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LATE HOLOCENE WIDENING OF KARST VOIDS BY MARINE PROCESSES IN PARTIALLY SUBMERGED COASTAL CAVES (NORTHEASTERN ADRIATIC SEA)

Abstract: FURLANI S., CUCCHI F. & BIOLCHI S., *Late Holocene widening of karst voids by marine processes in partially submerged coastal caves (Northeastern Adriatic Sea)*. (IT ISSN 0391-9838, 2012).

The coastal scenery of the Northeastern Adriatic sea is widely interested by caves and related coastal features, which are developed in correspondence of geological weaknesses of sea cliffs. We present the preliminary surveying of five partially submerged coastal caves cut in limestone cliffs, relating the dissolutionally widened vadose karst voids and the present-day forms. The analysis pointed out two well-defined morphological zones inside the caves. The boundary between the zones roughly coincides with the mean sea level. The submerged zone is mainly affected by abrasion processes on the bottom and the lateral walls, while the emerged zone is interested by karst processes and collapse of blocks from the roof. Their effects produce a bell-shaped cross-section, in which the submerged part of the caves is significantly larger than the emerged one.

Considering the tectonic behaviour of the area inferred from literature the caves were flooded about 6 ka BP, when marine processes started to shape their submerged part. Our results allowed, in particular, to evaluate processes shaping the partially submerged coastal caves in the Northeastern Adriatic Sea after the marine transgression. Considering the very preliminary surveyed data, we suggest that the early phases of cave evolution was mainly dissolutionally-controlled and produced the widening of pre-existing joints or faults, as demonstrated by the occurrence of karst features in the upper part of the caves. Recent evolution is instead marine-controlled and the widening is mainly due to the overlapping of marine processes effects on karst voids, since they are closely related to the Late Holocene sea level rise.

KEY WORDS: Coastal caves, Sea level change, Late Holocene, Gulf of Trieste, Istria, Italy, Croatia.

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Riassunto: FURLANI S., CUCCHI F. & BIOLCHI S., *Ampliamento Tardo-Olocenico delle cavità carsiche ad opera dei processi marini in grotte costiere parzialmente sommerse (Adriatico nord-orientale)*. (IT ISSN 0391-9838, 2012).

Il paesaggio costiero dell'Adriatico nordorientale è interessato da un certo numero di grotte marine che si sviluppano in corrispondenza di superfici di discontinuità lungo le falesie costiere. Vengono qui presentati i rilievi preliminari di cinque grotte costiere parzialmente sommerse. L'analisi morfologica evidenzia la presenza di due zone morfologiche ben distinte all'interno delle grotte studiate; il confine tra le due zone corrisponde grossomodo con il livello medio del mare. La zona sommersa è condizionata da processi di abrasione sul fondo e sulle pareti laterali, mentre la zona emersa è interessata da processi carsici e dal collasso di blocchi dal tetto delle cavità. Questi processi danno luogo ad una sezione a campana, nella quale la parte sommersa della cavità è significativamente più larga di quella emersa.

Considerando il comportamento tettonico dell'area desunto dalla letteratura, queste grotte sarebbero state sommerse circa 6.000 anni fa, quando i processi marini hanno iniziato a modellare la parte sommersa. I nostri risultati hanno permesso di valutare i processi che hanno modellato le grotte parzialmente sommerse nell'Adriatico nordorientale dopo la trasgressione marina. Considerando questi dati preliminari, supponiamo che le prime fasi dell'evoluzione di queste grotte è stata controllata in larga parte da processi dissolutivi che hanno prodotto un allargamento di giunti o fratture pre-esistenti. L'evoluzione recente è invece controllata principalmente da processi marini successivi alla risalita del livello marino tardo Olocenica, che hanno allargato le precedenti cavità.

TERMINI CHIAVE: Grotte costiere, Variazione livello del mare, Tardo Olocene, Golfo di Trieste, Istria, Italia, Croazia.

INTRODUCTION

Coastal caves, also known as littoral, sea or marine caves, are grouped in two major types: sea caves and flooded caves (Antonioli & Forti, 2003). The first ones, which are sea caves *sensu stricto*, include those caves formed by marine processes (i.e. wave attack, abrasion or bioerosion). The second group incorporates those caves developed by means of different processes (karst, eolian, tectonic or volcanic caves) occurred previously to marine transgression flooding. They have been widened by wave action (Bunnell, 2004). Moreover, there is a third group, flank margin caves, that are dissolutional features that form by water mixing as sealed chambers (Mylroie & Carew, 1990). The formation of sea caves is mainly controlled by geological weakness, such as bedding planes, joints and faults (Sunamura, 1992; Zezza, 1981). They start forming when wave action exploits a pre-existing weakness of the rock, causing differential erosion to produce a cave (Moore, 1954) otherwise, as suggested by Waterstrat & *alii* (2010), when wave energy focus on a uniform rock. Their form depends on the dip bedding planes and the number, persistence, spacing and direction of joints and fault planes (Guilcher, 1958). The prerequisites of sea cave formation are the presence of sea cliffs affected by erosive action of waves and currents (Moore, 1954). Geological structures, stratigraphy or sedimentological features of limestone beds allow differential erosion on the exposed face of the cliff. Moreover, rocks must be sufficiently resistant so as to prevent the formation of protective beaches at its base and to allow for a sizeable cavity to form without collapse (Moore, 1954). Present-day active coastal caves are partially submerged (Gracia & *alii*, 2001) and their longitudinal profiles are usually raising toward their inner part (Gracia & Vicens, 1998).

Sea caves occur along most of the limestone coasts of the Mediterranean Sea, insomuch as different aspects (biological, geomorphological, exploration, etc) have been studied. Published research results are mainly confined in local papers or proceedings of karst conferences. Noteworthy is the volume edited by Alvisi & *alii* (1994) on Italian marine caves, Chelli & *alii* (2008) on Tyrrhenian sea caves and Vicens & *alii* (2011) on Balearic Islands. Questions concerning speleothems have been treated in tropical settings (Taboroši & *alii*, 2006), but they have been successfully used as sea level markers (e.g. Surić & *alii*, 2009; Dutton & *alii*, 2009) in Mediterranean. Taboroši & *alii* (2006) identified two kinds of speleothems in tropical settings: exposed stalactites (1),which are formed in the enclosed atmosphere of caves and then exposed as remnants and stalactitic tufa (2), namely subaerial deposits of calcareous tufa.

