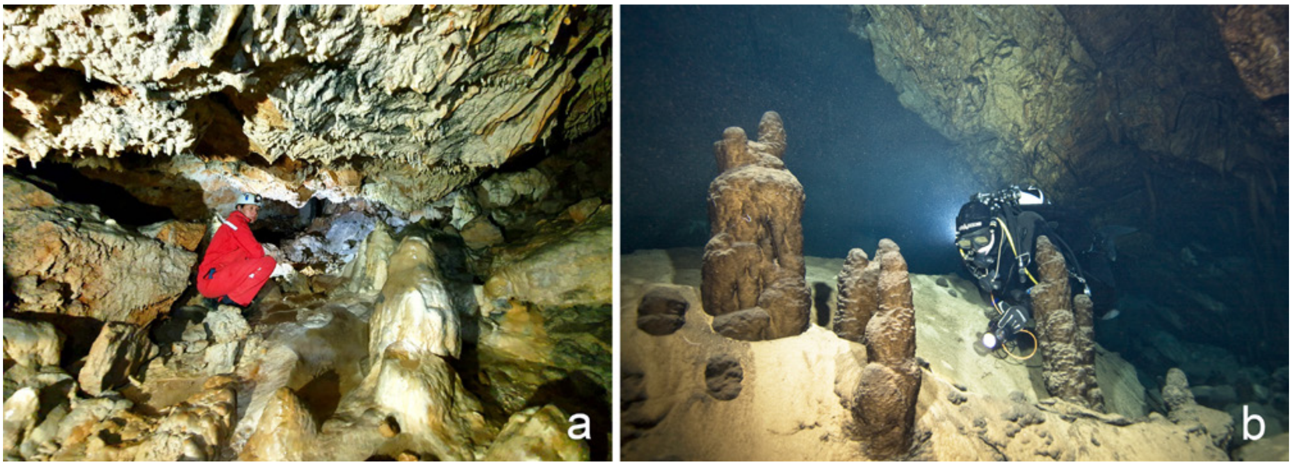

Figure 1: a) Urinjka cave entrance and b) stalagmites in submerged chamber (Photos: P. Kovač Konrad).
Figura 1: a) Entrada de la cova d'Urinjka i b) estalagmites a la cambra submergida (Fotos: P. Kovač Konrad).

the coastal region of Croatia hosts a wide range of caves, from dry air-filled systems to partially or fully submerged ones. These caves provide insights into the region's environmental history: climate change (RUDZKA et al. 2012; LONČAR et al., 2017, 2019), and sea-level changes (SURIĆ et al., 2009; SURIĆ & JURAČIĆ, 2010, LONČAR et al., 2024) during the Pleistocene and Holocene epochs. This paper aims to give an overview of the distribution, characteristics, and scientific significance of Croatia's coastal and submerged caves, with special emphasis on anchialine caves.

One of the first detailed descriptions of a coastal cave in Croatia was given in 1920 by Croatian geologist Josip Poljak, who described the cave "Urinjska špilja" near Rijeka (Figure 1). Between 1968 and 1975, Srećko Božičević and Mirko Malez conducted geological and paleontological research on coastal caves, primarily on the islands of Lošinj, Cres, and Rab. Research on anchialine caves along the Croatian Adriatic coast intensified after 2005, led by Branko Jalžić. Since then, a multidisciplinary team formed, conducting extensive studies on water, sediment, and biota, with contributions from the Croatian Biospeleological Society, Croatian Natural History Museum, Ruđer Bošković Institute (BILANDŽIJA et al., 2009), and various caving clubs and professional associations. Notably, cave diving in coastal karst environments is inherently difficult due to poor visibility, strong tidal currents, and the risk of structural instability. Many caves contain narrow passages that are difficult to navigate, and the presence of fine sediments can complicate sampling and data collection. In recent years, cave-diving research has contributed significantly to our understanding of these caves, especially those that are submerged. The research in Medvjeđa špilja cave on Lošinj island (Croatia) that led to discovery of first Phreatic Overgrowths on Speleothems (POS) in Adriatic contributed to the regional sea-level research, as these formations can provide accurate data on past sea levels. Therefore, the paper also highlights the importance of speleothem based sea-level research.

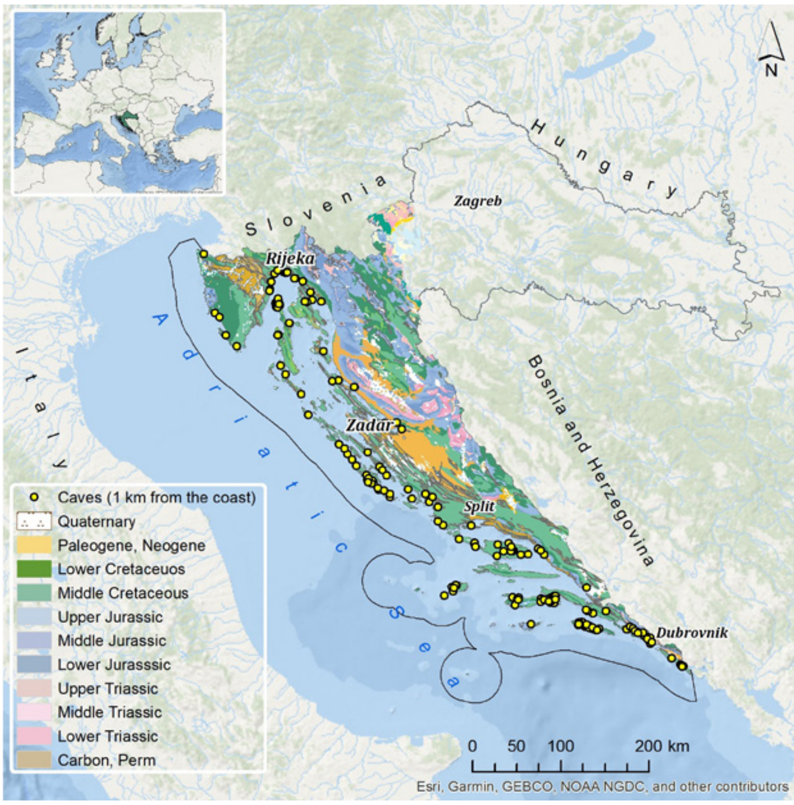

Figure 2: Lithostratigraphy of Croatian Dinaric Karst belt (based on the Geological Map of the Republic of Croatia, scale 1:300 000, Croatian Geological Survey) and cave distribution within 1 km from the coastline (N. Lončar).
Figura 2: Litostratigrafia del cinturó càrstic dinàric de Croàcia (basat en el Mapa Geològic de la República de Croàcia, escala 1:300 000, Servei Geològic de Croàcia) amb la distribució de les coves situades a menys d'1 km de la línia de costa (N. Lončar).

