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Late Pleistocene-Holocene environmental changes – records from submerged speleothems along the Eastern Adriatic coast (Croatia)

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ABSTRACT

U-Th and ^{14}C dating, and X-ray diffraction of parts of 16 submerged speleothems taken from depths of 1.5−41.5 m from 7 submarine caves and pits along the Eastern Adriatic coast, provided insight into the sea-level fluctuations during the last 220 ka, and to the palaeogeographic changes caused by sea-level changes. Due to climate changes, palaeoenvironmental settings also varied, but not so abruptly and intensely as in the rest of Europe. As the Alps and Dinarides acted as orographic barriers, the Eastern Adriatic coast was the border region between periglacial Europe and the temperate Mediterranean region. It was also a refuge area for plant species from the north. This study showed that appropriate temperature, humidity and vegetation cover ensured favourable conditions for karstification and speleothem formation even during the Last Glacial Maximum.

Keywords: Palaeoenvironment, Late Pleistocene-Holocene, U-Th dating, ^{14}C dating, sea-level change, submerged speleothems, Adriatic Sea, Croatia

1. INTRODUCTION

Environmental conditions in the coastal zones almost completely depend on sea-land distribution. Changes of this distribution during the Late Pleistocene-Holocene period were mainly the result of the sea-level oscillations caused by global climate changes, typical for the entire Quaternary period. Other than on the spatial (palaeogeographic) settings, sea-land distribution had an indirect impact on climatic settings on the local and regional level, (therefore influencing animal and plant distribution), and on the hydrogeological settings of the coastal zones. Apparently, all of these changes can be recorded in the speleothems from the submerged caves. Calcite speleothems are secondary mineral deposits formed in caves by degassing of CO_2 from supersaturated H_2O-CO_2-$CaCO_3$ solutions that have entered the cave (DREYBRODT, 2005). If these are typical subaerial features, their present positions under the sea, in submerged caves, are irrefutable evidence of former lower sea stands. As they grow, they may trap trace quantities of other minerals, flood debris, dust, organic matter, pollen, etc. (FORD, 1997). If they contain remnants of marine organisms or any other indicator of a marine phase incorporated between the carbonate layers deposited in a continental phase, intervals of higher sea levels can be revealed. Furthermore, speleothems are potentially excellent subjects for the study of long-term changes of continental mean temperature and perhaps other climatic parameters (FORD & WILLIAMS, 1989).

During their growth, speleothems incorporate stable and radioactive isotopes of various elements that can be used to reconstruct environmental settings. Variations of the ratio of stable oxygen isotopes ^{18}O and ^{16}O are the key for revealing changes of palaeotemperature, whilst the ratio of stable carbon isotopes ^{13}C and ^{12}C resolves the origin of the carbon i.e. condition of the vegetation at the surface during speleothem growth. Additionally, to date the onset of the changes that are recorded in speleothems (growth cessation or recommencement, shifts in stable isotope ratios, etc.), radioactive isotopes such as ^{14}C or the U-Th series are the most useful. The eastern Adriatic coast, a young ingressional karstic coast, offers a good potential for studying these phenomena as it has numerous submerged caves with speleothems from a wide range of depths.

Palaeoenvironmental changes recorded in speleothems primarily result in their deposition/non-deposition, depending on environmental conditions. Generally, during the Last Glacial Maximum (LGM) speleothem deposition ceased in most of Europe, and began again ~15 ka BP (GASCOYNE, 1992; LOWE & WALKER, 1998; MIHEVC, 2001). At the same time, in southern Europe, speleothem deposition was uninterrupted from 20 to 15 ka BP along the Tyrrhenian coast of Italy (ALESSIO et al., 1992) and during the last 60 ka in Israel (Soreq Cave) (BAR-MATHEWS et al., 1999) as it was influenced by the Mediterranean Sea. In addition, the palaeoclimatic signal (δ^{18}O oscillations) in this region differs markedly from Northern European terrestrial records. It shifts to more negative values during the warm periods and increases during glaciations due to the prevailing influence of the Mediterranean Sea (McGARRY et al., 2004).

In order to constrain the timing of sea-level oscillations by analysis of submerged speleothems, the youngest parts of the speleothems are usually dated to provide the maximum age of marine transgression, while the oldest parts provide the minimum age of continental conditions (note that cessation of speleothem growth can be caused by numerous other factors, RICHARDS & DORALE, 2003). The most reliable data for the minimum age of transgression is provided by the age of the marine overgrowth that usually covers the speleothems. Stalagmites with remnants of marine organisms incorporated between layers of continental origin are very peculiar, clearly distinguishing continental-marine-continental transitions (e.g. GASCOYNE et al., 1979; DUTTON et al., 2009). With the intention of reconstructing global and relative sea-level changes, submerged speleothems have been studied on Tyrrhenian coast (ALLESIO et al., 1992; BARD et al., 2002; ANTONIOLI et al., 2001; 2004; 2007; DUTTON et al., 2009), Bahamas (SPALDING & MATHEWS, 1972; GASCOYNE et al., 1979; LUNDBERG & FORD, 1994; RICHARDS et al., 1994), Bermuda (HARMON et al., 1978), Majorca (FORNÓS et al., 2002; VESICA et al., 2000), and Croatia (MALEZ et al., 1979; VRHOVEC et al., 2001; SURIĆ et al., 2005a; 2009).

Palaeoenvironmental studies of the eastern Adriatic region have been based mostly on the spatial distribution of habitats of Pleistocene fauna, (TEŠIĆ, 1958; MALEZ & BOŽIČEVIĆ, 1965; MALEZ & RABEDER, 1984; MALEZ & LENARDIĆ-FABIĆ, 1988; PAUNOVIĆ & RABEDER, 2000; ČEČUK & RADIĆ, 2005). In addition, geomorphological analyses of areas that could have experienced Pleistocene glaciations, such as Velebit Mt., where glacial and periglacial relief (i.e., moraine material of Würmian glaciers) were studied (NIKLER, 1973; BELIJ, 1986; BOGNAR et al., 1991). Palaeoclimatological studies have covered much a wider region, and approximations of the LGM temperature vary geographically. According to PRENTICE et al. (1992), the LGM in the Mediterranean region was marked by temperatures 5–10 °C lower than today during the winter season, and 1–3 °C lower in summer. Approximations by PEYRON et al. (1998), in the region south of the line defined by the Pyrenees and Alps, suggest the mean-annual temperature was 10 ± 5 °C lower than today, with the temperature of the coldest months 15 ± 5 °C lower than present. Meanwhile, the shift of annual precipitation in Greece and Italy was estimated to be –600 mm/a. Besides lower mean temperatures, MIRACLE (1995) suggests that the seasonal temperature variations during the LGM were larger than those of today. Additionally, seasonality of precipitation was also more pronounced, with relatively dry summers and rainy autumn-winter periods. Total precipitation was 10–20% lower than today, but, since the decreased temperatures reduced the evaporation potential, runoff from precipitation was even larger than that of today (MIRACLE, 1995). He also assumes that the area northwest of the Adriatic basin was considerably drier than that to the southeast.