All the prerequisites for the genesis and development of coastal caves are satisfied along the Eastern Adriatic coasts, where a large number of coastal caves occur, together with completely submerged caves (Suric & *alii*, 2010). Despite this, only the Plava Grota, a flank margin cave at Cres Island (Croatia), have been studied (Otoničar & *alii*, 2010).

We aim at shining a light on the genesis of partially submerged coastal caves along the Northeastern Adriatic Sea. Considerations to evaluate times and ways of their submersion have been made, starting from data collected via underwater surveying and comparing the morphological features of the caves with the published vertical tectonic rates in the study area.

THE STUDY AREA

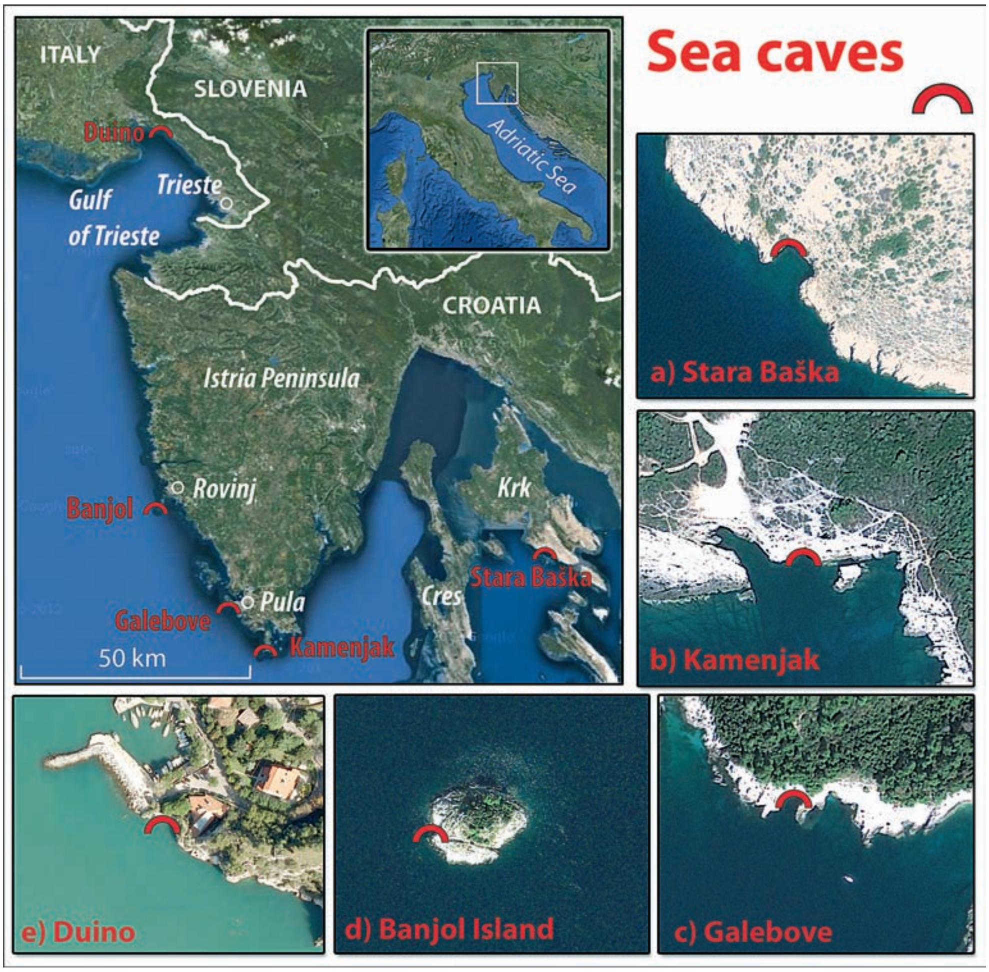
The five studied marine caves overlook the Northeastern Adriatic Sea (fig. 1). From a geodynamical viewpoint the area is part of the External Dinarides, dominated by limestones belonging to the Adriatic Carbonate Platform, spanning in time from Lower Jurassic to Eocene (Velić & *alii*, 2002). The Dinarides are characterized by compressional tectonics with maximum stress aligned NE-SW and consequently thrust and inverse faults NW-SE oriented (Vlahović & *alii*, 2005). This is the reason why the Cretaceous-Tertiary carbonate succession overlays the Eocene turbiditic one, which in turn has been involved in the thrust because of late compressional phases (Doglioni & Bosellini, 1987; Castellarin & *alii*, 1992).

Seismotectonic activity is not significant in the study area, while there are historical records of a number of very strong earthquakes in the Gulf of Rijeka (Faivre & Fouache, 2003). Benac & *alii* (2004) suggested that the famous 361 AD earthquake, that drowned the Roman town of Cissa, lowered the Northeastern Adriatic and consequently submerged the notch studied along most of the Northeastern Adriatic coast by many Authors (Pirazzoli, 1980; Benac & *alii*, 2004; Benac & *alii*, 2008; Fouache & *alii*, 2000; Antonioli & *alii*, 2004; Antonioli & *alii*, 2007; Faivre & *alii*, 2011; Furlani & *alii*, 2011a, b).

Sea-level change is the sum of eustatic, glacio-hydro-isostatic and tectonic movements. While the first is global and time-dependent, the latter two vary with location, sediment load and compaction (Lambeck & *alii*, 2004). The glacio-hydro-isostatic component of post-glacial sea-level rise has been recently predicted and compared with field data at several coastal sites all over the Italian and Mediterranean coasts (Lambeck & *alii*, 2004, Lambeck & *alii*, 2011) and also along the Northeastern Adriatic coasts (Antonioli & *alii*, 2007, 2009, Faivre & *alii*, 2011).