General characteristics and distribution of Croatian coastal caves

Croatian coastal region as a part of Dinaric karst, is characterized by thick, tectonically disturbed, and well-karstified carbonate rocks with a frequent occurrence of variegated caves (Figure 2) (VLAHOVIĆ et al., 2005; BOGNAR et al., 2012). Coastal karstification is a specific process that occurs in areas where karst landscapes intersect with the sea, resulting in the formation of caves and pits in both vadose (above the water table) and phreatic (below the water table) zones (VAN HENGSTUM et al., 2015). These karst caves develop over millions of years, influenced by both terrestrial and marine processes. Along the Adriatic coast, tectonic activity has played a major role in shaping the landscape, leading to the formation of faults and fractures that serve as pathways for water to dissolve the surrounding rock (SURIĆ et al., 2014; GARAŠIĆ, 2021) resulting in the formation of both vertical and horizontal caves. The Croatian coastal region, including islands, is dominated by karst aquifers, which exhibit high permeability and rapid water transmission through fissures, conduits, and underground channels (TERZIĆ et al., 2010, 2021). Most groundwater, especially on islands, is stored in these karst aquifers (BONACCI & ROJE-BONACCI, 2003) that are mainly accessible through vertical caves.

The Cadaster of Caves of the Republic of Croatia (BIOPORTAL, 2024) lists more than 5,500 caves, though the actual number is estimated to exceed 10,000 (SURIĆ et al., 2010; GARAŠIĆ, 2021). Among these are Croatia's coastal caves, which are distributed along the eastern Adriatic coastline (Figure 2). They differ by origin, type, geomorphological features, hydrology, and level of submergence (Figure 3). The highest concentrations of explored and described caves along the coast and islands in Croatia are found on islands: Mljet (71), Kornati archipelago (51), Cres (50), Korčula (40), and Brač (25). The specificity of Brač and Cres is that pits predominate (92%, 74% respectively), while on Korčula the proportions are equal. However, unlike Mljet and Kornati, the existence of anchialine caves has not been confirmed so far on Cres, Korčula, and Brač Islands.

Caves in the coastal zone can be classified into two main types: littoral or sea caves formed by a combination of wave erosion and tectonic activity (BUNNELL, 2004), and partially or completely submerged karst caves (BUNNELL, 2004; FURLANI et al., 2012). In the Croatian coastal zone, they typically appear as shallow notches and hollows in rocky coastlines at the waterline or slightly above it, though they can also be submerged (Figure 4). The term *garma* is often used to describe such caves, while in some cases, people use term *sea caves* when they refer to submerged karst caves where marine (euhaline) conditions are established. Many littoral caves are named Golubinka (Pigeon Cave) (Figure 4a), as they are often inhabited by pigeons, or Medvidina (Monk Cave), after the monk seals that once lived in them. Well-known examples include caves in the Kornati archipelago, Mljet Island (Figure 4b,d), Vis Island, Cres Island, and the Dubrovnik area. On the islands of Cres and Hvar, there are also numerous caves and semi-caves formed in coastal breccia (Figure 4e). Among these is Plava Grota on Cres Island, which is described as a flank margin cave formed in a coastal setting in talus breccia facies (OTONIČAR et al., 2010).

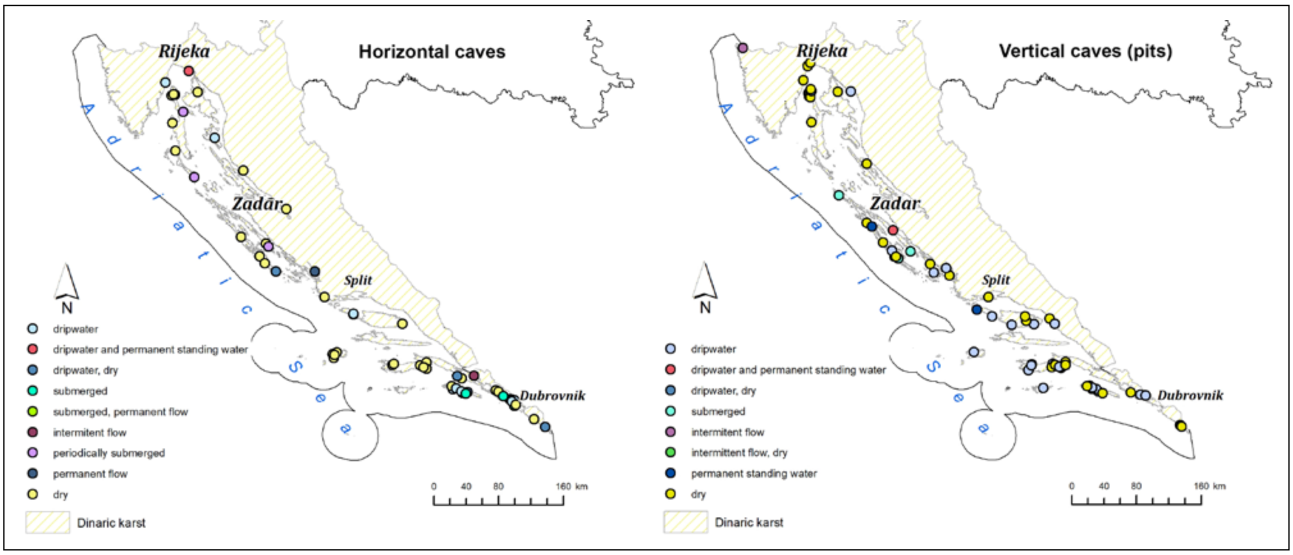

Figure 3: Types of coastal caves and their hydrologic characteristics (N. Lončar).
Figura 3: Tipus de coves costaneres i les seves característiques hidrològiques (N. Lončar).

Partially or fully submerged caves (Figure 5) formed during periods of lower sea levels and were subsequently inundated due to post-glacial sea-level rise (SURIĆ et al., 2010) particularly during the Holocene, making them important indicators of past climate changes. These caves primarily developed in Upper Cretaceous and Paleogene limestone, which was exposed subaerially during glacial maxima when sea levels were significantly lower. Submerged caves also include underwater karst springs (*vruljas*) (Figure 6), which occur along the karst coastline. These springs were flooded by sea-level rise or coastal subsidence resulting from climate change and geological processes. Most of these springs, likely formed during the Pleistocene low sea levels, are believed to still be active (KRANJC, 2004).

