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ORIGINAL ARTICLE

Submerged caves of Croatia: distribution, classification and origin

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Abstract Presently, 235 submerged caves and pits have been recorded along the Croatian coast and islands, partly or completely submerged by sea water. Contrary to the inland situation, recorded submerged features are predominantly horizontal (60%), though there are indications that the real situation is similar to that of the continental part where 69% are vertical pits. Completely marine conditions are established in 126 caves and the rest are anchihaline caves and submarine springs. Speleothems are found in more than 140 caves. By their origin, the investigated caves are all continental features formed in Mesozoic and Palaeogene carbonates, subsequently submerged owing to sea transgression. Due to the relatively low wave energy, rapid sea level rise and maturity of the host rock, they do not fit into concepts of a sea cave or a flank margin cave development, but they fulfil several conditions for being the blue holes. Since the term 'blue hole' is mainly associated with the Bahamian karst, our attempt is only to show the possible similarities with no intention of ascribing that term to the Croatian caves. Beside karstological issues, Croatian submerged caves are unique environmental, archaeological and tourism assets.

Keywords Submerged caves · Karst · Adriatic Sea · Croatia

Introduction

Caves drowned by the sea are the least explored features within the karstological landscape, mainly because of specific skills required for their exploration, but also owing to the general opinion that the karstification ceases at the absolute erosional base that is the sea level, although it is not the case (Ford and Williams 2007). With respect to the coastal karst distribution in the world, not much literature is dedicated to the coastal and submerged caves. Apart from broadly studied Bahamian caves (Schwabe et al. 2007; Walker et al. 2008), some aspects of the environments of submarine caves have been obtained in Italy (Onorato et al. 1999; Alessio et al. 1992), United Kingdom (Joint Nature Conversation Committee 2007), France (Allouc and Harmelin 2001), Balearic Islands (Vesica et al. 2000; Fornós et al. 2002; Ginés and Ginés 2007), Mariana Islands (Mylroie et al. 2001; Stafford et al. 2005), Puerto Rico (Frank et al. 1998; Lace 2008), Cuba (Bozanic 1993), Mexico (Smart et al. 2006) etc.

Croatian karstic coast and submarine, analogous to the mainland, super abounds with caves which offer good potential for different environmental studies, but also for non-scientific activities. Regrettably, no extensive researches have been undertaken to date. Owing to the more than 6,000 km long, highly indented coastline this research and inventory of the submerged caves has not been conducted systematically; all available data were collected and used thanks to the databases of the numerous generous speleodivers, and sparse literature. The criterion for this inventory was that the caves are at least partially submerged by the sea water regardless of the position of entrances, influence of the freshwater, etc. So, besides the caves completely within the marine environment (with the entrance at the sea floor), anchihaline pits with onshore entrances have also been taken into account.

The Croatian submerged karst can be regarded as a type of a relict karst—the one which is within the contemporary system but was removed from the situation in which it had

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been developed (Ford and Williams 2007). As mentioned above, a kind of general opinion is that all karstification processes are connected to the continental conditions above the absolute erosional base—the sea level. In other words, since the sea water is supersaturated with respect to $CaCO_3$ in the first 500 m (Kennett 1982) the resulting process could only be precipitation and not dissolution of carbonates. Yet, certain processes go on even under the sea surface such as corrosion within the mixing zone of the fresh and sea water where both saturated solutions compose a mixture undersaturated with respect to $CaCO_3$ corrosive to the carbonate bedrock. Additionally, in the case of siphonal channels of the submarine springs (vruljas), corrosion and mechanical erosion of groundwater continue also below the sea surface. Furthermore, biological activity that affects the carbonate rock occurs also within the marine environment, both in depositional and erosional ways. Therefore, submerged caves should not be considered as dead systems. All of these processes have already been recognised and studied in particular caves in the Croatian submarine environment (Surić 2005), but overall research is still to be done. Here we present a general insight into types, distribution, origin and research opportunities of presently recorded submerged caves of the Croatian Adriatic coast and islands.