The last glacial cycle is divided into five marine isotope stages (MIS), from MIS 5 to MIS 1, and includes the highest sea-level stand during the last interglacial (MIS 5e), the lowest sea-level during the LGM within MIS 2, and the series of oscillations of the stadials and interstadials between MIS 5e and MIS 2. The last period, MIS 1, corresponds to the Holocene, and is characterized by rapid ice decay (LAMBECK et al., 2002a). In tectonically stable regions, MIS 5e (~128–118 ka BP) sea-level records are found consistently at an elevation of several metres above present sea level (POTTER & LAMBECK, 2004). Unlike MIS 5e, records of sea-levels for the MIS 5a (~80 ka BP), range from –30 to +10 m (see COYNE et al., 2007; references therein and Fig. 18), which is explained by the effects of glacio-hydro-isostasy (POTTER & LAMBECK, 2004). Within the MIS 5a, two distinct sea-level highstands (double peak) have been identified, at ~84 and ~77 ka BP (POTTER et al., 2004; POTTER & LAMBECK, 2004; RADTKE & SCHELLMANN, 2005). An oft-cited timing of the LGM is 21 ka BP, with sea level 121±5 m below present (FAIRBANKS, 1989). If the LGM is considered to coincide with maximum global ice volumes, this period covers more than 10 ka with a rapid sea-level fall about 30 ka BP down to the LGM lowstand, and the onset of the global ice melting at about 19 ka BP (LAMBECK & CHAPPELL, 2001; LAMBECK et al., 2002a). The lowest sea-level stand appears to be at 26 ka BP, and it could have been as low as –135 m relative to present sea level (PELTIER & FAIRBANKS, 2006). A rapid rise started around 19.6 cal ka BP and reached some 10 m within 800 years (HANEBUTH et al., 2009). Further ice melting at an irregular rate lasted until 7 ka BP, when the oceans approached their present volumes (LAMBECK & CHAPPELL, 2001). Instrumental records today show global sea-level rise to be ~1.8 ± 0.3 mm/a (CHURCH et al., 2004).

In order to reconstruct palaeoenvironmental changes forced by climatic and sea-level changes on the Eastern Adriatic coast, this paper provides results from a variety of previous studies. These are based on the ^{14}C dating of speleothems from three submerged caves (SURIĆ et al., 2005a), their stable isotope composition (SURIĆ et al., 2005b), and new results from extensive ^{14}C and U-Th measurements from old and new speleothem samples from seven submerged caves. In addition, thanks to colleagues, cavers, and speleodivers, a list of all presently known submerged speleological features along the Croatian Adriatic coast has been compiled (SURIĆ, 2006).

2. GEOLOGICAL AND ENVIRONMENTAL SETTINGS

The Eastern Adriatic coast is an ingressive karstic coast formed during the last Late Pleistocene-Holocene transgression. It is characterized by the parallel extension of geological structures (folds, normal and reverse faults, overthrusts), geomorphological features, coast, channels and island chains, presenting a so-called *Dalmatian type coast* (VON RICHTHOFEN, 1901). Such a parallel characteristic of the *Dinaridic trend* (NW-SE) is the result of collision of the Adria microplate and Eurasian plate from the Alpine orogeny to the present, with maximal stress oriented SW-NE (VLAHOVIĆ et al., 2002; 2005; KORBAR, 2009). A thick carbonate succession (more than 8000 m) was deposited in several phases from the Middle Permian (or even Upper Carboniferous) to the Eocene (VLAHOVIĆ et al., 2005). This was intensively tectonically disturbed, periodically emergent, and exposed to exogenous processes resulting in karstification. Karstification took place down to the contemporary erosional base level (sea level), while in some places it extended below sea level (SURIĆ, 2005). According to the LGM low sea-level stand, karst features may be found down to depths of 120–130 m (LAMBECK et al., 2002b), but if we take into consideration the Messinian Salinity Crisis (~6 Ma BP), with sea level ~1500 m lower than today (MURPHY et al., 2009), evidence for karstification could be expected throughout the entire Adriatic region. Currently the deepest speleothems found within submerged Croatian caves are those from Brač Island at –71 m (GARAŠIĆ, 2006).

The Adriatic basin is characterized by a relatively shallow northern part with a low gradient (0.02°) down to –100 m. Such morphology makes this region very sensitive to eustatic sea-level changes, and consequently, it experienced considerable environmental changes throughout the Quaternary Period. During the LGM with sea-level 120–130 m lower than today, the entire northern part, down to the Zadar-Pescara line, was emergent as a wide fluvio-lacustrine plain with a coastline located at the northern edge of the Meso-Adriatic depression (PIRAZZOLI, 2000).

According to Köppen's climatic classification, the northern part of the investigated area (including Krk, Lošinj and Pag islands, and the Vrulja Zečica region) belongs to the contemporary Cfa-type of temperate humid climate with hot summers. The middle and southern part (Rogoznica and the islands of Iž and Brač) belong to the Csa-type, which is a Mediterranean climate characterized by temperate and rainy winters and hot, dry summers (ŠEGOTA & FILIPČIĆ, 2003). Mean-annual temperatures are between 13.2 and 16.2 °C, with winter temperatures between 5.4 and 9.4 °C, and precipitation ranging from 690 to 1561 mm/a.

3. SITE DESCRIPTIONS

This survey encompassed four pits, two caves, and one submarine spring, all located along the eastern Adriatic coast (Fig. 1). All of the surveyed features were formed within heavily fractured Upper Cretaceous rudist limestones with the exception of Vrulja Zečica, which was developed in Tertiary limestone.

Medvjeđa spilja Cave (Lošinj Island) is an anchialine cave with the entrance 17.5 m above mean sea level (a.m.s.l.), 55 m from the coast (Fig. 2a). Connection with the open sea, with distinct tidal oscillations, is established through channels and fractures in karstified bedrock. According to the findings of *Ursus speleaus* remnants (MALEZ et al., 1979), there might have originally been a horizontal entrance that is presumably now 8 m below mean sea level (b.m.s.l.), but which has been filled with collapsed material. The cave is well decorated with speleothems of varied age and genesis.

Cave in Tihovac Bay (Pag Island), with its entrance at 12 m b.m.s.l. (Fig. 2b), ca 100 m off-shore, is completely within the marine environment. Two massive stalagmites below the entrance indicate the existence of a major fissure at the loca-

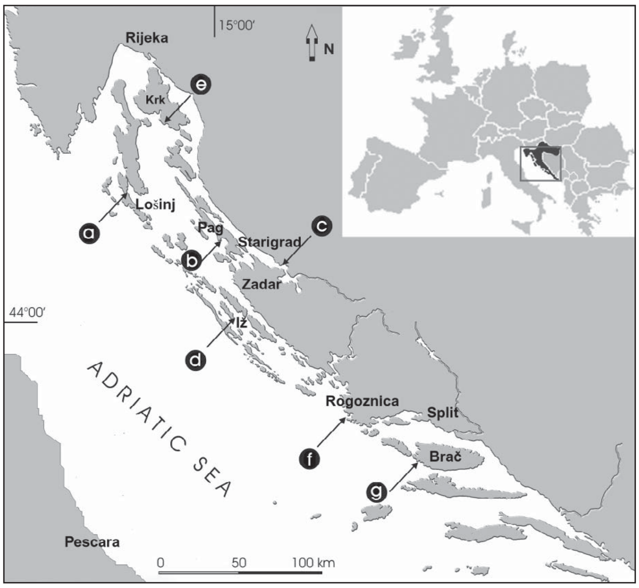

Figure 1: Studied localities: a – Medvjeđa spilja Cave (Lošinj Island), b – Cave in Tihovac Bay (Pag Island), c – the Vrulja Zečica submarine spring (near Starigrad), d – Pit near Iški Mrtovnjak Islet, e – U vode Pit (Krk Island), f – Zmajevo uho Pit (near Rogoznica), g – Pit in Lučice Bay (Brač Island).