Late Holocene sea level change in the North-eastern Adriatic Sea (fig. 1) has been studied by a number of Authors (Degrassi, 1957; D'Ambrosi, 1959; Antonioli & *alii*, 2004, 2007; Degrassi & *alii*, 2008; Fouache & *alii*, 2000; Benac & *alii*, 2004, 2008; Faivre & *alii*, 2011, Furlani & *alii*, 2011a, b). Several geomorphological, biological and archaeological markers have been used as source of information from which the relative movements between land and sea have been evaluated. Holocene submersion was largely completed about 7 kyr cal BP and subsequently the sea level rose slowly to the current elevation (Antonioli & *alii*, 2007, 2009). On the whole, sea level markers indicate, for this area, a vertical tectonic signal at a rate of about -0.75 mm/yr occurring during the last two millennia and producing a significant relative downdrop of the coastline of about 1.5-1.8 m (Antonioli & *alii*, 2009). Faivre & *alii* (2011) reconstructed sea level changes along the Istrian coast since about 5 kyr cal BP. Moreover no marine notches or fossils have ever been found in this sector at elevations higher than the present sea-level (Antonioli & *alii*, 2007). On the contrary, a submerged tidal notch have been surveyed along the whole Eastern Adriatic (Pirazzoli, 1980; Fouache & *alii*, 2000; Benac & *alii*, 2004, 2008; Antonioli & *alii*, 2004, 2007; Furlani & *alii*, 2011 a, b; Faivre & *alii*, 2011). Its depth is about –0.5/–0.7 m and increases up to –1.1 m in the Bakar bay and up to –2.8 m in the gulf of Trieste, due to local tectonics (Benac & *alii*, 2008, Furlani & *alii*, 2011a; Stiros & Moschas, 2012). Anyway, Surić & *alii* (2009) suggested long-term tectonic uplift of 0.15/0.25

FIG. 1 - Location of the study caves in the Northeastern Adriatic Sea. Zoom on the entrances of the studied sea caves on the satellite images (from Google Earth). A) Stara Baska; B) Kamenjak; C) Galebove; D) Banjol; E) Duino.



mm/yr of the Krk Island area with occasional subsidence events and Altiner & *alii* (2006) suggested an uplift of more than 10 mm/yr in the Southeastern part of Krk Island using GPS measurements.

From a geomorphological point of view, the study area can be classified as a Dalmatian coast (Holmes, 1965). It is mainly dominated by up to 70 metres high limestone plunging cliffs, variously inclined, from gently sloping to vertical.

The coast of the Gulf of Trieste and the Kvarner coast are characterized by the presence of large submarine springs. In particular, the Timavo River (mean 30 m^3/s, min 7.4 m^3/s, max 158 m^3/s) discharges fresh water from a large subterranean karst area (700-1000 km^2) (Gemiti, 1995) and together with the Isonzo River (mean 134 m^3/s, max 4400 m^3/s) contributes to decrease the salinity of the Gulf of Trieste. Seawater salinity displays higher values in winter than during summer and ranges between 34 and 39 psu (Miramare oceanographic buoy). Large differences in salinity values have been measured during the floods of Timavo and Isonzo rivers, when abundant freshwater lowers the values, mainly in the northern sector of the Gulf of Trieste.

The area is characterized by a prevalence of winds blowing from the first quadrant, mainly from the ENE (Bora or Bura) (Carrera & *alii*, 1995). South-easterly winds (Scirocco or Jugo) are important because of the long fetch (over 800 km). Tides are semi-diurnal, with mean spring-tide values of 0.86 m in Trieste, and mean neap-tide values of 0.22 m (Dorigo, 1965; Polli, 1970). The concomitance of spring tides, seiches, south-easterly winds and low atmospheric pressure can cause a sea level rise of 1.60 m (locally called «acqua alta»). Along the Croatian coasts, tides are less significant than in Trieste (30% in Zadar, 40% at Bakar and 70% at Rovinj). Mean significant wave height during the year is lower than 0.5 m (Dal Cin & Simeoni, 1994), and the highest offshore wave height, both for Bora and Scirocco storms, is about 5 m (Cavaleri & *alii*, 1996). An estimate of wave energy for the northern Adriatic area in the form of H^2T^2 (H and T corresponding to the significant wave height and period) was studied using the complete series of 2000-2003 three-hourly measurements available from the RON-APAT (Fontolan & *alii*, 2007) wave gauge located offshore Ancona. The annual value is 15.61 m^2s^2. The highest mean hourly speed for southeast wind in the period 1958-1987 was 27.3 m/s. Southeast winds do not generate waves that directly enter the Gulf of Trieste or the Gulf of Rijeka, but only as refracted waves. Generally, the Bora lowers the sea level, whereas the winds of the southwest and the northwest quadrant raise it, thus leading to «high-water» phenomena, mainly in Trieste and Istria.

METHODS

Coastal caves have been surveyed along the Gulf of Trieste, Istrian and Krk Island limestone shorelines. The topographic description has been provided following the surveying methods suggested by Alvisi (1994). In particular, a cross-section of each cave has been provided. Moreover, marine and subaerial forms have been added to the topographical sketch to define the morphological elements functional to study their genesis. The scuba team was usually composed of two or three scuba divers. The surveying has been carried out with the instruments commonly used for the underwater speleology: distances have been measured using a flexible meter (for distances > 2 m) or a wood meter (for max 2 m in length) or an ultrasonic distance meter for measurements above the water. Directions in submerged environment have been collected using a scuba compass, while strikes and dips of geological features outcropping close to the cave have been measured using a geological compass. Measurements have been reported on a polyvinyl chloride white board. Depths have been collected using a dive computer Bravo One. The surveying has been improved with a number of images which have been collected using a camera CANON G12 with a WP-DC34 waterproof housing and an underwater Wide-Angle BigEyes Lens.

RESULTS OF THE SURVEYING

Five partially submerged sea caves facing the Northern Adriatic coasts (fig. 1) have been surveyed and shortly described. Their sizes and geomorphological features are reported in tab. 1. All the studied caves develop at the present-day mean sea level and are partially submerged (fig. 2). They develop on plunging cliffs ranging from few meters (5 m at Duino) to some dozen of meters (20-30 m at Stara Baška) in height. Their length is variable between 10 m and 47 m. Galebove cave is completely dark in the innermost part.

The features of each cave are described in the following paragraphs.

Stara Baška cave (Stara Baška, Krk Island, Croatia)

The cave is located in a small bay near the village of Stara Baška (fig. 1). The bay is about 30 m long and 20 m large (fig. 1, 3b). The cave is cut in massive Eocene limestone and it develops parallel to the coast along a prominent fault (NNW-SSE). It is exposed towards the Southwest, but it is protected by dominant Northeast winds (Bora). Southwesterly winds (Libeccio) have very a short fetch, that is the distance of open water across which a wind blows or over which a wind-generated water-wave travels, unobstructed by major land obstacles (Whittow, 2000), limited by the island of Cres. Subangular pebbles and cobbles cover the bottom of the bay, while locally sand outcrops. The cave is about 20 m long and, at the entrance, 6 m wide (tab. 1). The maximum emerged height is 4 m a.s.l., while the maximum depth is –5 m a.s.l. at the entrance.

Few speleothems and flowstones occur inside the cave above mean sea level and are covered by green algae, in particular near the entrance.