According to the available data (SURIĆ et al. 2010; BIOPORTAL, 2024; personal archive; oral communications) 267 of all coastal caves are partially or completely submerged caves. However, considering the official and estimated number of caves on the mainland, this number is likely significantly higher. Completely marine conditions are present in 153 of these caves, while the rest contain water of varying salinity and underwater springs.

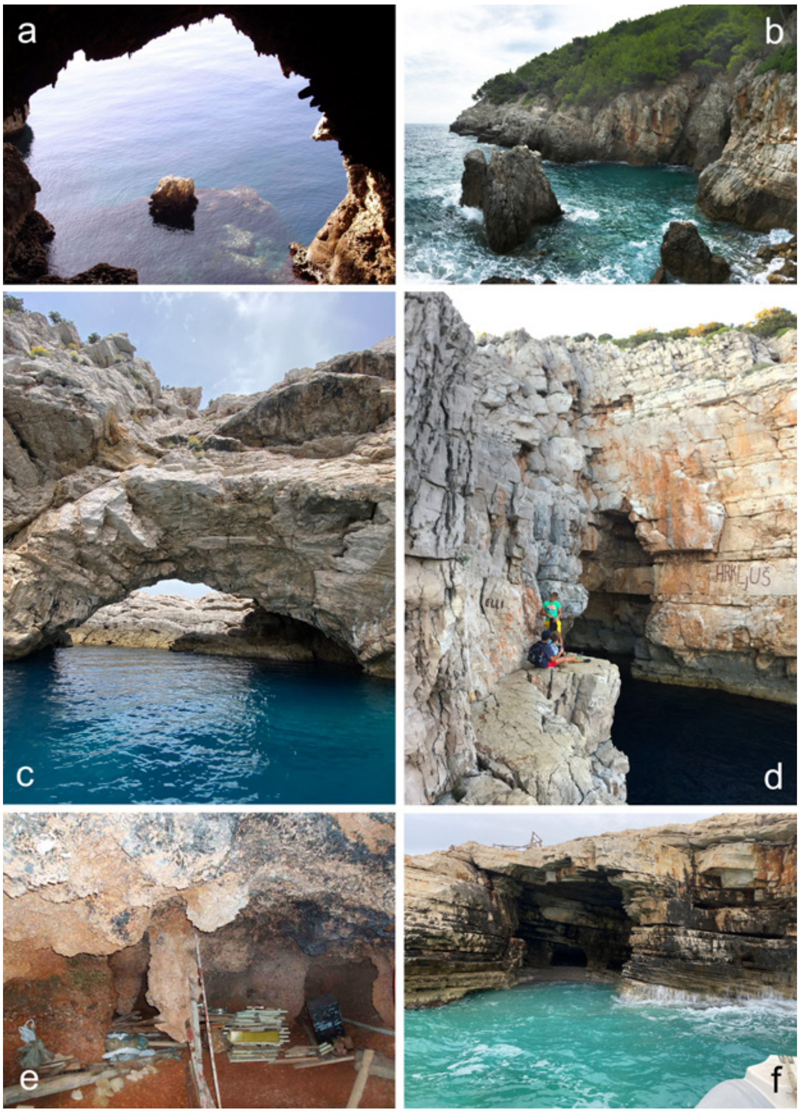

Figure 4: a) Golubinka, Dugi otok island, b) Ropa, Mljet island, c) Plava špilja, Koločep island, d) Odisejeva špilja, Mljet island, e) coastal cave formed in breccia, Hvar Island, and f) špilja u uvali Kolobarica, Kamenjak peninsula, Istria (Photos: N. Lončar).

Figura 4: a) Golubinka, illa de Dugi otok, b) Ropa, illa de Mljet, c) Plava špilja, illa de Koločep, d) Odisejeva špilja, illa de Mljet, e) cova costanera formada dins bretxes, illa de Hvar, i f) špilja u uvali Kolobarica, península Kamenjak, Istria (Fotos: N. Lončar).

Anchialine caves

From an ecological point of view, anchialine caves are characterized by stratified water columns containing layers of freshwater, saltwater, and brackish water, formed through the mixing of these sources (HOLTHUIS, 1973; ILIFFE, 2000). Together with marine caves they support unique ecosystems adapted to these dynamic conditions (STOCK et al., 1986). These systems are part of karst groundwater networks, accessed through features like sinkholes, blueholes, and flooded caves, which host unique anchialine and marine cave ecosystems and provide space for sediment deposition (LITTLE & VAN HENGSTUM 2019). The overview of the history of the term "Anchialine" is given by BISHOP et al. (2015) who proposed a new definition: '*a tidally-influenced subterranean estuary located within crevicular and cavernous karst and volcanic terrains that extends inland to the limit of seawater penetration*.' Anchialine caves are hydrographically connected to the sea via groundwater circulation through primary porosity or host rock fractures, and can be flooded by saline groundwater or a meteoric freshwater lens (ILIFFE, 2000; LITTLE & VAN HENGSTUM, 2019). Their upper meteoric water body, separated from a saline groundwater mass below, is progressively mixed and discharged into the ocean (LITTLE & VAN HENGSTUM, 2019). Their tidal fluctuations of the groundwater column can be influenced by the horizontal inflow of seawater into the karst basin, and even the freshwater discharge of the coastal aquifers (STOCK et al., 1986; VAN HENGSTUM et al., 2011).

In Croatia, there are around 100 known anchialine caves (Figure 2), most of which have been found within 1 km of the coastline (BAKRAN-PETRICIOLI, 2016), with the majority located within 100 m (BILANDŽIJA et al., 2009). These caves are widespread along the coast, on the

Figure 5: Rikavica (Roar) Cave, an example of a formerly dry cave submerged due to sea-level rise. The cave is named after the roaring sounds produced by waves passing through cracks during strong wave action. (a) Entrance, (b) speleothems covered by biogenic overgrowths (Photos: M. Baričević).
Figura 5: Cova Rikavica, un exemple de cova antigament seca submergida a causa de la pujada del nivell de la mar. La cova rep el nom dels rugits produïts per les ones que travessen les esquerdes durant l'acció de les fortes onades. (a) Entrada, (b) espeleotemes coberts per un fort creixement biogènic (Fotos: M. Baričević).