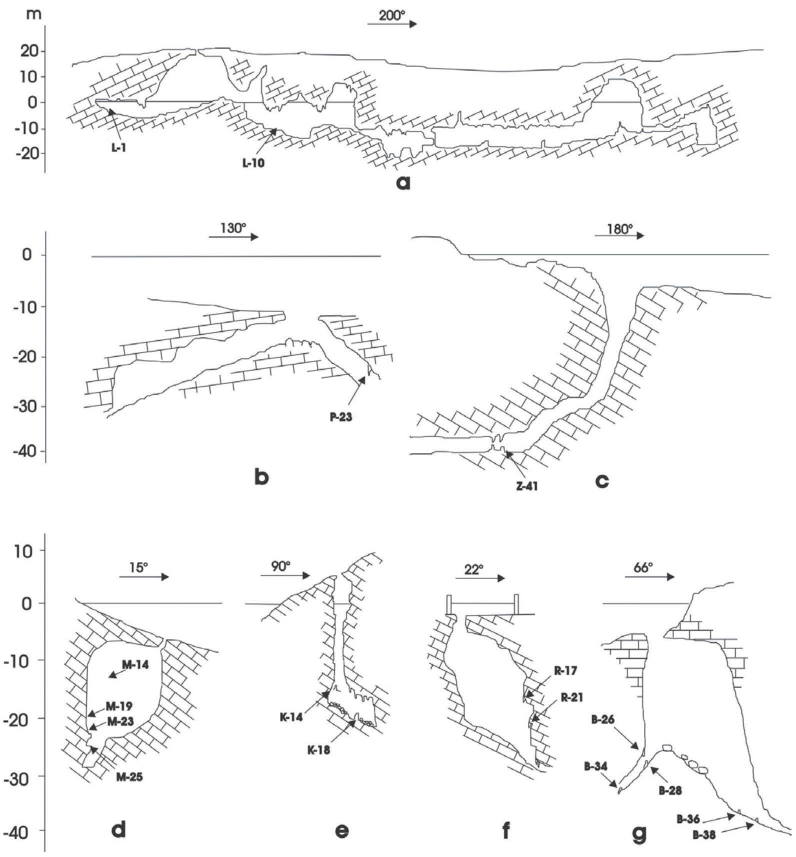

Figure 2: Cross sections of studied caves with marked positions of sampled speleothems: a – Medvjeđa spilja Cave (Lošinj Island); b – Cave in Tihovac Bay (Pag Island); c – the Vrulja Zečica submarine spring (near Starigrad); d – Pit near Iški Mrtovnjak Islet; e – U vode Pit (Krk Island); f – Zmajevo uho Pit (near Rogoznica); g – Pit in Lučice Bay (Brač Island) (note the different scale).

tion of the present-day entrance that was opened by roof collapse. Two passages were explored down to 30 m b.m.s.l.

Vrulja Zečica, near Starigrad, is a periodically active submarine spring with its outlet 20 m off the coast at 9 m b.m.s.l. (Fig. 2c). Speleothems at 41.5 m b.m.s.l. indicate a former vadose phase. Due to sea-level rise, it was subsequently transformed to a coastal spring and finally to a submarine one. Unlike some other dispersed fresh-water outlets, Vrulja Zečica has a wide funnel-like shape.

The **Pit near Iški Mrtovnjak Islet** lies entirely in the marine environment and is rich in speleothems completely covered with marine biogenic overgrowths. The entrance is 12 m off-shore at 5 m b.m.s.l., and the pit has been explored down to 25 m b.m.s.l., where it continues as a narrow passage (Fig. 2d).

U vode Pit (Krk Island) is a vertical speleological feature with the entrance at 5.5 m a.m.s.l. (Fig. 2e). Although free circulation between the cave and the open sea is present, there is a thin brackish water lens of 0.5 m. The deepest part of the cave is within the marine environment, with marine organisms (serpulids) covering the rock and speleothem surfaces. The bottom of the pit is at 24 m b.m.s.l.

The **Zmajevo uho Pit,** near Rogoznica, was originally located in a shallow bay 40 m from the coast, but after the construction of an artificial island, its entrance is now within the pool connected to the open sea by the pipe. The opening was formed by roof collapse and is presently at 2.5 m b.m.s.l., while collapse debris covers the bottom of the pit (Fig. 2f). Rich marine biogenic overgrowths indicate the absence of a fresh-water influence.

The **Pit in Lučice Bay** (Brač Island) has two entrances formed by roof collapses at a depth of 5 m b.m.s.l. some 10 m off-shore, on a horizontal rock ledge (Fig. 2g). The maximum explored depth is 40 m. Marine conditions prevail in the whole pit and marine overgrowth is quite abundant.

4. SAMPLING

Sampling of submerged speleothems was conducted according to the National Speleological Society (USA) Code of Conduct, suggesting that ‘the scientific collection should be professional, selective, and minimal’. Seventeen speleothems were collected by SCUBA divers from 1.5 to 41.5 m b.m.s.l. from 7 submerged caves, as follows:

- U vode Pit: two stalagmites from 14.5 m (K-14) and 18.8 m b.m.s.l. (K-18) (Pl. 1)
- Medvjeđa spilja Cave: ‘fallen stalactite’ from 1.5 m b.m.s.l. (L-1) and stalagmite from 10 m b.m.s.l. (L-10) (Pl. 1)
- Cave in Tihovac Bay: stalactite from 23 m b.m.s.l. (P-23) (Pl. 2)
- Vrulja Zečica: stalagmite from 41.5 m b.m.s.l. (Z-41) (Pl. 1)
- Pit near Iški Mrtovnjak Islet: three stalactites from 14 m (M-14), 19 m (M-19) and from 23 m b.m.s.l. (M-23) (Pl. 1), and ‘fallen stalactite’ from 25 m b.m.s.l. (M-25)
- Zmajevo uho Pit: two stalactites from 17 m (R-17) and 21.4 m b.m.s.l. (R-21) (Pl. 2)
- Pit in Lučice Bay: stalactite from 26 m b.m.s.l. (B-26) and four stalagmites from 28 (B-28), 34 (B-34), 36 (B-36) and 38.5 m b.m.s.l. (B-38) (Pl. 2).