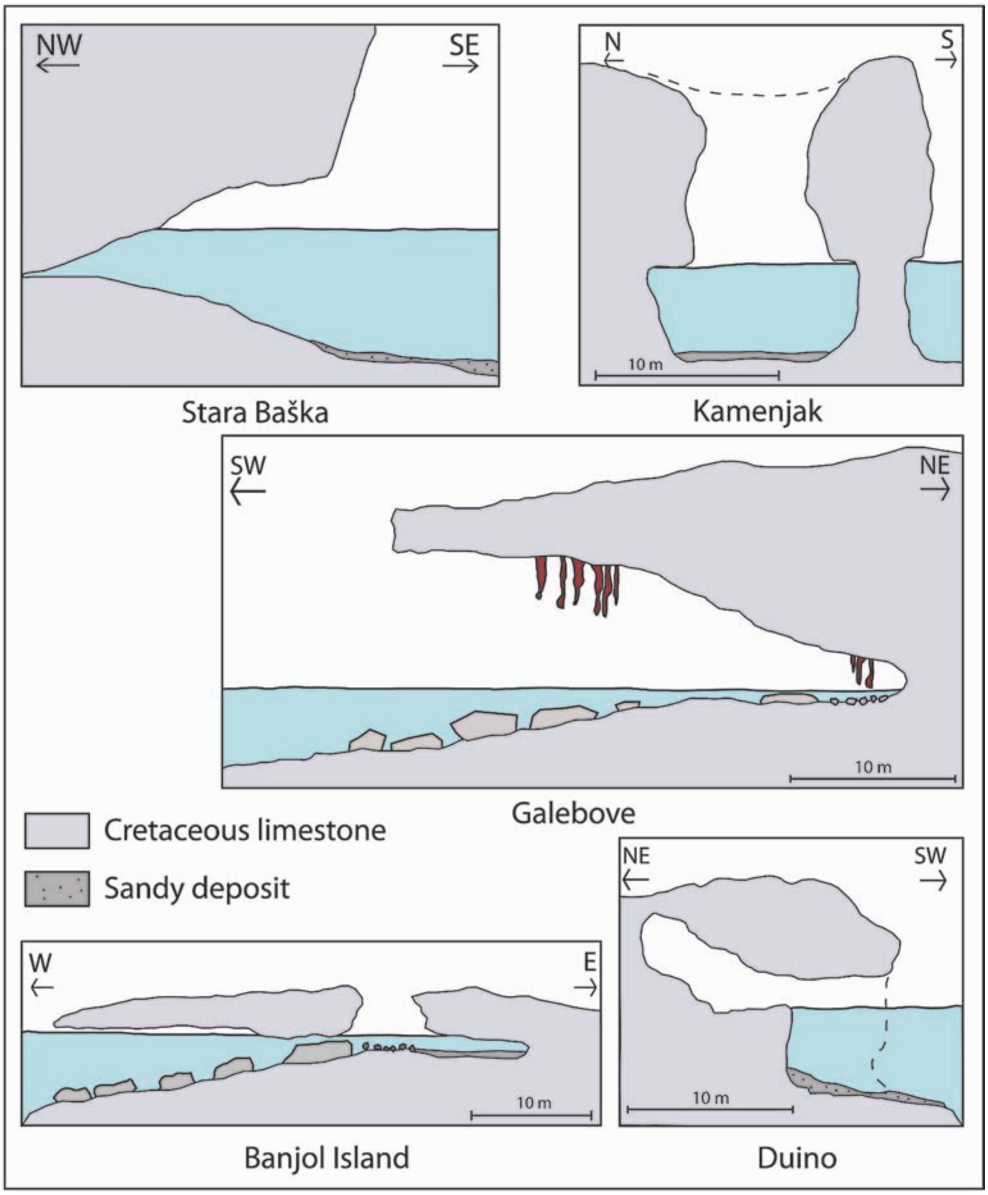
The bottom of the cave is partially covered by subangular pebbles and cobbles. On the lateral walls, abrasion processes dominate and produce rounded rock surfaces (fig. 5d).

A submerged tidal notch has been surveyed along the coast close to the cave at –0.6 m a.s.l.. It gradually disappears moving inside the cave. 2-3 m from the entrance there is no more trace of the submerged tidal notch (fig. 5d).

TABLE 1 - The main features of the studied sea caves in the Northeastern Adriatic. A) identification number; B) name; C) location; D) WGS 84 centesimal coordinates; E) maximum length of the cave (perpendicular to the entrance); F) maximum width (parallel to the coast); G) direction of the main axis of development; H) direction of maximum exposure; I) presence of tidal notch (inside/outside the cave); L) presence of abrasion notch inside the cave; M) presence of speleothems (emerged or submerged)

A n°	B Cave name	C Location	D WGS84 coordinates	E Max length (m)	F Max width (m)	G Axis of development (°)	G Submerged height / emerged height (m)	H Exposure (direction)	I Tidal notch (int/ext)	L Abrasion notch	M Speleothemes (emerged/submerged)
1	Stara Baska	Stara Baska (Croatia)	45.64861 13.7675	15	6	**320/140**	**–5/4**	**SW**	**No/Yes**	**Yes**	**Yes/No**
2	Kamenjak	Premantura (Croatia)	45.64861 13.7675	12	30	**15/195**	**–6/4**	**S**	**No/No**	**Yes**	**Yes/No**
3	Galebove	Stoja (Croatia)	44.861340 13.804538	40	12	**200/20**	**–5/7**	**SW**	**No/No**	**Yes**	**Yes/No**
4	Banjole	Banjole (Croatia)	45.074063 13.610668	47	14.2	**275/95**	**–6/0**	**SW**	**No/Yes**	**Yes**	**Yes/No**
5	Duino	Duino (Italy)	45.64861 13.7675	10	10	**20/200**	**–4/2**	**SW**	**No/Yes**	**Yes**	**No/No**

FIG. 2 - Cross-section perpendicular to the entrances of the studied caves. A) Stara Baska; B) Premantura; C) Banjol; D) Kamenjak; E) Duino.



Kamenjak cave (Premantura, Medulin, Croatia)

The Kamenjak cave is located in the Southernmost headland of the Istrian peninsula, at Premantura (fig. 1). It develops on a plunging cliff in correspondence of a system of faults and fractures (fig. 1) and is cut on sub-horizontal centimetric Cretaceous limestone beds. The cave is exposed towards the south, in the most exposed sector of the Istrian coast. The bay is very indented due to its own structural features, with the presence of spectacular coastal forms, like a stack (it. *faraglione*). The cave extends about 12 m in length and 30 m in width. The maximum depth is –6 m a.s.l. at the entrance (fig. 2). On the contrary, the emerged height at the entrance is only a few centimetres. Other 3 entrances have been surveyed: the first is completely submerged in the easternmost part of the cave, the second cuts the cliff, facing the sea, the third is represented by the collapsed roof.