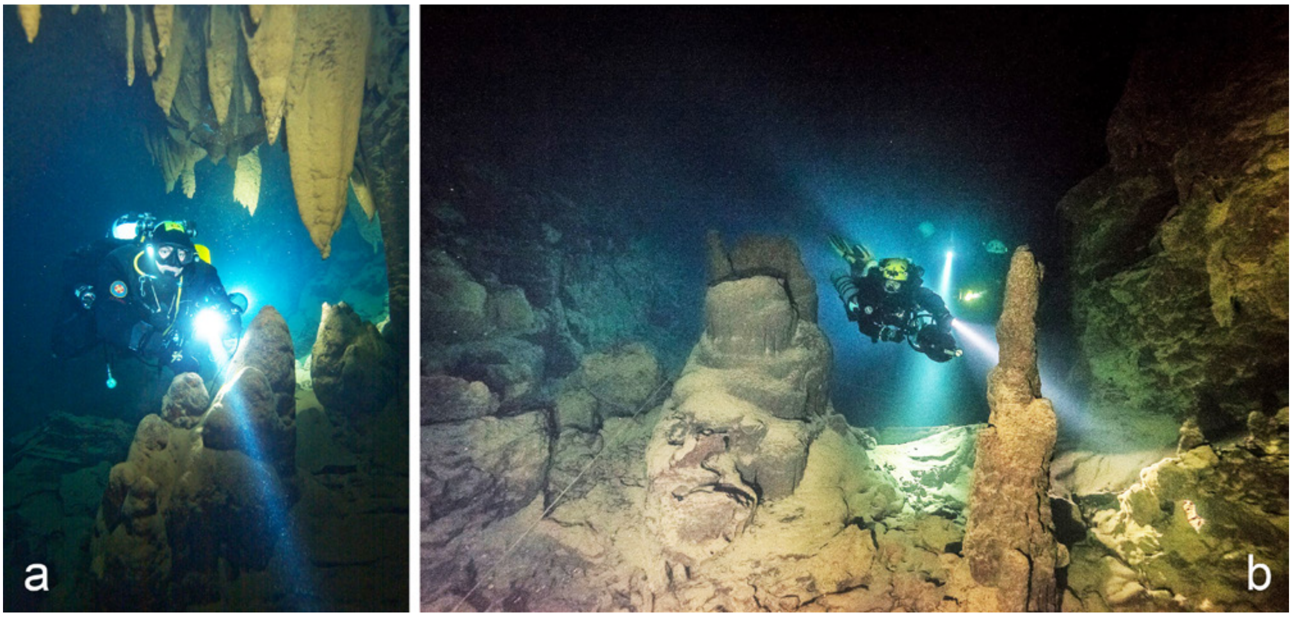

Figure 6: Speleothems in submerged pasages in *vruljas* near Starigrad-Paklenica. a) Zečica, b) Modrič (Photos: P. Kovač Konrad).
Figura 6: Espeleotemes en galeries submergides (*vruljas*) prop de Starigrad-Paklenica. a) Zečica, b) Modrič (Fotos: P. Kovač Konrad).

islands, and at the lower reaches and mouths of rivers flowing into the Adriatic, from the Istrian Peninsula to the Dubrovnik area (GOTTSTEIN MATOČEC et al., 2002; BAKRAN-PETRICIOLI, 2016). Croatian anchialine caves are generally small to medium-sized pits with simple morphology, characterized by narrow entrances and steep vertical shafts, often leading to deeper submerged sections. Many feature submerged passages and chambers, shaped by both tectonic activity and karst processes. Hydrologically, these caves have limited water circulation, resulting in stratification and the formation of haloclines, where freshwater overlays denser saline layers (KAJAN et al., 2021). The hydrodynamics are influenced by tidal movements, though these effects are often dampened due to restricted connectivity with the open sea (RADOLOVIĆ et al., 2015). The lack of direct surface connection and variable hydrodynamics result in distinct salinity gradients within their water columns (KAJAN et al.,2021; TERZIĆ et al., 2021). One exception is the almost completely submerged Y-Cave on Dugi Otok Island. Despite its shallow depth (max. –11.5 m) and exposure to the open sea, tidal and wave energy do not disrupt water stratification (RADOLOVIĆ et al., 2015). The cave exhibits stratified water layers, with varying influences from seawater and freshwater mixing, and distinct hydrodynamic effects. A dissolution effect (mixing corrosion) has also been observed in the shallowest part of the cave (RADALOVIĆ et al., 2015).

The longest and one of most researched anchialine cave is Medvjeđa špilja (Bear Cave) (Figure 7) on Lošinj Island (N. Adriatic). Discovered in 1926, the cave spans 245 m in length, with most

Figure 7: Dry (a) and submerged (b) parts of Medvjeđa špilja anchialine cave (Photos: P. Kovač Konrad, N. Lončar).
Figura 7: Parts seques (a) i submergides (b) de la cova anquihalina de Medvjeđa špilja (Fotos: P. Kovač Konrad, N. Lončar).

sections submerged. It has been explored multiple times between 1974 and 2004 (JALŽIĆ, 2007). The entrance, measuring 1.5 m x 1.0 m, is located approximately 55 m inland from the sea and 17.5 m above sea level. From the entrance, it descends to a lake (Figure 7a) at the base of a bell-shaped hall before diving into submerged channels (Figure 7b). These submerged sections contain multiple halls and channels connected by narrow passages. The significant presence of large speleothems suggests long-term paleoclimatic conditions favorable for their growth (SURIĆ et al., 2007; LONČAR et al., 2024). Some areas feature cave columns up to 4 m tall and over 2 m in diameter. In addition to its geomorphological significance, the cave is also an important paleontological and biospeleological site. One of the most noteworthy paleontological discoveries in the cave is the finding of cave bear remains (*Ursus spelaeus*) in 1926, after which the cave was named.

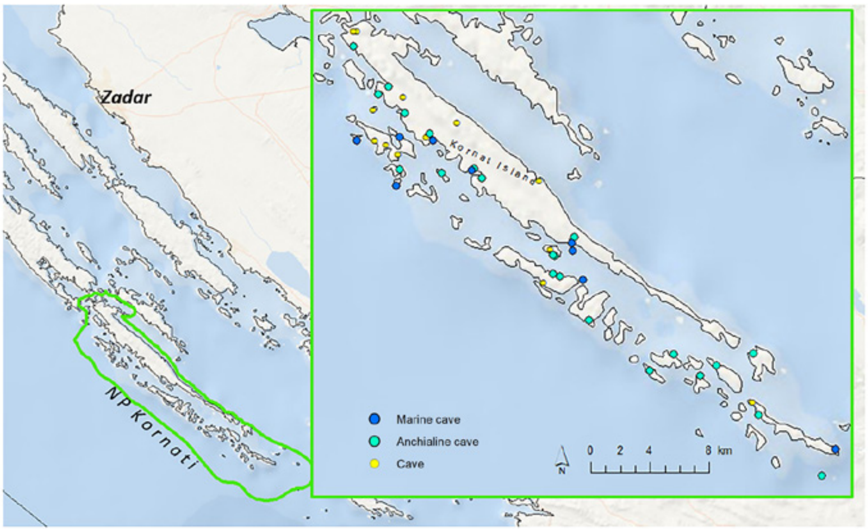

Figure 8: Distribution and types of caves within NP Kornati (N. Lončar).
Figura 8: Distribució i tipus de coves dins del Parc Nacional de Kornati (N. Lončar).