Geographical and geological outline

Dinaric karst, worldwide known as the *locus typicus* of classical karst covers half of the Croatian territory, including the whole coast and all islands with the exceptions of volcanic Brusnik and Jabuka Islands. The coastal and insular area is developed in Mesozoic and Palaeogene limestone deposited within the Adriatic carbonate platform (Vlahović et al. 2002, 2005). During the Alpine orogeny, that carbonate succession with total thickness of >8 km (Velić 2007) was intensively folded, faulted and overthrusted in the Dinaric direction (NW–SE) and exposed to the exogenic processes which resulted in its karstification. Throughout numerous Quaternary sea-level fluctuations, the Adriatic basin experienced several emergent events, specially its northernmost part which is relatively shallow (up to 120 m) and of low gradient (0.02°) thus being very sensitive to the eustatic changes. The final shape of the present littoral region is the consequence of the last Late Pleistocene–Holocene sea-level rise of the order of 135 m (Peltier and Fairbanks 2006) and it is worldwide known as *Dalmatian type coast* (Fairbridge 1968) characterised by the parallelness of the coastline, island chains and major geological and geomorphological structures. Presently, the Croatian coast is one of the most indented with 1,777 km along the coastline (a straight distance of 530 km), and with 4,398 km of additional coastline contributed by the 1,246 islands, islets, and rocks (Duplančić Leder et al. 2004).

Despite thousands of years within the marine environment, karst features such as karrens, dolines, caves, etc., are still recognisable on the sea floor, primarily due to the prevalence of easily soluble carbonate rocks in the drainage area of most of the rivers debouching along the Croatian coast, while only approximately 20% of river-borne material is in suspended (particulate) form. Additionally, cyclonic sea-current circulation (Orlić et al. 1992) preserves the eastern Adriatic Sea from a vast input of suspended matter delivered by the Po and Apennine rivers whose catchment areas are predominantly in clastic rocks (Correggiari et al. 1996).

An unofficial number of registered caves in the continental part of Croatian karst (26,000 km^2) is currently >9,500 (Garašić 2006a), and the number of those under the sea-water influence in the littoral part and submarine is 235 (Surić 2006) (Fig. 1). Comparing with the mainland and multiplying appropriately, estimated number of submerged caves should be probably in the thousands as well.

Spatial distribution of caves and pits, classification and their hydrology

Out of the 235 recorded caves and pits with sea water influence, 163 are located along the islands' shore, and 72 of them are along the mainland coast (Fig. 1), which closely match the ratio between the length of the island and the mainland coastline (4,398 and 1,777 km, respectively). In fact this ratio, and especially the distribution shown on Fig. 1, reflects the preferred area of investigation, i.e., the fact that diving usually takes place in the near-shore, shallower parts. Actually, like in the continental part, they are probably evenly distributed on the sea floor, on the whole surface that once was exposed to the subaerial karstification during the low sea-stands.

The continental part of the Croatian karst is characterised by the predominance of vertical objects over horizontal ones with 69% pits, 29% caves and 2% of combined features (Garašić 1991). The coastal and submarine situation appears to be quite opposite; within recorded features 60% are horizontal caves and 40% are pits (Fig. 2a). However, most of these caves and pits are not completely investigated, therefore, in reality the ratio could be different. For example, Brač Island (the Middle Adriatic) is known as the one with the densest distribution of speleological features with 1 (recorded) object per 1.8 km^2, and out of >200 caves, pits and caverns, 80% go to the vertical shafts (Baučić 1984). Apparently, such a setting could also be expected in the submarine, so it can be presumed that