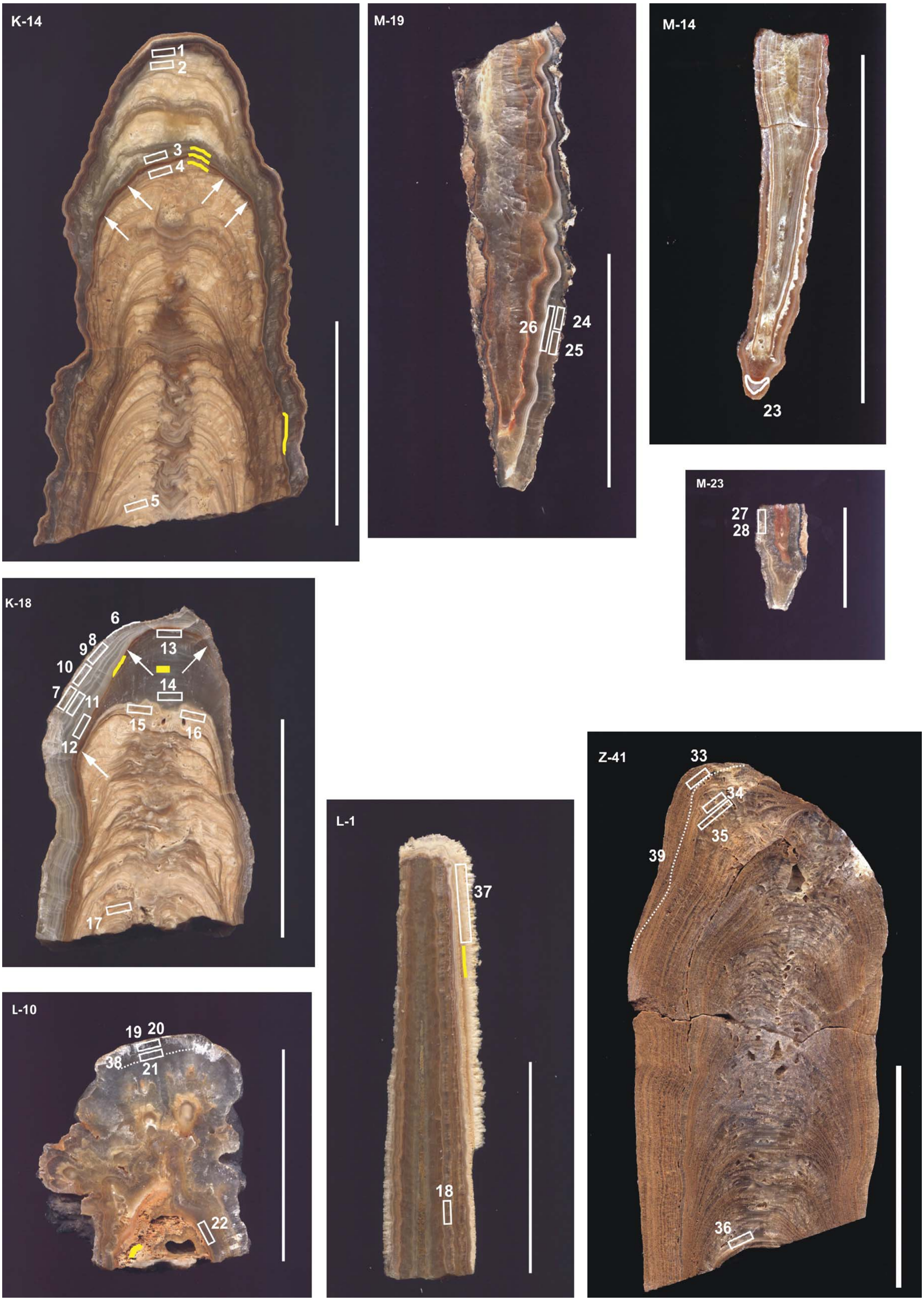

Plate 1: Longitudinal sections of speleothems K-14, K-18, L-1, L-10, M-14, M-19, M-23 and Z-41, with marked locations of subsamples for U-Th and ^{14}C dating (white squares and dotted lines) and XRD (yellow lines). White arrows (K-14 and K-18) mark hiatuses where the white substance apeared (see text). Scale bar 10 cm, except for M-23, which is 5 cm.

We use the expression 'fallen stalactite' for speleothems that were collected from the cave floor in the growth position of stalagmites, but whose origin was primarily stalactitic (reported in SURIĆ et al., 2007)

Since stalagmites provide better stratigraphic resolution than stalactites and generally have less ionic mobility, stalagmites are preferred for palaeoenvironmental reconstructions and geochronological studies (RICHARDS & DORALE, 2003). Yet, in submarine caves, it is not possible to follow this sampling strategy thoroughly, since the bottoms of the caves, together with stalagmites, are sometimes covered with marine sediments and fallen rock debris. Hence, some stalactites were also collected and analysed.

After collecting speleothems from the sea, and prior to any mechanical modification, biological species covering the samples were determined. Afterwards, speleothems were longitudinally cut and polished to provide a view of their growth layers. Samples for measurement and analysis were taken from the youngest and the oldest parts of the speleothems and along distinct hiatuses, in order to constrain the timing of cessation/recommencement or where distinct changes in morphology and mineralogy that affected speleothem deposition occurred. Speleothem carbonate samples for measurement were separated by micro-drill and diamond saw: 250–450 mg for the U-Th analyses, and for ^{14}C dating ca 30 g for the measurements on a gas proportional counter (GPC) and ca 20 g for a liquid scintillation counter (LSC).

The aim of mineralogical analyses on two speleothems from U vode Pit (K-14 and K-18; Pl.1) was to qualitatively determine the composition of the material associated with presumed hiatuses. In fresh cuts the hiatuses were highlighted by a thin red layer, but after several days of exposure to air, a white substance appeared along the discontinuities. Speleothems from Medvjeđa spilja Cave were also mineralogically analysed in order to resolve the composition of the needle-like surface of L-1 that resembled aragonite, and the inhomogeneous material from the base of stalagmite L-10 which might have been of marine origin (Pl. 1).

For stable isotope measurements reported earlier (SURIĆ et al., 2005b), samples of 5–10 mg of speleothem carbonate were drilled from the successive growth layers every 5–10 mm.

5. METHODS

The main goal of this study was the dating of certain events recorded in speleothems. Therefore, three different dating techniques were employed: U-Th Multi Collector Inductively Coupled Mass Spectrometry (MC-ICPMS), and conventional β-spectrometry ^{14}C dating using gas proportional counting (GPC) and liquid scintillation counting (LSC) methods.

U-Th measurements were undertaken in the Bristol Isotope Group facilities at University of Bristol, UK, using a ThermoFinnigan Neptune MC-ICPMS. Carbonate samples were dissolved in HNO_3, spiked with ^{229}Th/^{236}U, and processed through ion exchange columns for the separation of U and Th. The instrumental procedure with the mass spectrometer is reported in full in HOFFMANN et al. (2007) and briefly in SURIĆ et al. (2009).

The ^{14}C dating was undertaken in the Radiocarbon and Tritium Laboratory of Ruđer Bošković Institute in Zagreb, Croatia, using a liquid scintillation counter Quantulus 1220 and conventional gas proportional counter. Carbonate samples were treated with dilute HCl to obtain CO_2 which was subsequently converted to benzene for LSC measurements (HORVATINČIĆ et al., 2004), and to methane for GPC (SRDOČ et al., 1971). The conventional protocol for calculation of ^{14}C value was followed (OBELIĆ, 1989; MOOK & VAN DER PLICHT, 1999). The ^{14}C activity is expressed as percent of modern carbon (pMC), which relates the ^{14}C content of a sample to the ^{14}C content of a modern standard. The ^{14}C age is expressed in conventional ^{14}C years BP, adjusted to initial ^{14}C activity ($A_0 = 85\%$), and measured δ^{13}C (or –8‰ when not measured). Calibrated ages for ^{14}C age <22000 BP were obtained as a mean of the range obtained by OxCal v.3.10 calibration software (BRONK RAMSEY, 2005), and for ^{14}C age >22000 BP by the extension of the calibration curve proposed by BARD et al. (2004).