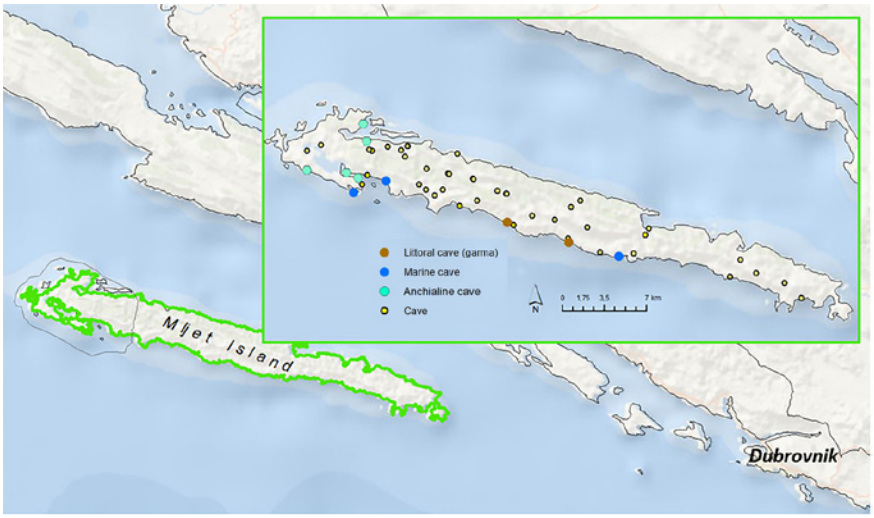

Figure 9: Distribution and types of caves on Mljet Island (N. Lončar).
Figura 9: Distribució i tipus de coves a l'illa de Mljet (N. Lončar).

Among the most explored coastal caves and pits are of National Parks (NP) "Kornati" (Figure 8) and "Mljet" NP, including the entire island (Figure 9), due to the good cooperation between the management of public institutions and speleological associations and the need for an inventory. By the end of 2019, 51 caves were explored within the Kornati NP. Most of the caves (33) are anchialine. The water on their pool surfaces is nearly entirely

Figure 10: Traces of a rope (at the right side of the picture) in the Jama iznad Vrulja pit (NP Kornati), used for water extraction (Photo: B. Jalžić).
Figura 10: Empremta d'una corda usada per a l'extracció d'aigua (a la dreta de la imatge), en el pou d'accés a Jama iznad Vrulja (Parc Nacional de Kornati) (Foto: B. Jalžić).

fresh, and salinity increasing with depth. The abundance of underground water has made these caves valuable resources for early humans and more recent inhabitants along the coast, who used them for water extraction (Figure 10) and other purposes making them important archeological sites (RADIĆ ROSSI & CUKROV, 2017).

The Kornati archipelago covers 320 km², with about 69.5 km² across 150 islands, islets, and rocks, some periodically inundated. Kornati National Park spans 217 km², including the main island Kornat (32.5 km²) and 88 other islands and islets (17.5 km²) (Figure 8). A common characteristic of most caves in the Kornati region is their shallow depth, short length, and limited number of side channels. One reason for their shallow depth is the altitude of the entrances, which are typically situated up to 20 meters from the shoreline (Figure 6) and between 10 and 20 meters above sea level. Analysis of Cave Cadastre data showed that such characteristics are also common in caves found in other coastal areas and islands. The deepest cave (70 m) in Kornati, and overall one of the deepest anchialine explored in Croatia so far is Blitvica cave (Figure 11) on the island of Piškera. The dry part is 20 m deep and the submerged part is 50 m deep, thus a collapsed material at the bottom of the pit has blocked access, suggesting the cavity may extend deeper. Cave is rich in speleothems especially in the submerged parts.

Besides Blitvica, two of the deepest anchialine caves in Croatia are Jama u Podstražišću on Brač Island, with a 45 m dry section and a cave lake over 50 m deep, and Stračinčica on Korčula Island, which reaches a depth of 88 m, including a 40 m water column (CUKROV et al., 2009).

Mljet Island, the southernmost large island in Croatia, stretches 37 km in a NW-SE direction. Mljet National Park spans nearly 5,300 ha in the NW, including a 500 m sea zone, islets, and rocks, covering about one-third of the island (Figure 9). Among notable natural features in NP are Veliko and Malo Jezero (the Mljet Lakes), semi-enclosed karst depressions submerged due to the Holocene sea-level rise, now connected to the open sea by a narrow, shallow channel (VANIČEK et al., 2000). Today, 71 caves are known on the island of Mljet, of which 9 are sea caves, 4 contain freshwater, and 5 are anchialine (JALŽIĆ et al., 2021) (Figure 9). The most notable caves are located in Bjejajka Bay, on Cape Lenga, and at the foot of Sv. Spasa, where one of the largest dripstones in the Croatian karst is found (OZIMEC, 2003). Jama Bjejajka (Figure 12) is particularly significant for its vertical entrance, leading to a submerged section characterized by varying salinity and the presence of speleothems. The entrance descends 10 meters, with collapsed rocks and sediment partially covering the lake. The lake extends to the end of the pit, divided by a narrow passage and a stone barrier. Beyond this point, there is a steep dry section, rich in various speleothems, which are also found in the submerged parts of the passage. The lake continues through a submerged passage to the pit's terminus, with a maximum water depth of 16.5 meters.

Figure 11: The interior of the Blitvica cave (Piškera island, Kornati NP) (Photo: P. Kovač Konrad).
Figura 11: Interior de la cova Blitvica (illa de Piškera, Parc Nacional de Kornati) (Foto: P. Kovač Konrad).