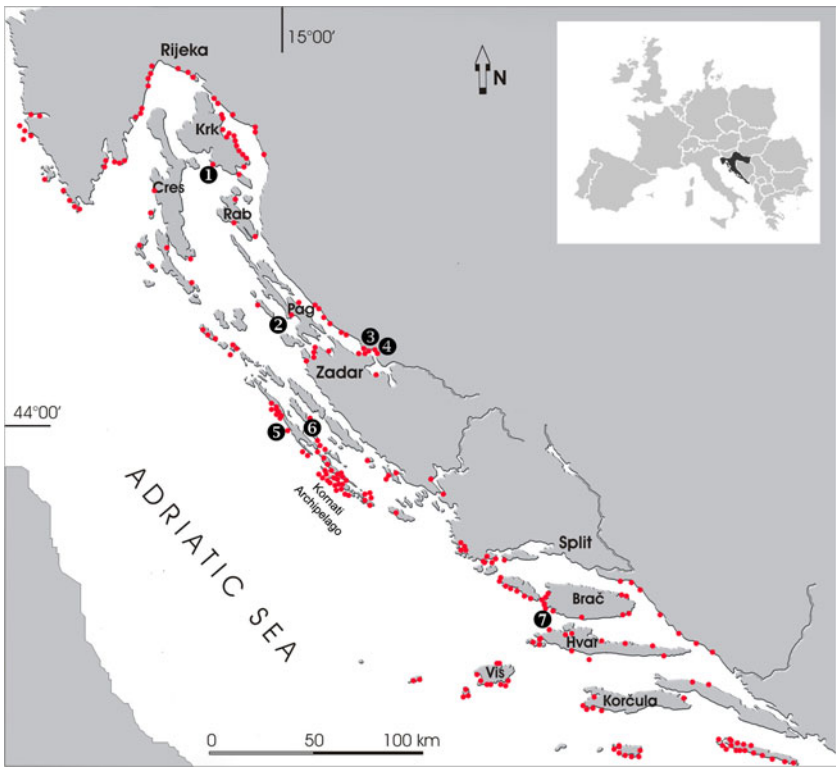

Fig. 1 Geographical position of studied area with marked submerged caves. Localities mentioned later in text: *1* Pit U Vode, *2* Cave in Tihovac Bay, *3* Vrulja Zečica, *4* Vrulja Modrič, *5* Y-Cave, *6* Cave near Iški Mrtovnjak, *7* Pit in Lučice Bay

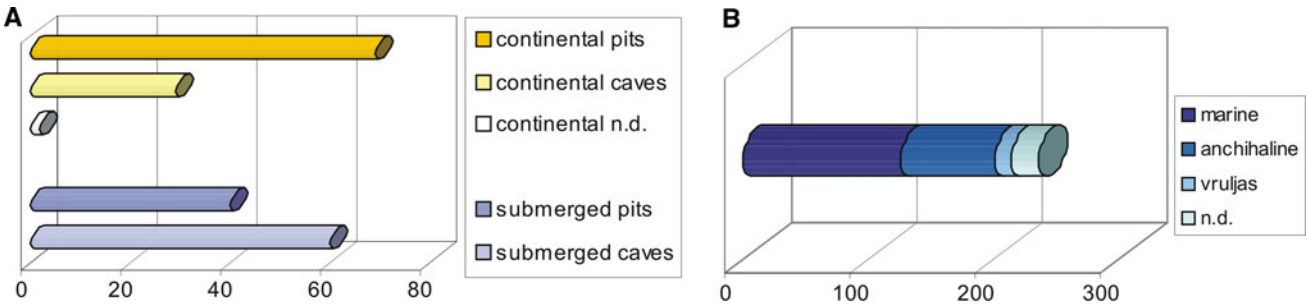

Fig. 2 Distribution of **a** caves and pits in continental (*yellow*) and coastal/submarine (*blue*) part of Croatian karst (in %); **b** investigated submerged caves according to their hydrological function (in total number); (*nd* non-determined)

prevalence of horizontal features occurs because they are more approachable and easier for the investigation.

As for the hydrological settings, we determined three categories (plus one for non-determinable settings) according to the influence of the fresh water (Fig. 2b). The majority of the investigated caves, 126 of them, were completely under marine conditions (euhaline) (Figs. 3a, b) characterised by abundant marine biogenic overgrowth covering the walls. It is an assemblage of exclusively animal species adapted to the darkness, low nutrient inflow and stable temperature, belonging to biocenosis of caves and ducts in complete darkness. The other category encompasses 75 anchihaline (mainly) pits with characteristic onshore entrance, vertical shaft and stratified water column with fresh groundwater overlying the sea water (Fig. 3d). Marine species are distributed accordingly. Although most of these features have the onshore entrances thus being easily discovered, systematic research was performed only in Kornati Archipelago (Fig. 1) (Gottstein Matočec and Jalžić 2003), and the total number is anticipated to be much bigger. The third category relates to submarine springs (vruljas) which are common features all along the eastern Adriatic coast either in the form of passable channels or as disperse flow. The former (Fig. 3c) often contain the evidences of their subaerial history such as speleothems, flowstones, etc. Due to the relatively risky exploration, only 13 vruljas have been explored and listed in the inventory. Data about hydrological function of 21 caves were not available, so their hydrological status is regarded as non-determinable.