Qualitative mineralogical composition of the samples was determined by the X-ray diffraction method (XRD). Measurements were made in the Faculty of Natural Science, University of Zagreb, using a PANalytical X'pert Pro theta-theta diffractometer equipped with multilayer parabolic monochromator using CuKα radiation. Analyses of the white substance from the hiatuses were preformed by in situ measurements directly on the speleothems, then on the powder removed from the polished surface, and finally, samples of 2–5 mg were drilled out. Moreover, speleothem carbonate was also analysed both along the discontinuity and at a distance from it.

Stable isotope measurements of the speleothem carbonate were undertaken by continuous-flow isotope ratio mass spectrometry (CF-IRMS), using a Finnigan GasBench and Delta-S mass spectrometer located in Datierungen und Isotopenhydrologie Sektion, Institut für Geowissenschaftliche Gemeinschaftsaufgaben in Hannover, Germany. The procedure reported in SURIĆ et al. (2005b) was followed. δ^{13}C and δ^{18}O values in carbonate are expressed in ‰ deviations from the international standard PDB. The analytical error ranges from ±0.05‰ to ±0.2‰ depending on the type of sample.

6. RESULTS

6.1. Marine biogenic overgrowth determination

Marine biogenic overgrowths can be regarded as a proxy record of prevailing environmental conditions in submerged caves, so in completely marine conditions as in the Cave in Tihovac Bay, the Pit near Iški Mrtovnjak, Zmajevo uho Pit, and the Pit in Lučice Bay, submarine speleothems are covered with a marine overgrowth, in places more than 1 cm thick. In contrast, within the caves with fresh water input, as in the U vode Pit, Medvjeđa spilja Cave, and Vrulja Zečica, marine organisms, mostly Polychaeta (serpulids), have scarcely settled on the speleothems. Marine overgrowths include various species of Foraminifera, Porifera, Polychaeta, Bivalvia, Gastropoda and Bryozoa. However, certain organisms

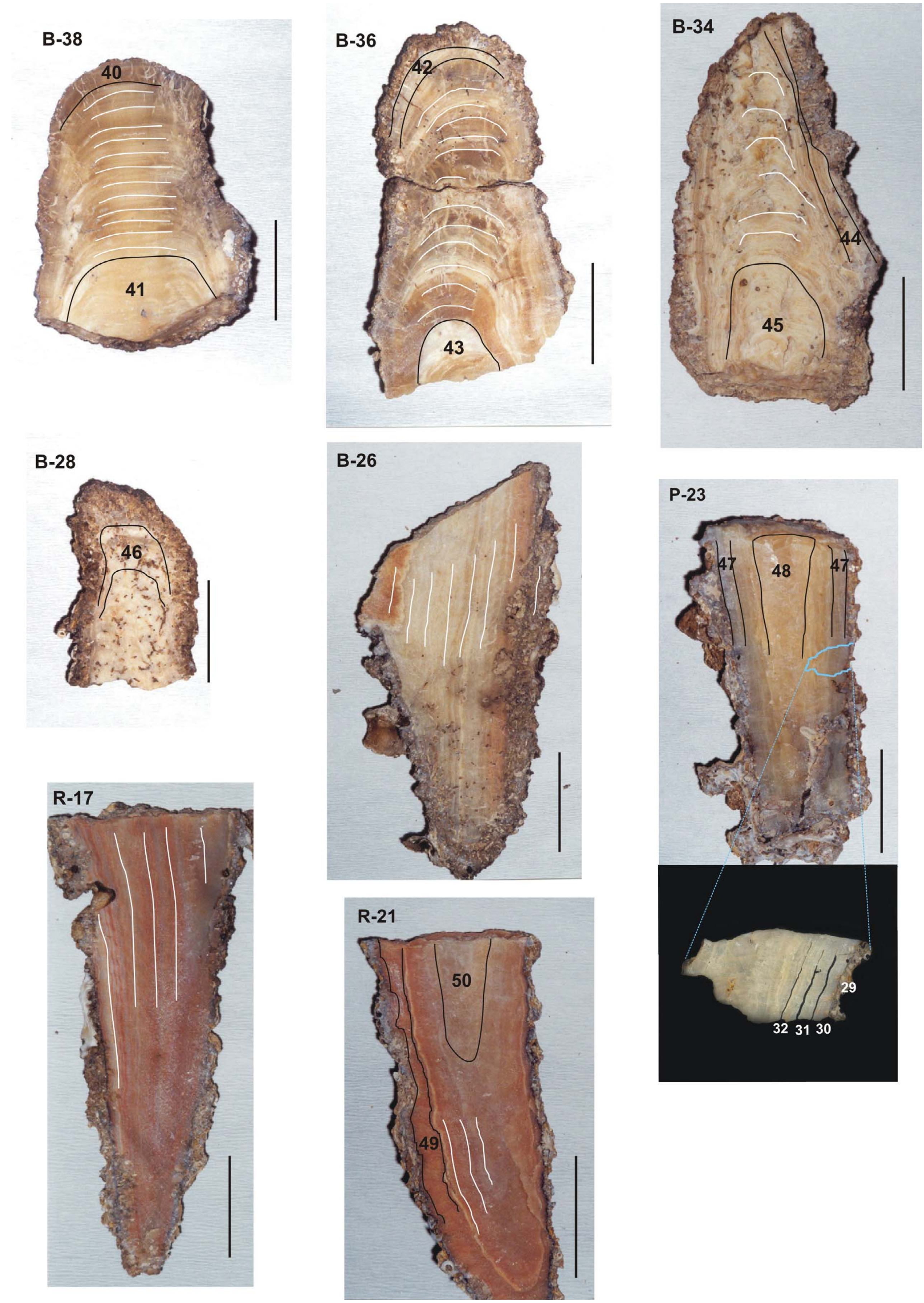

Plate 2: Longitudinal sections of speleothems B-38, B-36, B-34, B-28, B-26, R-17, R-21 and P-23, with marked locations of the subsamples for the U-Th and ^{14}C dating (bracketed with black lines) and for stable isotope analyses (white lines). Scale bar 5 cm.

were identified only to generic level and for some it was not possible to identify even the genus. Identified organisms belong to the biocenosis of caves and ducts in complete darkness (JURAČIĆ et al., 2002) that consists exclusively of animal species adapted to complete darkness, limited seawater circulation and nutrient inflow, and stable sea-water temperature.

6.2. Mineralogical composition

The mineralogical composition of samples analysed from U vode Pit stalagmites was determined as follows: (i) the main components of the white material measured directly on the speleothems were halite, gypsum and calcite; (ii) the same material scratched from the surface showed the presence of halite and calcite (and possibly dolomite); (iii) in the samples drilled from the discontinuities only calcite and halite were determined; (iv) calcite was the only mineral determined far from the discontinuities (SURIĆ et al., 2009).

The needle-like surface of the speleothem L-1 from Medvjeđa spilja Cave was determined to be calcite, with only one peak that could be ascribed to aragonite. Probably metastable aragonite changed its crystal structure to stable calcite preserving the external habit of aragonite (ONAC, 2005). In porous and inhomogeneous material from the base of the stalagmite L-10 from the same cave, apatite and calcite were determined. This eliminates the possibility that it was of marine origin, because marine biogenic deposits consist mostly of calcite, high-magnesium calcite, aragonite and quartz (SURIĆ et al., 2005a).