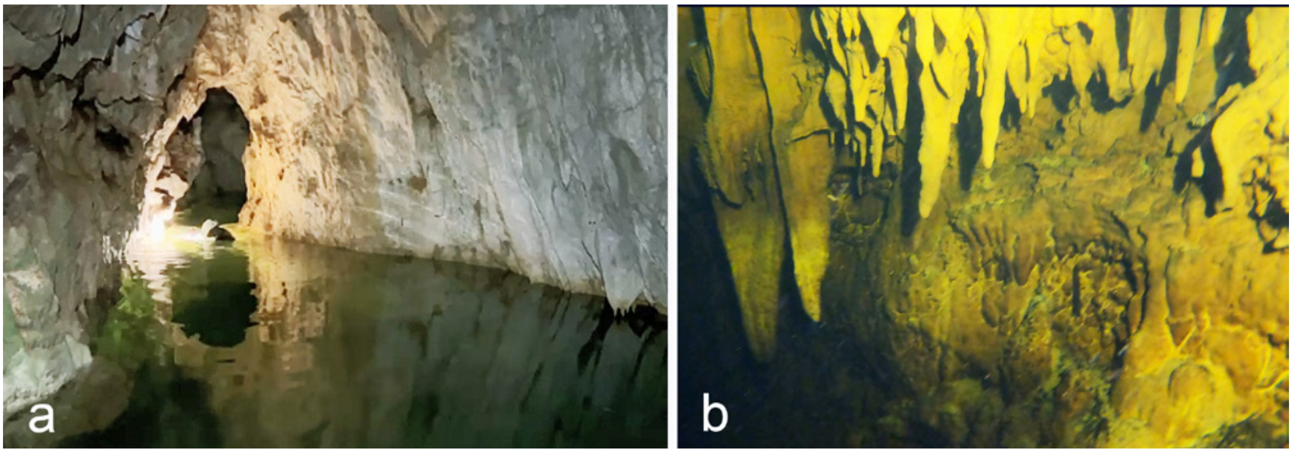

Figure 12: Bjejajka cave passage (a) and submerged speleothems (b) (Photos: M. Baričević, N. Lončar).
Figura 12: Galería de la cova de Bjejajka (a) i espeleotemes submergits (b) (Fotos: M. Baričević, N. Lončar).

Water levels fluctuate, mainly influenced by tides and freshwater inflow from the surface (JALŽIĆ et al., 2021).

One of the unique features of Mljet Island is the presence of caves at the bottom of Mljet lakes. In Malo Jezero, two pits reach depths of 38 and 50 meters, respectively, and continue further into impassable fissures. While no freshwater outflow has been observed, it is likely that freshwater flows under certain conditions. One of them, Onofrijeva jama, is a former freshwater spring which likely lost its hydrological role when Malo Jezero was connected to the sea by an artificial channel. This change led to poor water circulation, eutrophication, temperature extremes, and anoxia (JALŽIĆ et al., 2021).

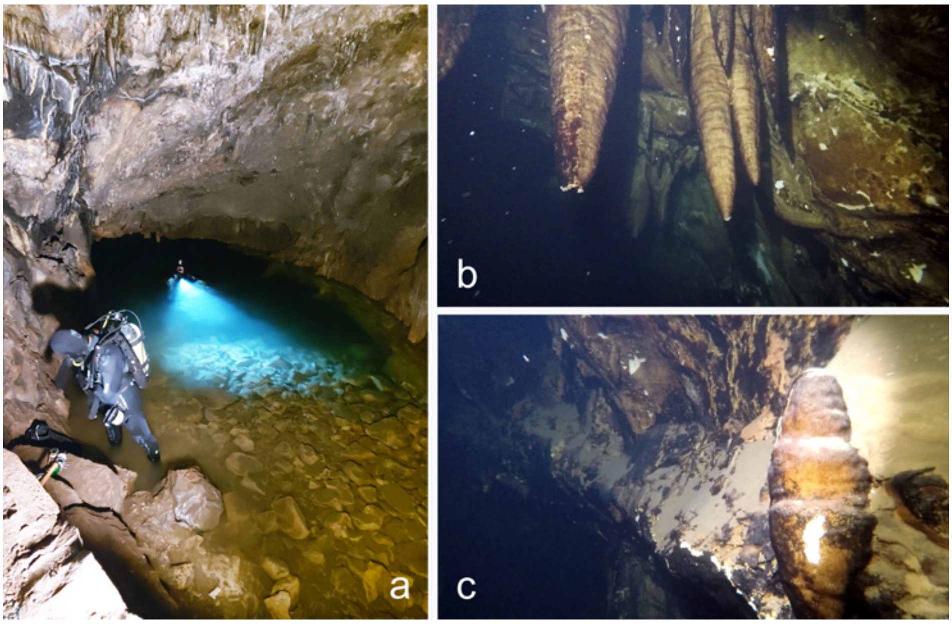

Figure 13: Šipun cave lake (a), corroded speleothems (b), and sediment (c) in submerged parts (Photos: I. Konjevod, N. Lončar).
Figura 13: Llac de la cova de Šipun (a), espeleotemes corroïts (b) i sediment (c) en les parts submergides de la cova (Fotos: I. Konjevod, N. Lončar).

Besides their various morphological characteristics, anchialine caves of the eastern Adriatic Sea are biologically unique and rich in species. They display high microbial diversity and endemism, with distinct community patterns influenced by salinity gradients and cave location (KAJAN et al., 2021) reflecting complex adaptations to dynamic environmental conditions. One of the most significant caves is Šipun (Figure 13), where over 100 species of fauna and around 10 species of protists were discovered. By 2017, 19 species had been described, the highest number in Croatia, with 15 recognized as taxonomically valid (OZIMEC, 2012; OZIMEC & BAKOVIĆ, 2017). Šipun Cave, located near Dubrovnik at an elevation of 24 m above the Adriatic Sea, is a half-submerged cave with a single main passage stretching 120 m. This passage is divided into a dry section and a lake (Figure 13a). The dry part, arranged for tourism, contains numerous speleothems, many of which are broken, likely due to tectonic activity. The submerged section begins at the lake featuring stalactites, cave curtains, and some columns and stalagmites. Certain stalactites show corrosion from exposure to brackish water (Figure 13b). Fine-grained sediment, likely washed in from outside, has accumulated throughout the gallery (Figure 13c) leading to poor visibility and challenging diving conditions.