Speleothems and flowstones, which are abruptly interrupted at the mean sea level, occur in the emerged part of the cave (fig. 4c). They are completely covered by green algae coats near the entrances.

Pebbles and cobbles occur on the floor together with collapsed angular blocks, the latter up to more than 1 m in size (fig. 5b). Limestone bedrock prevails at the bottom of the cave, in particular in the innermost sectors, where centimetric runnels (fig. 5b) and submarine centimetric to decimetric potholes, occur. Potholes are sometimes filled with abrasive materials, as sand, gravel or large pebbles.

No tidal notch has been surveyed in the area close to the cave, probably because of the horizontal and very thin beds, nor has it been seen inside. On the contrary, the walls of the cave are cut just below the mean sea level forming abrasional features (fig. 2).

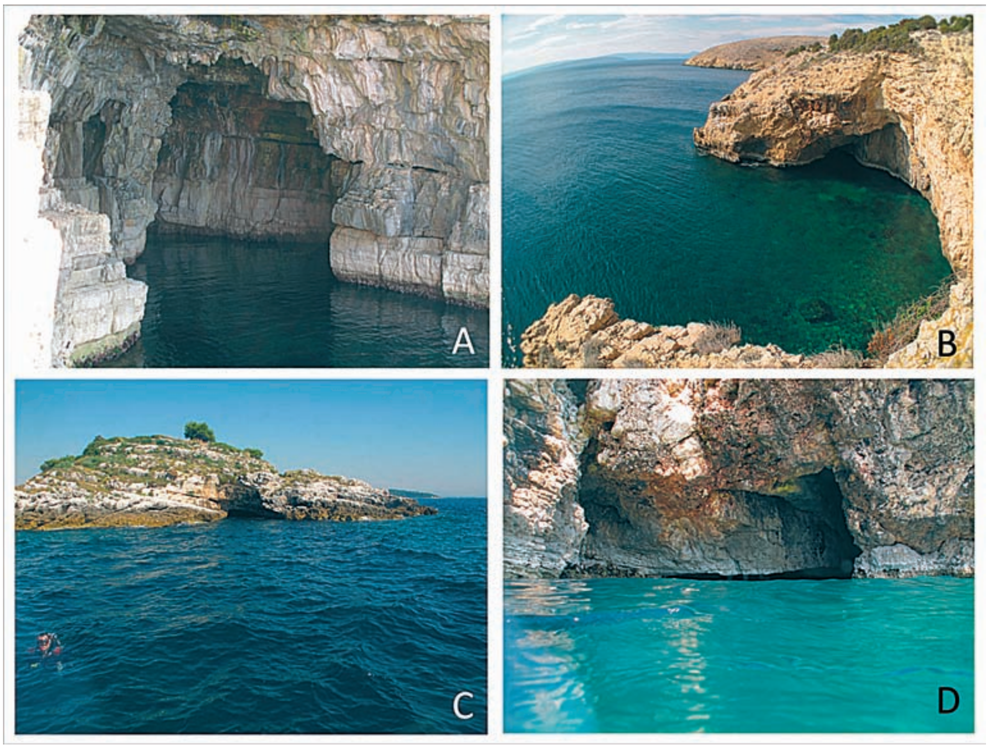


FIG. 3 - Some example of the entrances of the studied caves. A) Galebove cave; B) Stara Baska cave; C) Banjol cave; D) Kamenjak cave.

Galebove cave (Pula, Croatia)

Galebove cave is located in the Mužilj Bay in the homonymous peninsula, which is located 3 km West of Pula (fig. 1). The area is characterized by high plunging cliffs, alternatively higher in correspondence of headlands and lower in correspondence of bays, which are sometimes characterized by very small pocket beaches. The cave is cut in sub-horizontal centimetric to decimetric limestone beds and it develops roughly perpendicular to the coast along prominent faults, NNE-SSW and NNW-SSW. Other variable size karst and marine features (bays, submarine

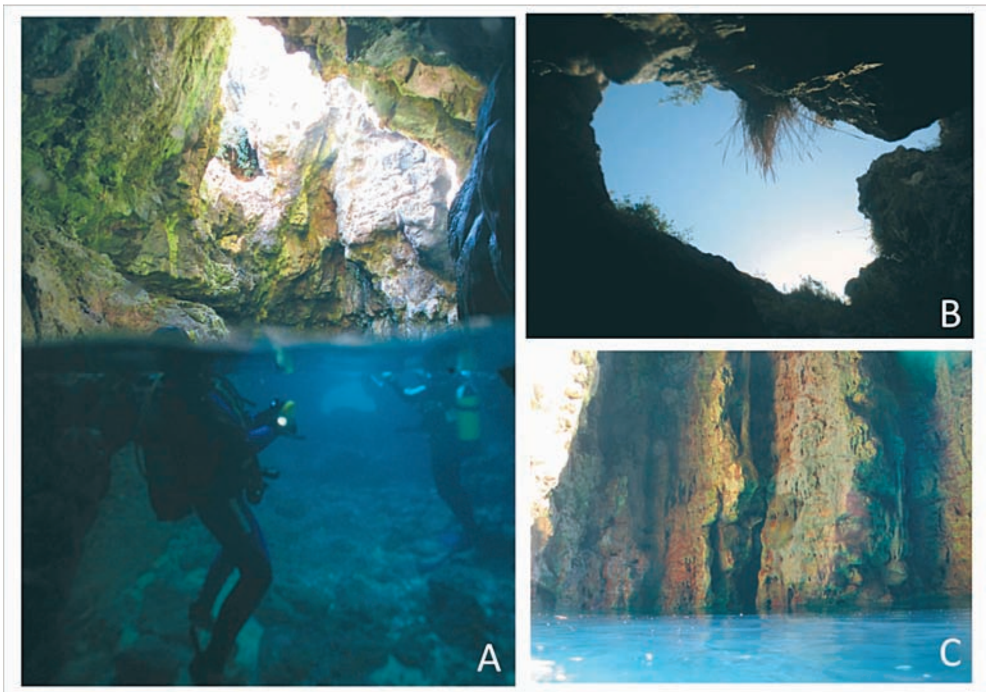


FIG. 4 - Some example of prominent morphologies studied in the Northeastern Adriatic sea caves. A) view of the main room of the Banjol. At the bottom, collapsed blocks occur, while the walls are covered by mosses and lichens; B) the hole at the top of the main room at Banjol; C) Speleothems covered by green algae coats at Kamenjak.

caves, etc) are developed along these lines. Next to the entrance, a structural bay occurs, insomuch as the cave system seems to be originally developed toward SSW (fig. 1), even if probably the remnants of the roof have been completely removed by wave action. Galebove cave is exposed towards Southwest. It is protected by dominant wind (Bora), but exposed to southwest wind (Libeccio), which occasionally produces very large storm waves.