6.3. U-Th and ^{14}C ages

The results of U-Th MC-ICPMS and ^{14}C measurements are given in Tables 1 and 2, respectively. Locations of samples are shown in Plates 1 and 2.

A total of 36 U-Th measurements were made on 32 speleothem subsamples and one sample of the marine biogenic overgrowth (no. 29). Some samples were measured twice in order to check or confirm the results. Concentrations of ^{238}U were in the range 29–437 ng/g (ppb), and for ^{232}Th the range was 0.08–427 ng/g, except for values of 1260 ng/g for ^{238}U and 1217 ng/g for ^{232}Th that were recorded in the sample of marine overgrowth. An extremely high ^{232}Th concentration of 427 ng/g in speleothem carbonate was also measured at the contaminated surface part of the K-18 speleothem. Such surface parts were usually avoided during sampling. Initial contamination by ^{230}Th from the detritus was estimated from the ^{230}Th/^{232}Th activity ratio, so when necessary, corrections were made using the bulk Earth value of Th/U=3.8. Three samples (MS-08, MS-12, MS-13) that had an activity ratio ^{230}Th/^{234}U >1 gave unreliable or indeterminable ages. The U-Th ages that we consider reliable cover the period from ~210 to ~20 ka BP.

6.4. Stable isotope records

Stable isotope ratios from measured speleothems (B-28, B-34, B-36, B-38, R-17 and R-21) were given in detail in SURIĆ et al. (2005b). In the speleothem samples the δ^{13}C ranges from –10.4‰ to –6.2‰ and the δ^{18}O from –6.7‰ to –4.1‰. However, a weak correlation between δ^{13}C and δ^{18}O indicates that kinetic isotope fractionation probably occurred during calcite precipitation. According to theory and the early suggestions of HENDY (1971), δ^{18}O values are directly related to the cave temperature only when calcite deposition takes place under equilibrium conditions. In the sampled speleothems deposited during the LGM, the δ^{18}O values range from –6.7‰ to –4.1‰, being very similar to the –6‰ to –3.5‰ range recorded within the Holocene continental speleothems from the marine-influenced regions (Mediterranean) (HORVATINČIĆ et al., 2003).

6.5. Submerged speleological features

So far, 235 submerged voids have been discovered, and partially explored, in the Croatian part of the Adriatic Sea. Among them, 163 are on or along island coasts, and 72 are along the mainland coast. This distribution matches the proportion of the lengths of island coastline (4398 km; DUPLANČIĆ et al., 2004) and mainland coastline (1777.3 km; STATISTICAL YEARBOOK 2008, 2009). According to their inclination, 60% are caves and 40% are pits, although in many cases only the entrance parts were explored, and more remote channels may have a different morphology. In the continental part of the Dinaric karst, 29% are caves, 60% are pits, and 2% are combined features (GARAŠIĆ, 1991). Among the 235 features, 126 have completely marine conditions, 75 are anchialine (mostly) pits, 13 are submarine springs (vruljas), and 21 features are not determined by hydrological or environmental conditions. Detailed analysis is given in SURIĆ et al. (2010), and the list of the submerged caves is available in SURIĆ (2006). Speleothems, as the material for these investigations, were discovered in more than 140 submerged caves.

7. DISCUSSION

7.1. Sea level changes during the last 220 ka

Sea-level changes are the result of vertical readjustment of the ocean-bordering landmasses at locally varying rates (hydro-isostasy) in addition to the global (eustatic) meltwater-related sea-level fluctuations (HANEBUTH et al., 2009). Global sea-level changes with amplitudes of several hundred metres are generally induced by plate tectonics and they occur on a time scale of millions of years, while Quaternary sea-level changes are primarily induced by cyclic growth and decay of ice sheets, i.e. by climatically induced periodic exchange of mass between ice sheets and oceans (LAMBECK & CHAPPELL, 2001). Three different approaches are generally used for the reconstruction of Late Pleistocene-Holocene sea-level changes: (i) field observations using datable sea-level markers, (ii) simulation of global sea level based on the water-equivalent ice volume on the continents, (iii) use of proxy data, such as stable oxygen isotopes, to define temperature minima that correspond to sea-level minima (e.g., HANEBUTH et al., 2009).

Table 1: U-Th ages of speleothems K-14, K-18, L-1, L-10, Z–41, P-23, M-14, M-19 and M–23 and of marine overgrowth of speleothem P-23. Numbers in the first column correspond to the sample locations indicated in Plates 1 and 2.