Speleothems were found within ca 140 caves with predominance of stalactite over the stalagmites. The reason for

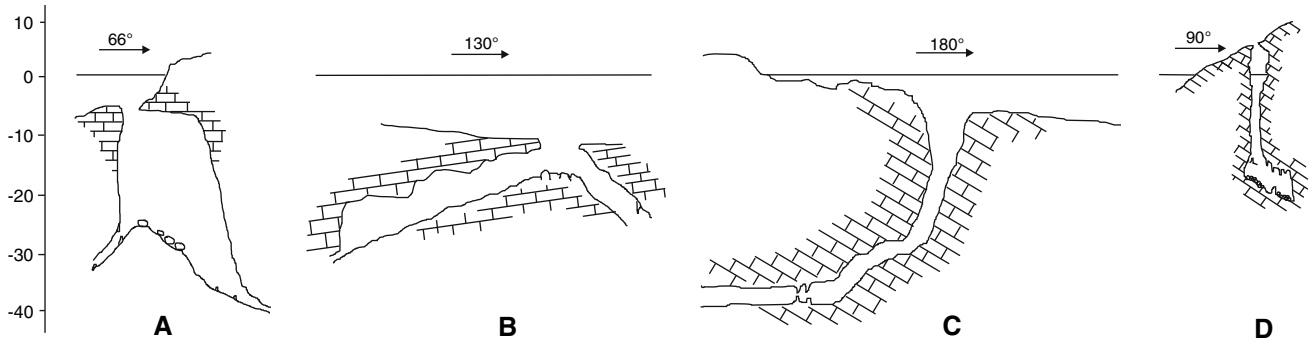

Fig. 3 Some examples of the different submerged caves along the Croatian coast **a** Pit in Lučice Bay (Brač Island) and **b** Cave in Tihovac Bay (Pag Island), both completely under marine conditions (euhaline); **c** submarine spring Vrulja Zečica (near Starigrad) and **d** anchihaline Pit U Vode (Krk Island)

such a situation is that stalactites stay preserved while stalagmites used to be covered by marine sediments. Regarding the salinity i.e., marine influence, speleothems are more or less covered with biogenic overgrowth, so in completely marine caves speleothems are entirely covered and sometimes heavily destroyed by boring organisms (Fig. 4a), whilst in caves with periodical brackish or freshwater events the overgrowth is reduced or even lacking. Of special interest are the zones of mixed water which corrode the speleothem carbonate (Fig. 4b). According to the lowest sea level of −135 m reached during the last glacial maximum 26 ka BP (Peltier and Fairbanks 2006), speleothems are expected to be found down to that depth. Until now, the deepest speleothem is recorded at 71 m below the mean sea level (Garašić 2006b).

Origin of the caves

The abundance and variety of the Croatian caves invaded by the sea water hamper unique explanation of their origin. Problems arise from the relatively mature host bedrock which is in addition intensively tectonically disturbed and, due to its position, quite sensitive to eustatic and relative sea-level changes.

Generally, coastal caves can be divided into three main groups: sea (littoral or wave-cut) caves, flank margin caves and blue holes (Mylroie 2005). Sea caves form along the coastline by wave erosion which requires pre-existing fractures in the host rock and sufficient wave energy. Numerous features that resemble sea caves could be found along the Croatian coast, but they are mainly formed by intersection of continental caves by coast retreat instead of being shaped by the waves (Fig. 5). However, the predominant speleogenic mechanism could be determined in detail by using morphometric analysis as in Lace (2008).