The cave is about 40 m long and 7 m large at the entrance (fig. 2). In the innermost part of the cave a pebble beach occur. It is about 8 meters large and 5 meters wide. The bottom of the cave is widely covered by cobbles and well-rounded blocks up to 1 m in size. Limestone bedrock is carved by abrasional features, in fact centimetric to decimetric potholes, sometimes filled with abrasive materials, occur. Blocks are sometimes etched by centimetric bioerosive pits. Green algae occur at the entrance and disappear in the innermost part because light is almost absent. Even submerged biocenoses decrease quickly and dark sectors of the cave are almost completely lacking of organisms. A small pebble beach occurs inside the cave.

No tidal notch has been surveyed in the area outside the cave, probably because of the horizontal and very thin beds as in the case of the Kamenjak cave. It has been surveyed neither inside the cave, but lateral walls are interested by abrasional features below the mean sea level (fig. 5a), less marked than the ones occurring at Kamenjak.

Banjol cave (Banjol Island, Rovinj, Croatia)

Banjol cave is located at the homonymous island, about 2 km southwest of Rovinj (fig. 1). The island is part of an archipelago of 11 small (less than 1 km) islands. The cave is located in the southern part of the island, which is about 100 m x 100 m in size (fig. 1). It is cut in decimetric to metric subhorizontal cretaceous limestone beds. The coastline is characterized by low plunging cliffs which quickly descend to the sea bottom. Banjol cave is exposed towards south and southwest.

The cave develops roughly in E-W direction in correspondence of a fault and the cave is 47 m long. The entrance is 14.2 m wide, with a depth of –6 m a.s.l. at the entrance and decreases to –1 m a.s.l. in the innermost part. Ripplemarks on sand deposits occur in the innermost part (fig. 5c).

Pebbles and cobbles occur at the bottom. They are subangular to angular at the entrance, while they are well-rounded in the innermost part. The roof in the central part of the cave is collapsed (fig. 4b) so that a number of fallen blocks occur. Potholes occur on the bedrock outcropping at the bottom. Limestone beds below sea level are well-rounded by wave action, while above sea level they are sometimes covered by flowstones.

A submerged tidal notch has been surveyed close to the cave at –0.6 m a.s.l. near the entrance, but it lacks inside the cave.

Duino cave (Trieste, Italy)

The Duino cave is located in the northern sector of the Gulf of Trieste, roughly at the northernmost end of the Classical Karst (fig. 1). The coast is characterized by limestone plunging cliffs, which vertically descend to the sandy sea bottom. Unlike the Istrian coast, the northern sector of the Gulf of Trieste is characterized by intense flows of the

FIG. 5 - Some example of the submerged landscape inside the Northeastern Adriatic sea caves. A) Well-rounded blocks are scattered on the sea bottom at the Galebove cave. At the left side, the limestone bedrock is affected by significant abrasion processes; B) the sea bottom at Kamenjak is characterized by the occurrence of collapsed blocks (bottom left), while the bedrock is cut by abrasion channels. The main entrance of the cave is in the middle center; C) ripple marks at the sand deposits at the innermost part of the Banjole cave; D) the entrance of the Stara Baska cave. Since the cave is in a relatively sheltered zone, the tidal notch occurs also at the entrance, but it was not recognised inside the cave. For the same reason, on the contrary of the other caves, the sea bottom is covered by poorly reworked subangular fragments.

Timavo and Isonzo rivers, (fig. 1), with significant sediment load. The cave is cut in Cretaceous decimetric limestone beds inclined toward the sea (35°). The cave is exposed towards the Southwest, but the Gulf of Trieste is sheltered with respect to the Istrian coast.

The cave is about 7 m wide at the entrance and 10 m long (fig. 2). The depth is –5 m a.s.l. and the arched entrance is about 2 m high. The innermost part of the cave is characterized by the presence of a human-made dock. The bottom of the cave is covered with sand and rounded pebbles (fig. 2). Due to the aforementioned hydrological conditions; the visibility is often very low.

The lower part of the cave is enlarged. A submerged tidal notch has been surveyed close to the cave at a depth of about –2.5 m a.s.l., but it lacks inside the cave. No significant abrasion features have been recorded on the lateral walls.

DISCUSSION

The underwater surveying of five partially submerged sea caves along the Northeastern Adriatic coast (fig. 1) allowed us to shine a light on their genesis and to evaluate the contribution of subaerial and marine processes in their development. All the studied caves are located in correspondence of zones of relative weakness of the rock mass (faults and joints), so that erosion and rock decay enlarge these points with respect to the rest of the equally exposed cliffs. Their present elevation with respect to the mean sea level and the surveying of the related morphologies suggest that subaerial karst and also marine processes affected their evolution, but nowadays the latter are the most effective. Morphological features of the caves suggest that erosion rates increase at increasing depth, since their submerged parts are wider than the emerged