Sample No.	Lab. no.	Sample	^{238}U (ng g^{-1})	^{232}Th (ng g^{-1})	Measured				Corrected		Uncorr. age (ka)	Corrected age (ka)
					(^{230}Th/^{232}Th) activity	(^{232}Th/^{238}U) activity	(^{230}Th/^{238}U) activity	(^{234}U/^{238}U) activity	(^{230}Th/^{238}U) activity	(^{234}U/^{238}U) activity		
1	MS-43	K-14-B-50d	60.9	57.11	2.3	3.07E-01	0.7184	1.1221	0.6348	1.1584	108.7	**84.7 ± 12.3**
2	MS-44	K-14-B-45	67.1	7.16	18.4	3.49E-02	0.6416	1.1250	0.6320	1.1287	90.3	**87.8 ± 1.3**
3	MS-42	K-14-B-1d	44.9	1.39	62.2	1.01E-02	0.6296	1.1655	0.6268	1.1668	82.9	**82.2 ± 1.1**
4	MS-41	K-14-A-172d	69.6	15.53	8.6	7.30E-02	0.6314	1.0888	0.6102	1.0939	93.2	**87.7 ± 3.7**
5	MS-25	K-14-A-10	100.3	21.11	9.3	6.89E-02	0.6383	1.0825	0.6187	1.0870	95.7	**90.6 ± 2.9**
6	MS-08	K-18-S	212.3	426.56	1.5	6.57E-01	1.0116	1.2062	1.0228	1.4045	183.1	**131.4 ± 28.4**
7	MS-05	K-18-C-14L	33.4	3.25	17.2	3.19E-02	0.5506	1.3515	0.5396	1.3601	55.7	**53.8 ± 2.1**
8	MS-06	K-18-C-14R	38.8	4.00	17.1	3.37E-02	0.5749	1.3818	0.5639	1.3916	57.2	**55.2 ± 1.4**
9	MS-06	K-18-C-14R	34.4	3.46	17.6	3.29E-02	0.5806	1.4917	0.5700	1.5041	52.3	**50.5 ± 5.3**
10	MS-17	K-18-C-14M	34.8	3.16	18.5	2.97E-02	0.5483	1.3687	0.5381	1.3770	54.5	**52.8 ± 1.1**
11	MS-04	K-18-C-11	35.8	1.05	61.3	9.65E-03	0.5910	1.3911	0.5880	1.3939	58.7	**58.1 ± 1.4**
12	MS-03	K-18-C-2	66.5	2.03	59.3	1.00E-02	0.5933	1.2951	0.5902	1.2973	65.2	**64.5 ± 1.2**
13	MS-02	K-18-B-40	65.4	0.94	138.6	4.68E-03	0.6491	1.2464	0.6479	1.2472	78.1	**77.7 ± 1.4**
14	MS-45	K-18-B-10	48.7	1.03	96.9	6.91E-03	0.6694	1.2290	0.6677	1.2300	83.3	**82.9 ± 0.6**
15	MS-46	K-18-A-95L	90.2	10.69	17.6	3.88E-02	0.6833	1.1240	0.6739	1.1273	99.9	**97.2 ± 1.4**
16	MS-47	K-18-A-95R	80.6	10.79	15.3	4.38E-02	0.6694	1.1430	0.6582	1.1479	93.9	**90.8 ± 1.5**
17	MS-01	K-18-A-5	48.3	4.25	25.0	2.88E-02	0.7199	1.2167	0.7137	1.2214	94.7	**93.7 ± 3.4**
18	MS-23	L-1-2	205.1	36.77	12.5	5.87E-02	0.7352	1.0681	0.7231	1.0712	124.9	**120.4 ± 3.2**
19	MS-24	L-10-T1	254.7	6.63	37.0	8.51E-03	0.3153	1.1731	0.3110	1.1742	33.8	**33.2 ± 0.5**
20	MS-24	L-10-T1	253.3	6.59	37.1	8.51E-03	0.3155	1.1618	0.3112	1.1629	34.2	**33.7 ± 0.6**
21	MS-30	L-10-T2	259.1	4.32	35.4	5.45E-03	0.1929	1.1147	0.1896	1.1152	20.6	**20.2 ± 0.5**
22	MS-29	L-10-25	265.8	4.88	156.2	6.01E-03	0.9383	1.0713	0.9380	1.0716	217.3	**216.8 ± 10.5**
23	MS-18	M-14-T	437.1	74.85	6.3	5.60E-02	0.3531	1.0651	0.3249	1.0679	43.6	**39.3 ± 2.0**
24	MS-19	M-19-T1A	359.7	1.33	350.5	1.21E-03	0.4231	1.0560	0.4226	1.0561	55.4	**55.3 ± 1.9**
25	MS-20	M-19-T1B	388.6	5.78	74.4	4.86E-03	0.3620	1.0622	0.3597	1.0624	45.2	**44.8 ± 1.0**
26	MS-21	M-19-T2	222.8	0.08	4198.2	1.16E-04	0.4865	1.0418	0.4865	1.0418	68.1	**68.1 ± 0.7**
27	MS-22	M-23-T	231.1	7.99	77.7	1.13E-02	0.8793	1.0350	0.8782	1.0353	202.2	**201.3 ± 5.5**
28	MS-22	M-23-T	230.8	7.93	77.6	1.12E-02	0.8717	1.0264	0.8707	1.0266	202.9	**202.0 ± 7.4**
29	MS-09	P-23-MO	1259.9	1217.40	1.4	3.16E-01	0.4490	1.1510	0.2789	1.1976	53.2	**28.7 ± 11.2**
30	MS-10	P-23-T1	148.1	57.07	3.1	1.26E-01	0.3867	1.0987	0.3230	1.1090	46.9	**37.3 ± 4.2**
31	MS-11	P-23-T2	363.6	1.36	233.6	1.22E-03	0.2857	1.0812	0.2850	1.0813	33.3	**33.2 ± 0.7**
32	MS-31	P-23-T3	91.5	4.21	18.5	1.50E-02	0.2789	1.0609	0.2708	1.0616	33.1	**31.9 ± 0.9**
33	MS-12	Z-41-B-40	76.3	265.54	1.5	1.14E+00	1.6677	1.1141	5.4493	1.7603	–	**–**
34	MS-13	Z-41-B-28	50.0	124.82	1.4	8.17E-01	1.1845	1.1765	1.4726	1.4521	371.2	**308.1 ± 53.8**
35	MS-28	Z-41-B-26	28.6	15.59	2.3	1.78E-01	0.4078	1.2585	0.3169	1.2982	42.1	**30.2 ± 5.2**
36	MS-27	Z-41-A3	60.1	48.02	1.5	2.61E-01	0.3843	1.2277	0.2351	1.2829	40.4	**21.9 ± 8.2**

* Data 1–5 and 7–17 were presented in SURIĆ et al. (2009)

Eustatic sea-level changes are worldwide changes which can be reconstructed only in tectonically stable areas. In tectonically unstable regions sea-level changes take place through movement of both the land and/or sea, and they are referred to as relative sea-level changes (changes in the position of the sea relative to the land) (LOWE & WALKER, 1998). Since the eastern Adriatic coast is considered tectonically active (PRELOGOVIĆ et al., 2003) only the relative sea-level curve can be reconstructed. Taking into account known eustatic sea-level changes, regional or local tectonics could be revealed.

Table 2: ^{14}C ages of speleothems L-1 and L-10 measured by a liquid scintillation counter, and of speleothems Z-41, B-38, B-36, B-34, B-28, P-23 and R-21 measured by a gas proportional counter. The youngest parts are marked with A and S, while B regards the oldest parts. ^{14}C ages are expressed as conventional ^{14}C corrected for A_0 = 85% and measured δ^{13}C (–8‰ when not measured), and as calibrated ages. Numbers in the first column correspond to the sample locations on Plates 1 and 2.

Sample No.	Lab. no.	Sample	^{14}C activity (pMC)[1]	δ^{13}C (PDB ‰)	^{14}C conventional age corrected for A_0 (BP)	Calibrated range (cal BP)[2]	Calibrated age (cal BP)[3]
37	Z-3495	L-1-S	57.4 ± 0.9	–8.0	3150 ± 125	3490 – 3210	**3350**
38	Z-3661	L-10-S	35.5 ± 0.7	–8.0	7015 ± 170	7990 – 7670	**7830**
39	Z-3660	Z-41-S	25.2± 0.8	–8.0	9760 ± 280	9700 – 8750	**9225**
40	Z-3032	B-38-A	2.7 ± 0.5	–7.4	27 550 ± 1600		**32 200**
41	Z-3033	B-38-B	0.0 ± 0.5	–9.5	**> 37 000**		
42	Z-3036	B-36-A	3.8 ± 0.5	–8.7	25 120 ± 1200		**29 800**
43	Z-3037	B-36-B	1.0 ± 0.5	–9.0	**> 37 000**		
44	Z-3039	B-34-A	8.5 ± 0.6	–8.8	18 500 ± 540	22 750 – 21 250	**22 000**
45	Z-3040	B-34-B	0.5 ± 0.5	–9.7	**> 37 000**		
46	Z-3042	B-28-A	8.9 ± 0.6	–7.2	18 150 ± 520	22 350 – 20 850	**21 600**
47	Z-3054	P-23-A	3.6 ± 0.5	–7.5	25 480 ± 1230		**30 300**
48	Z-3055	P-23-B	2.1 ± 0.5	–8.5	29 730 ± 2110		**34 800**
49	Z-3057	R-21-A	5.0 ± 0.5	–6.8	22 750 ± 890		**26 900**
50	Z-3058	R-21-B	2.4 ± 0.4	–6.2	28 505 ± 1320		**33 500**

[1] Measured ^{14}C activity is expressed as pMC (percent of modern carbon).
[2] Calibrated range for the ages <22 000 BP is obtained by calibration software OxCal v.3.10 (BRONK RAMSEY, 2005)
[3] Calibrated age for ^{14}C ages <22 000 BP is obtained as a mean of the calibrated range, and for ^{14}C ages >22 000 BP by the proposed extension of the calibration curve (BARD et al., 2004).
* Data 40–50 were presented in SURIĆ et al. (2005a)

On the basis of the U-Th and ^{14}C ages of particular parts of submerged speleothems, a partial sea-level curve can be reconstructed for the eastern Croatian coast for the last 220 ka (Fig. 3).