Speleothems in coastal and submerged caves

Speleothems are essential for reconstructing past environmental conditions in karst caves. Unlike inland vadose caves, the formation of speleothems in anchialine and submerged caves is influenced by the presence of marine waters, which can inhibit growth or cause dissolution (BUNNELL, 2004). Coastal caves generally exhibit fewer speleothems. Speleothems, mostly stalactites and stalagmites, have been found in over 140 partially or completely submerged caves (SURIĆ et al., 2010). Research on submerged speleothems in Croatian caves has advanced significantly over the past decade. Surić and colleagues (e.g., SURIĆ et al., 2009; SURIĆ & JURAČIĆ, 2010) conducted one of the first comprehensive studies on marine biogenic overgrowth on submerged speleothems in the eastern Adriatic. By 2018, 22 submerged speleothems from 10 caves, at depths ranging from –1.5 m to –53 m, were analyzed, yielding radiometric ages (U-Th, ^{14}C) from 310 ka to 3.3 ka BP (SURIĆ, 2018). More recent work by LONČAR et al. (2020, 2021, 2024) has focused on sea-level reconstruction using phreatic overgrowths on speleothems (POS), while also collecting and analyzing submerged speleothems as part of these investigations. The latest and oldest submerged speleothems were collected as part of the SeaLeveL project. Speleothem subsamples were dated using the U-series disequilibrium method with 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. For further details on the methodology, refer to ASMEROM et al. (2006). In Medvjeđa špilja at depth of -12 m a stalagmite ML-12 was collected. The upper part is dated to approximately 400,000 years, while older sections are beyond the range of uranium-thorium dating. A stalactite from Kravljačica submerged pit (Figure 14) in the Kornati archipelago collected at the depth of -36 m was dated to 436,013 ± 25,099 years BP.

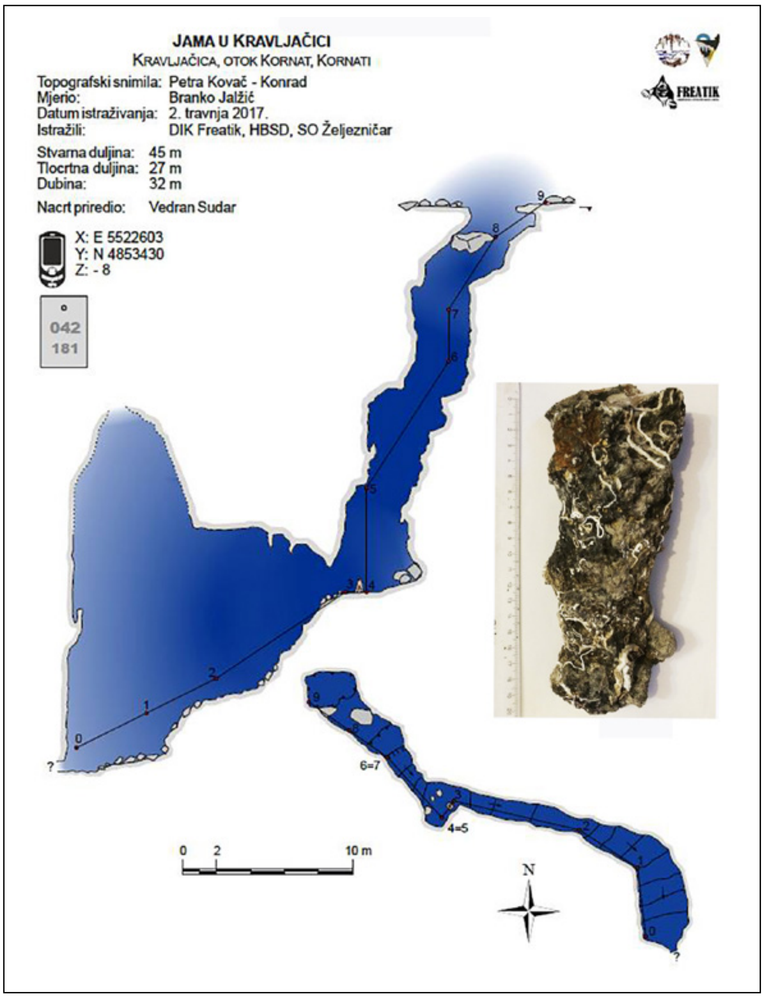

Figure 14: Kravljačica cave plan and profile and sample KRA-1.
Figura 14: Planta i perfil de la cova de Kravljačica i mostra KRA-1.

Phreatic Overgrowths on Speleothems (POS) in Croatia

The formation of POS in partially submerged caves challenges traditional assumptions about speleothem development, demonstrating that coastal karst caves can, under specific conditions, support the growth of unique calcite formations that serve as sea-level indicators. POS are secondary carbonate encrustations that form around existing vadose speleothems in coastal caves under favorable geochemical conditions (GINÉS et al., 1981; FORNÓS et al., 2002). Their growth occurs at sea level and within the tidal range, as long as sea level remains stable (DUMITRU et al., 2021). The first detailed study of POS as sea-level indicators in Mallorca began in 1972 at Cova de sa Bassa Blanca (GINÉS & GINÉS, 1974). POS have since been used for sea-level reconstructions in Sardinia (TUCCIMEI et al., 2012), Japan (MIKLAVIČ et al., 2018), Cuba (DE WAELE et al., 2017, 2018), Bermuda (HARMON et al., 1978), and Mexico (JENSON, 2018), contributing significantly to our understanding of Late Pleistocene sea-level highstands and Holocene stability.

The finding of POS at –1.28 ± 0.15 m below present sea level in Medvjeđa Špilja (LONČAR et al., 2024) (Figure 15), the first finding of POS in the Adriatic, represents one of the most significant findings in recent years. Uranium-series of POS sample from Medvjeđa Špilja confirmed that these

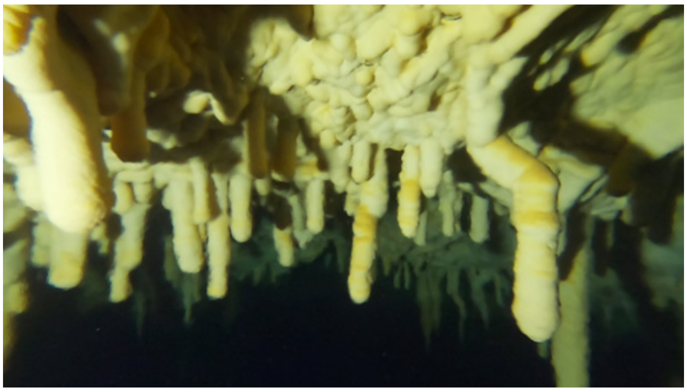

Figure 15: POS in Medvjeđa špilja “little lake” (Photo: N. Lončar).
Figura 15: POS al petit llac de la cova de Medvjeđa (Foto: N. Lončar).

formations date back to the Holocene (LONČAR et al., 2024), providing new sea-level index points for the eastern Adriatic coast. Mineralogical analyses identified the fibrous overgrowth as calcite, with both the overgrowth and supporting soda straw showing similar trace element compositions, indicating a chemically consistent drip and groundwater source. Uranium-series dating of POS MLp-1 suggests that approximately 2,800 years ago, sea level remained stable for about 300 years at this depth of around –1.28 ± 0.15 m. This aligns with the previously recorded stable period between 3,250 and 2,800 cal yr BP in the southern Adriatic (LONČAR et al., 2024; and the references therein).