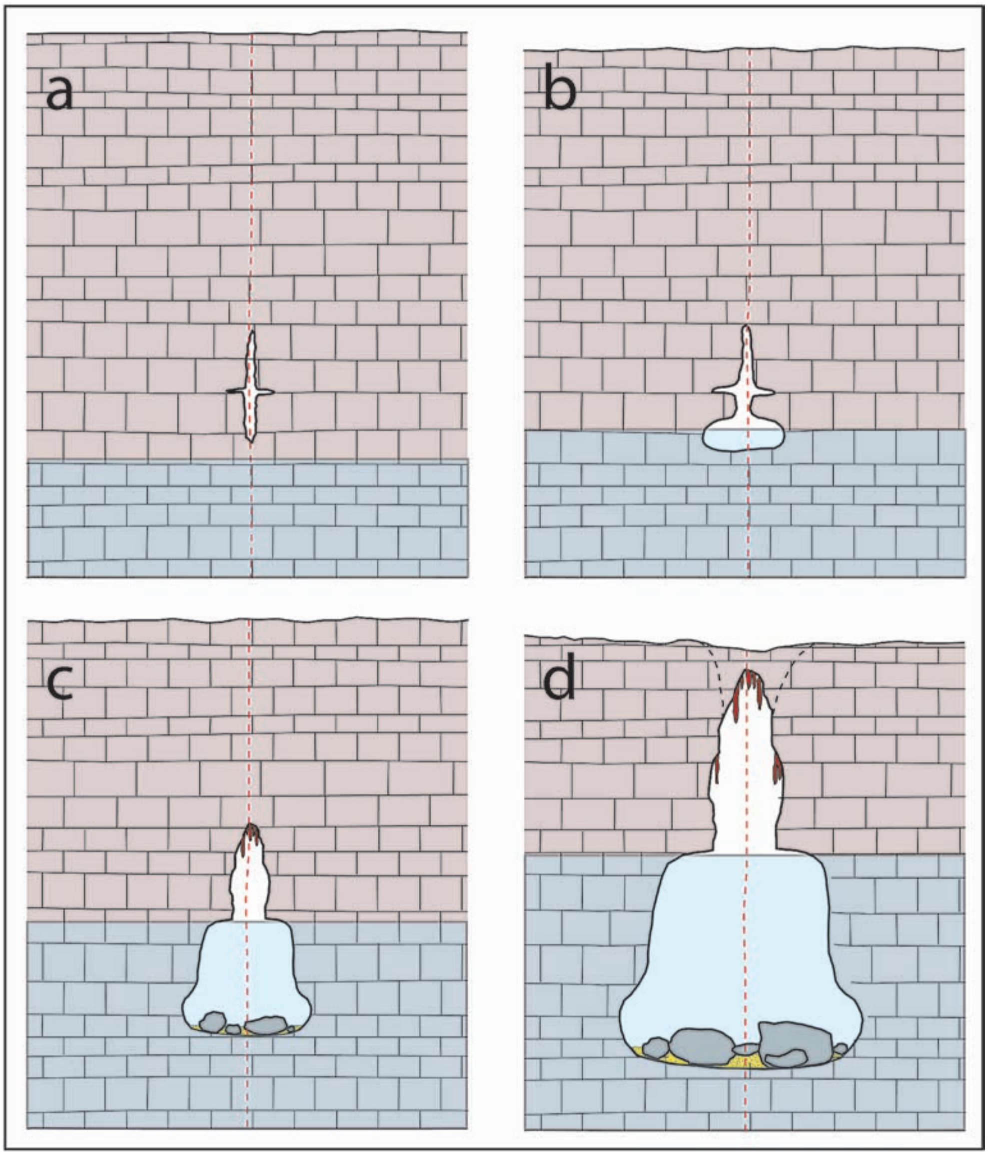


FIG. 6 - Sketch of the evolution of the sea caves studied along the Northeastern Adriatic coast. a) small karst voids develop along fractures, joints or limestone beds. The sea level is lower and the voids are not affected by marine processes; b) the sea level rises and increases its influence to the base of the voids producing an enlargement at the bottom of the cave; c) the significant differences in lowering rates between the emerged and the submerged part enhance, so the caves become bell-shaped. The collapse of blocks reduces the thickness of the roof; d) the widening of the cave continues, both in the submerged part, mainly affected by abrasion processes, and in the emerged part, affected by subaerial weathering and spray and splash processes. The natural processes of ground surfaces from above downwards and mainly of mechanical processes from the bottom upwards will eventually involve failure of the thinning roof. As the consequence, the cave will be opened upwards.

ones (fig. 6), therefore the resulting shape reflects differential erosion.

Caves at the junction between sea and land are part of the littoral environment (Moore, 1954) and therefore are subject to variables such as winds, wave direction and energy, currents, depending on the nature of sea-bottom and the hosting rock mass. Moreover, following Sunamura (1992), the equilibrium of the resisting and assailing forces is in turn related to the mean sea level, which controls the types of waves approaching the coast. Tides have no direct influence on the morphology of the littoral caves, but indirectly control the types of waves approaching and determine the degree of wave attack. Anyway, wave attack is strongest on microtidal coasts, as wave energy is not dispersed across a wide tidal range (Sunamura, 1992). Moreover, tide significantly affects the width of the small pocket-beaches which occur inside the caves, as in particular in the innermost part of the Galebove cave.

Two morphological zones can be recognized, according to the tide, inside the caves: i) an upper zone, above mean sea level, which is characterized by predominant subaerial or spray and splash processes. In this zone, lateral walls are often covered by green algae coats; ii) a lower zone, which is characterized by the dominance of abrasion. The intermediate zone, which corresponds roughly to the intertidal zone, where bioweathering or seawater processes dominate, gradually disappears moving inside, since coastal caves are affected by an effect of biological confinement, which produces a decreasing in the percentage of biological covering inside the cave (Harmelin & *alii*, 1985; Bianchi & Morri, 1994; Balduzzi & *alii*, 1989).

In the submerged part of the studied caves, well-rounded pebbles and blocks up to more than 1 m in size are scattered at their bottom. Straight ripple marks occur on sand deposits, even in the innermost part of the longest caves (Banjol and Galebove), therefore waves are effective even far from the entrance. Moreover, potholes and rounded abrasion features occur both on the exposed bedrock and on the lateral walls, in particular in the more exposed caves. These features testify that abrasion is the most powerful morphological factor in the submerged part. The assailing force of waves and the accompanying load of rock fragments and sand particles provide very strong erosive action on the rocks, in particular below the mean sea level. The erosive power of waves varies, in fact, directly with the supply of fragmental material carried in suspension by waves (Moore, 1954). Abrasion processes are mainly related to storm waves. Considering the average depth of the studied caves, on the bedrock outcropping at the bottom, rolling and sliding seem to be fundamental processes since waves carry material of relatively larger size by traction. On the contrary, in sheltered sites, e.g. at Stara Baška, even if the cave is generally bell-shaped, subangular features are dominant.