Flank margin caves have been extensively studied for over 35 years, as part of the recently described *Carbonate Island Karst Model* (Mylroie and Mylroie 2007). They owe their formation to the mixing corrosion along the halocline in very young (diagenetically immature) carbonates with high degree of primary porosity, like in late Quaternary limestones of Bahamas (Mylroie and Carew 1995; Florea et al. 2004). Such or similar features have not been recorded along the Croatian coast and islands which was expected due to the oldness of the bedrock, although flank margin caves developed in telogenetic limestones were recently described in New Zealand (Mylroie et al. 2008). Nevertheless, there are caves with notable corrosion (e.g., Y-Cave on Dugi otok Island; Juračić et al. 2002) but not so extensive to reshape the existing cave.

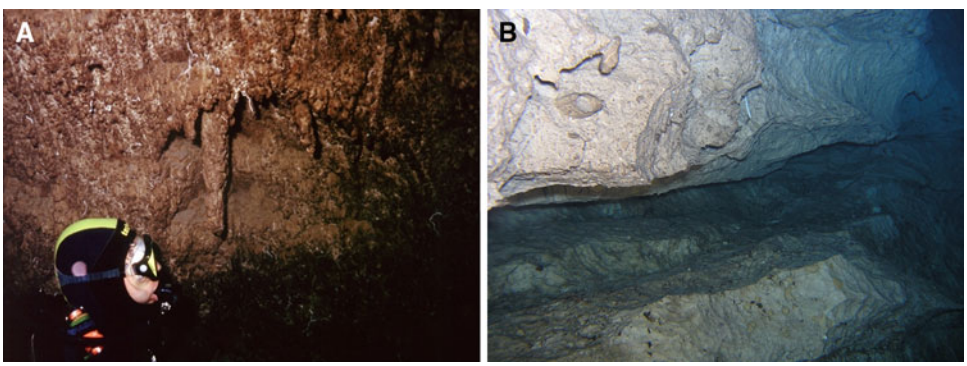

Fig. 4 Interior of **a** Cave near Iški Mrtovnjak with typical marine biogenic overgrowth covering stalactites and the cave walls (photo by M. Kvarantan); **b** Y-Cave (Dugi otok Island) with corroded flowstone (photo by D. Petricioli)

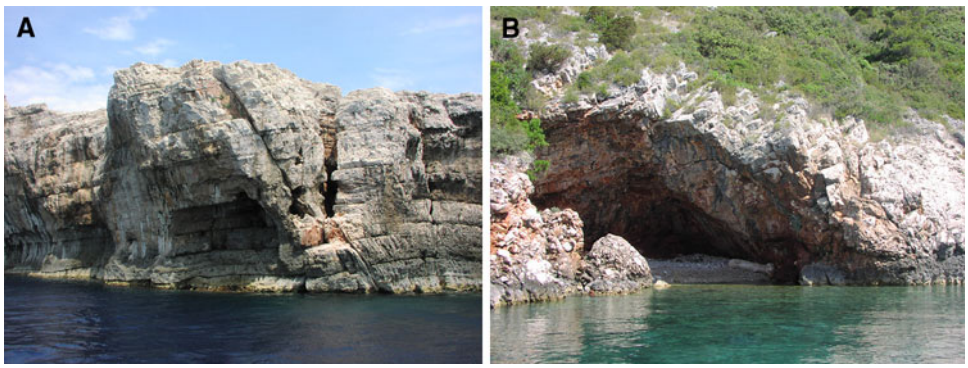

Fig. 5 Features resembling sea caves on **a** Mana Island (Kornati Archipelago) and **b** Šolta Island