Additionally, two presumably POS samples (SIP-1 and SIP-2) have been collected in Šipun Cave at depth of -1.2 m and -2.2 m below current mean sea-level. U-Th dating revealed that the youngest parts of SIP-1 are over 479,394 ± 33,634 BP (Figure 16a), while dating of SIP-1’s older laminae and sample SIP-2 showed that they were deposited beyond the U-Th method’s range, indicating an age of over 600,000 years (Figure 16a, b) or a slight alteration of the calcite. After cutting and XRD analysis, SIP-1 was identified not as a POS, but as a well-laminated stalactite, making it the oldest dated stalactite from an anchialine cave in Croatia.

Mineralogical analyses of SIP-2 revealed minimal magnesium levels, suggesting a non-marine or brackish origin for the carbonates, except in the outer crust. The zoned crystals in the inner part of SIP-2 (Figure 16c) resemble those found in POS from Japan (MIKLAVIČ et al., 2018). Exposure to brackish conditions could stimulate the growth of fibrous calcite crystals, as fluctuations in water chemistry, such as varying magnesium or calcium concentrations, favor fibrous or layered crystallization. Thus, the speleothem could undergo diagenetic alteration, with partial dissolution followed by the re-precipitation of new mineral phases influenced by the water’s chemistry. Therefore, it is not possible to clearly characterize SIP-2 as a POS.

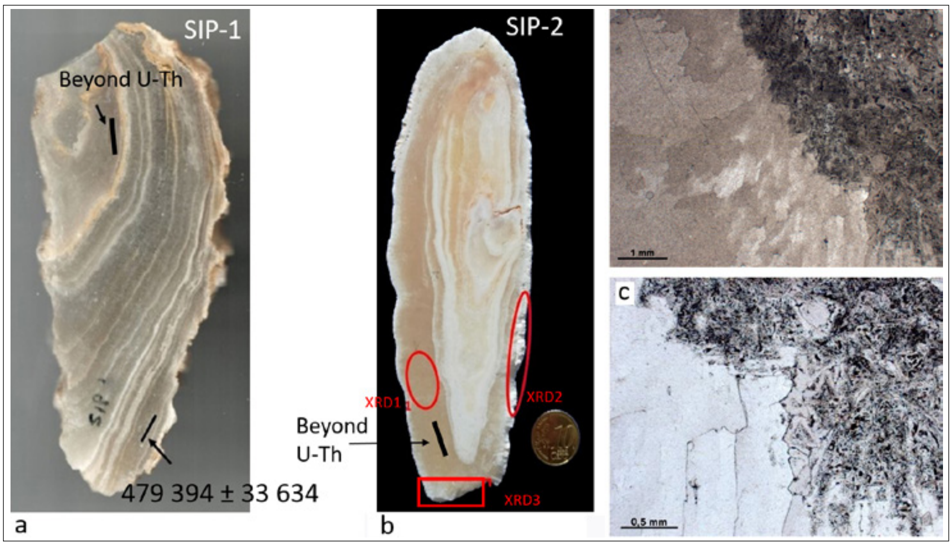

Figure 16: Cross section and ages of speleothems SIP-1 (a) and SIP-2 (b) and SIP-2 thin sections (c).
Figura 16: Secció transversal i edats dels espeleotemes SIP-1 (a) i SIP-2 (b) i làmines primes del SIP-2 (c).

Conclusions

Croatia’s coastal and submerged caves represent a unique intersection of marine and terrestrial geological, hydrological, and biological processes, offering valuable insights into past sea-level changes, karst formation, and paleoclimate. The spatial distribution of these caves highlights the complex interplay of tectonic activity, sea-level rise, and karst processes, with notable regional variations in cave morphology and hydrology. Tectonic activity has played a significant role in shaping coastal cave morphology, particularly where fault zones intersect with the coastline. The gradual rise in sea levels since the Last Glacial Maximum (~21,000 years ago) has transformed many karst caves into partially or fully submerged systems and anchialine or euhaline environments, particularly along the eastern Adriatic coast.

This study reveals significant regional variations in the distribution and characteristics of Croatia's coastal caves. The highest concentration of caves is in middle and south Dalmatia (middle Adriatic). The most of partially and completely submerged caves have been explored in Kornati National Park and on Mljet Island, where the combination of well-stratified carbonate rocks, tectonic activity, and post-glacial sea-level rise has created ideal conditions for coastal cave presence, with both horizontal and vertical passages.

Recent cave-diving research, particularly within the SeaLeveL project, has expanded the knowledge of these caves, uncovering new sites and providing valuable speleothem samples for geochronological analysis. The speleothems ML-12, SIP-1, and KRA-1, dating back over 500,000 years, provide insights into the long-term karst development and past environmental conditions of the Adriatic region. Their age suggests that these caves were formed during periods of lower sea levels, with karst processes actively shaping the landscape. The continued deposition of speleothems in anchialine caves (Medvjeđa špilja and Šipun) after the last sea-level rise indicates that certain parts of these caves remained suitable for mineral growth despite partial submersion, reflecting complex geomorphological and hydrological conditions.

The discovery of the first Phreatic Overgrowths on Speleothems (POS) in the Adriatic marks a significant milestone in the study of coastal karst systems in Croatia, providing a precise marker for past sea levels and contributes to the understanding of the region's paleoenvironment. Speleothem MLp-1 exposed that ca. 2,800 years ago, 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. The presence of POS in the Adriatic suggests that this phenomenon may be more widespread than previously thought. These findings highlight the potential for further discoveries of POS in other coastal caves, particularly those located near paleo-shorelines.

Future research should focus on exploring previously unexplored caves, particularly in regions likely to contain POS and other significant speleothems. The integration of advanced technologies such as underwater drones and remote sensing could further enhance our ability to explore submerged caves and collect high-quality data. Additionally, further geochronological studies of POS and other speleothems are needed to refine the timeline of sea-level changes in the Adriatic, contributing to a broader understanding of global climate change.

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