The tidal notch has not been observed inside the studied caves, while it is well-carved outside them, as reported by the Authors who studied the notches along the North-eastern Adriatic coasts (Fouache & *alii*, 2000; Antonioli & *alii*, 2004, 2007; Benac & *alii*, 2004, 2008; Furlani & *alii*, 2011a, b). The lacking of this form inside the caves could be due to the rapid decreasing in erosive organisms inside the caves, since bioerosion and bioweathering seem to be responsible of notch development (Pirazzoli, 1986) and its related high erosion rates (Torunski, 1979; Furlani & *alii*, 2009). Moreover, it is possible that the submerged notch could have been completely dismantled by the violence of mechanical processes. As proof of this, at Stara Baška, the submerged notch is preserved few meters inside the cave because its entrance is more sheltered than the other case studies. In place of the tidal notch, mainly due to biological (Pirazzoli, 1986; Furlani & *alii*, 2011b) or solution (Higgins, 1980) processes in the intertidal zone, a well-carved abrasion notch, due to abrasion processes (Sunamura, 1992), occurs inside, deeper than the submerged notch, since abrasion may be at a maximum in the lower shore (Trudgill, 1985). Anyway, the present-day notch is completely lacking in the study area, both inside and outside the caves.

The emerged part of the caves is often affected by the occurrence of speleothems and flowstones, which are cut a few centimeters above mean sea level. The emerged walls are also partly covered by algal coats, or by a coating of salty moisture or lichens. Anyway, limestone beds are better recognizable in the emerged part because abrasion processes produce very smooth surfaces. In fact, the rounding caused by abrasion hides the underlying structure of the rock mass, while differential erosion preserves the periodicity of beds. At Premantura and Banjole the roof of the caves collapsed, leaving large blocks at the bottom, some of them subangular in shape. The latter are probably the result of relatively more recent rock-fall events. No speleothems growth initiated on the broken surfaces.

Regarding the evolution of the caves, it is of fundamental importance to consider the relative Late Holocene sea level rise because, together with some considerations on limestone denudation rates, it is possible to highlight times and ways of cave widening, as following described.

The studied caves were originally very small karst voids (fig. 6a), but no data can be used to evaluate their initial size. Considering that present-day limestone denudation rates in the inner Karst range from 10 μm/yr to 40 μm/yr (Furlani & *alii*, 2009), the widening of the original voids was relatively low, with respect to lowering rates in seawater environment. However, as the relative sea level rose, the lower part of karst voids was increasingly affected by sea spray and splash processes, which increase limestone lowering rates (Furlani & *alii*, 2009). When the sea level was at the base of the voids, the enlargement of the lower part by marine processes started and it was due both to abrasion processes and hydraulic action (fig. 1b). The latter occurs during storm waves, mainly during relatively small time periods; the strong pressure which they are able to exert is well-known (Kuenen, 1950), since the small gaps in the rock are subjected to a wedging action resulting from compressed air. When the wave recedes, the air is forced to escape with an explosive violence. Moreover, even normal waves exert a hydraulic action effective in removing previously weathered rock particles. Furlani & *alii*

(2011b) underline that abrasion processes contribute to increase rock lowering rates of two order of magnitude, from some tens of microns to millimetres. Differences in lowering rates explain the bell shape of the studied caves, with a large widening of the base (fig. 6b-d). In the emerged part, speleothems and flowstones develop, but they can be deleted both by the rising sea level and by the aforementioned collapse from the roof.

Marine processes enhance following the relative sea level rise and their effects produce a bell-shaped cave (fig. 6c). The enlargement at the base of the lateral walls is related to the strong abrasive action at the bottom. Eventually, the mechanical action can carve an abrasive notch. At the bottom, mainly collapsed blocks occur and increase the abrasive action of waves inside the cave. The processes of ground surfaces from above and mainly of mechanical processes from the bottom will eventually involve failure of their thinning roof. As a matter of fact, as the cave widens at its base, the probability of a sudden or progressive collapse of the roof into the underlying cavern increases. Collapse occurs following undermining from below as the roof of the cavity stops upwards (Williams, 2004).

Regarding the genesis and evolution of the studied coastal caves, Chelli & *alii* (2008) and Mylroie & Carew (1988) suggest that morphological insights on the evolution of sea caves allow us to use them as rough sea level indicator. In our case, past sea levels indicators inside the caves are not well defined and therefore considerations are subject to significant errors. Despite the lacking of dated proxies, the comparison of morphological features and the number of researches about sea level changes in the Northeastern Adriatic Sea (Pirazzoli, 1980; Fouache & *alii*, 2000; Antonioli & *alii*, 2004, 2007; Benac & *alii*, 2004, 2008; Furlani & *alii*, 2011a, b; Faivre & *alii*, 2011) allow to reconstruct their evolution. Considering the aforementioned erosion rates, their evolution almost fully occurred during the Late Holocene. The Northeastern Adriatic is accepted to be tectonically subsident, with rates ranging from –0.7 to –0.8 mm/yr (Antonioli & *alii*, 2007; Faivre & *alii*, 2011) since Roman Age. MIS 5.5 markers have not been found in the Northeastern Adriatic Sea. Lagoonal shells near Rovinj, at a depth of –4.0 m a.s.l., provided an age of 4.8 ka BP (Faivre & *alii,* 2011). Since the bottoms of the studied caves are at max –6 m a.s.l., they were flooded about 6 ka BP and marine processes or their effects, as the rock-falls, can be considered as the main responsible for their widening.

The present research must be considered very preliminary. Processes and morphologies of plunging cliffs are still almost unknown, mainly because of the difficult accessibility of the surveying sites, while few more studies have been carried out on sea cave morphologies, in particular in the Adriatic sea. Future researches must concentrate on the age and typology (*sensu* Taboroši & *alii,* 2006) of speleothems, namely stalactitic tufa or, found inside these caves and a more detailed topographical and morphological characterization of the chambers, both above and below mean sea level.

CONCLUSIONS

This paper has presented a surveying of five partially submerged coastal caves along the Northeastern Adriatic coast. Morphological features related to their position with respect to the present-day sea level highlight the contribution of different factors in their morphological evolution. The surveying allowed us to identify and evaluate the relationships occurring between subaerial and seawater processes related to their widening and to study the relationships with Late Holocene sea level change. The emerged and the submerged part of the caves are well distinguished and correspond to different morphological zones. Their boundary coincides with the mean sea level. The submerged part is mainly affected by abrasion processes while the emerged zone by karst processes. The collapse of blocks from the roof widens the emerged part but it contributes to provide tools for the abrasive action of waves. Their joint effects produce a bell-shaped cross-section, in which the submerged part of the caves is significantly larger than the emerged one.

The results of the surveying and the comparison with published sea level change data have been used to infer time and modes of marine transgression in the studied caves, which probably occurred about 6 ka BP. Early phases of cave evolution started following joints or faults, while the enlargement was mainly dissolutionally-controlled, as demonstrated by the karst features in the upper part of the caves. Anyway, most of the widening occurred during the Late Holocene and is marine-controlled.

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