According to comprehensive work of Mylroie et al. (1995) that covers the majority of scientific literature dealing with blue hole features, they are defined as: "…subsurface voids that are developed in carbonate banks and islands; are open to the Earth's surface; contain tidally influenced waters of fresh, marine or mixed chemistry; extend below sea level for a majority of their depth; and may provide access to cave passages." Furthermore: "…Blue holes are found in two settings: ocean holes open directly into the present marine environment and usually contain marine water with tidal flow; inland blue holes are isolated by present topography from surface marine conditions, and open directly onto the land surface or into an isolated pond or lake, and contain tidally influenced water of a variety of chemistry from fresh to marine." Consistent with these definitions, practically all of recorded Croatian caves could be regarded as blue holes. Taking into account the genesis of the blue holes that "…may form by drowning of dissolutional sinkholes and shafts formed in the vadose zone, by phreatic dissolution along the rising halocline, by progradational collapse of deep dissolution voids produced in the phreatic zone, and by fracture of the bank margin" (Mylroie et al. 1995), the Croatian submerged caves fulfil either the first or the third prerequisite. Thus, it would not be pretentious to assign the term 'blue hole' to, at least, some of the Croatian submerged caves (e.g., Vrulja Modrič, Fig. 6), although that term is most associated with the Bahama Islands and similar carbonate bank settings (Mylroie et al. 1995). But if we consider works of Schwabe and Carew (2006) and Schwabe et al. (2007) appointing to inappropriate moniker 'blue hole' for scientific discussion of Bahamian features, we would also incline towards the idea of describing and classifying submerged caves similarly as continental ones. Their present position is, in fact, only contemporary.

Other aspects of submerged caves significance

Apart from the contribution to the understanding of the karstological principles, submerged caves are interesting from other perspectives, as well. They tender insight into palaeoenvironmental settings, unique habitats, archaeological background and even contribute to contemporary social activities.

Being typical subaerial features subsequently drowned by the rising sea, speleothems within the submerged caves are recognised as reliable indicators of the sea-level changes. The youngest part of the submerged speleothem can provide the maximum age of the marine transgression that caused a cessation of growth, while the oldest parts provide a minimum age of the growth commencement enabled by the sea regression. Yet, it must be kept in mind that other factors (changes in water chemistry, flooding, aridity, shifts in flow routing etc.,) could be responsible for the growth cessation (Richards and Dorale 2003). Additionally, precisely dated onset of marine overgrowth can reveal the timing of the marine condition establishing. Submerged speleothems from the Croatian submarine have already been used in order to reconstruct late Quaternary relative sea-level fluctuation on the eastern Adriatic coast (Surić et al. 2005a, 2009), as well as associated palaeoenvironmental changes (Surić et al. 2005b).

Karst ecohydrology as a scientific subdiscipline concerned with the ecological and hydrological processes in karst areas (Bonacci et al. 2009) should be intensively applied in the Croatian submerged cave studies. Prominent results were obtained by Bakran-Petricioli et al. (2007) by the discovery of sponges *Oopsacas minuta* and carnivorous *Asbestopluma hypogea* which are both typical deep sea species but in the Adriatic Sea they occur in several submerged caves in the shallow (5–30 m) water. The occurrence of these sponges in such shallow water can be assigned to the specific shape of cave channels sloping inwards thus allowing the cold winter water (12–13°C) to be preserved inside the cave year round (Bakran-Petricioli et al. 2007). The abundance and diversity of submerged caves on the eastern Adriatic coast almost certainly store other peculiarities yet to be discovered.

Taking into account lower sea levels during the Pleistocene glaciations, currently submerged caves could have been common shelters of the early humans in addition to

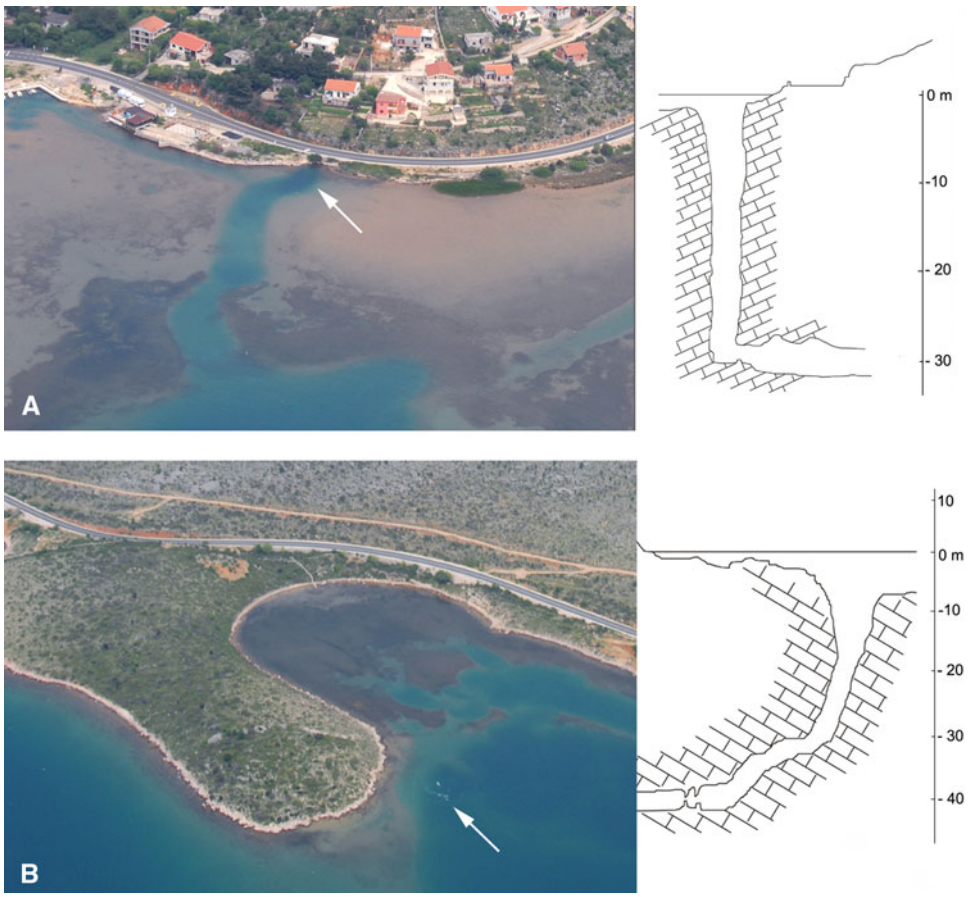

Fig. 6 Aerial view and the cross-sections of submarine springs **a** Vrulja Modrič (meaning the blue), and **b** Vrulja Zečica, with typical funnel entrances, vertical shafts, horizontal landward channels and intensive *blue colour*. *Arrows* indicate the entrances. Note the white foam on figure b—the result of emerging ('boiling') freshwater on the sea surface during the intensive groundwater discharge

those presently onshore and widely explored. Besides, the submerged caves could preserve useful evidences of the human adaptation to the cold periods and probable migrations. Unfortunately, very few such researches have been conducted within the Croatian submerged caves (e.g., Mesić 2006), although there are numerous promising submarine archaeological sites.

Finally, submerged caves should not be neglected as valuable contribution in Croatian tourist offerings. Although the geotourism is in its early stages in Croatia, cave-diving tourism is well developed due to the vicinity of relatively accessible submerged caves to almost every diving centre. This advantage of the Croatian coast is already well-known among the diving community and its popularity will undoubtedly result with the new discoveries and scientific achievements.

Conclusions

The eastern Adriatic Sea covers a vast part of the Dinaric classical karst formed within Mesozoic and Palaeogene carbonates, and stores a large variety of karst features developed during numerous emergent phases prior to the last Late Pleistocene–Holocene transgression. From many aspects, submerged caves appear to be the most interesting features. The total number of presently known submarine and coastal caves inundated by the sea water is 235 with predominance of horizontal caves (60%) over the vertical pits (40%). When compared to the continental part and islands, it is an unexpected ratio, so the anticipated ratio from forthcoming researches should probably be opposite. According to their hydrology, we distinguish caves with complete marine conditions (126), anchihaline caves (75), submarine springs (vruljas) (13) and the rest are currently considered as non-determined. More than 140 caves contain speleothems, irrefutable evidences of former lower sea levels. Although the term blue hole was not ascribed to Croatian submerged caves, development, shape, size and present position of many caves fit the blue holes definition. Yet, we lean towards the designations based on common speleological descriptions.

Given the geographical settings i.e., total coastline length of >6,000 km with 1,246 islands, islets and rocks, thousands of submerged caves are yet to be discovered and explored, not only in terms of karstology but also for the hydrology, biology, archaeology and other environmental aspects. Their commercial benefit through touristic diving contributes to their overall worth, as well.

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