MIS 7 (245–190 ka BP) was the earliest interglacial recorded in the sampled speleothems. This stage was marked with three high sea-level stands at ~238 ka BP (MIS 7e), ~216 ka BP (MIS 7c) and ~195 ka BP (MIS 7a) (BARD et al., 2002). Deposition of speleothem L-10 probably started right after the MIS 7c peak, while the growth of speleothem M-23 had ceased by the subsequent MIS 7a sea-level rise.

MIS 6 (190–130 ka BP) was the glacial event with a sea level probably as low as during the LGM (BARD et al., 2002), and from that period, no speleothems have been

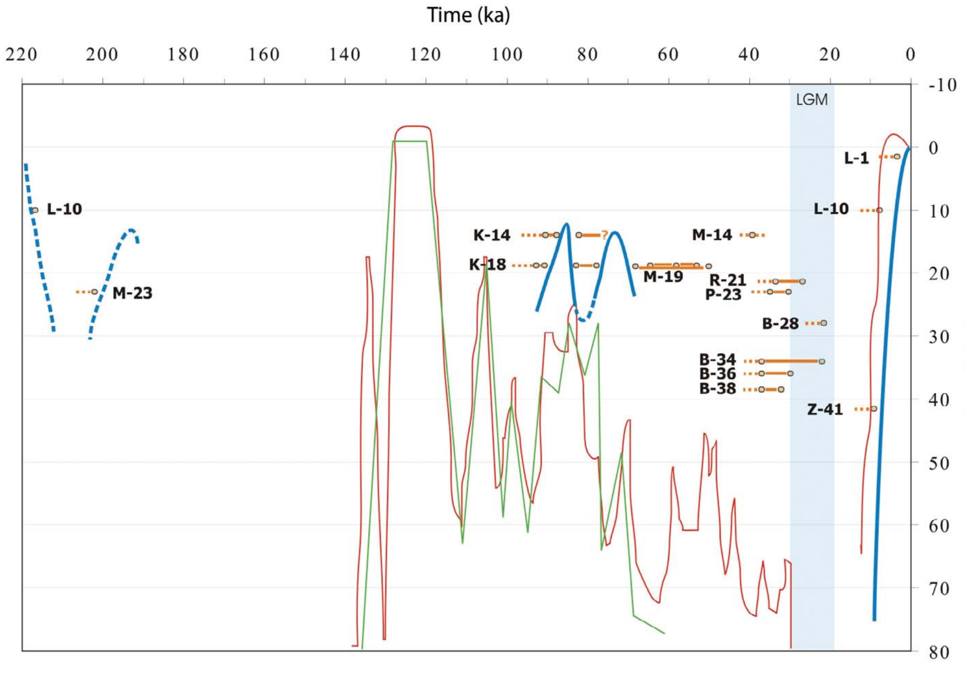

Figure 3: Late Pleistocene-Holocene relative sea-level curve (blue) based on ^{14}C and U-Th ages of 16 submerged speleothems (orange), correlated with the global sea-level curve (red), reconstructed from U-Th ages of coral reefs from Huan (Papua New Guini) and Bonaparte Bay (Australia) (adapted from LAMBECK et al., 2002a), and the mathematically derived curve (green) (adapted from POTTER & LAMBECK, 2004). Last Glacial Maximum (LGM) period (light blue) according to LAMBECK & CHAPPELL (2001) and LAMBECK et al. (2002a; 2002b).

found. This could indicate glacial conditions unfavourable for speleothem deposition, as recorded throughout most of Europe during the LGM. Yet, we can assume that in coastal Croatia, speleothem deposition was possible during the MIS 6 glacial similarly to that during the LGM (SURIĆ et al., 2005a).

The **MIS 5** (130–73 ka BP) interglacial was marked by three distinct high sea levels, with the first (MIS 5e at ~130 ka BP) being 6 m ± 3 m higher than at present (LAMBECK et al., 2004). Two subsamples had ages from that period. The surface parts of the stalagmite K-18 showed a U-Th age of 131.4 ka BP, but, as we know that the sea level was much higher than –18 m, the measured age was probably distorted by contamination of the surface by thorium from sea water or by leaching of uranium. An additional indicator for that contamination is the sequence of inner (younger) speleothem layers with correct stratigraphy. Another doubtful value is the age of 120.4 ka BP of the inner part of L-1 speleothem found at the depth of 1.5 m, which should have been submerged during the MIS 5e. Investigation of the interior reveals an initial straw morphology (Pl. 1), which shows that it was originally a stalactite (although it was found on the cave floor in growth position of a stalagmite), probably at an elevation higher then the MIS 5e sea level (SURIĆ et al., 2007). Speleothems from the U vode Pit recorded some events from the MIS 5a period; precipitation of speleothems K-18 had been more or less continuous in subaerial conditions from >93 to ~90 ka, from ~82 to ~77 ka and from ~64 to 54 ka, whereas K-14 had been growing from >90 to ~87 ka and for a brief period at 82 ka. Hiatuses were marked by mineral associations (calcite, gypsum, halite) that precipitate due to the evaporation of seawater (Ca-carbonates, gypsum, anhydrite, halite, K-Mg chlorides, arranged from least to most soluble; SEIBOLD & BERGER, 1996). Apparently, these hiatuses recorded the periods 90–82 ka and 77–64 ka in K-18 and 87–82 ka in K-14, which can be attributed to two MIS 5a sea-level highstands known as the *double peak* at ~84 and ~77 ka, which has also been noticed on the uplifted island of Barbados (POTTER & LAMBECK, 2004; POTTER et al., 2004; SCHELLMANN et al., 2004; RADTKE & SCHELLMANN, 2005). Comparison of the present elevation of speleothems K-18 and K-14 to the ice-volume-equivalent global sea-level curve (LAMBECK & CHAPPELL, 2001) shows a difference of at least ~13–17 m (speleothems should have been located ~13–17 m lower than today in order to be submerged by MIS 5a sea-level highstands). This difference could have resulted from long-term regional uplift at a rate of 0.15–0.25 mm/a (SURIĆ et al., 2009).

During the **MIS 4** (73–58 ka BP) glacial, precipitation of speleothem K-18 in U vode Pit continued with homogenous, dense carbonate indicating slow deposition in much dryer conditions, typical for glacial periods. Growth of speleothem M-19 also continued during MIS 4, and the preceding hiatus could have been of the same origin as that in K-18 caused by MIS 5 transgressions.

During **MIS 3** (58–22 ka BP), deposition of speleothem K-18 ceased, but not because of submergence, (sea level was probably ~70 m below the present one; LAMBECK et al., 2002a), nor because of environmental changes (it grew even during the colder MIS 4). A possible reason could be a change in groundwater flow paths or infilling of the feeding channel. A change of growth direction during the last growth phase is also evident (Pl. 1). Similarly, the cessation of M-19 and M-14 growth during MIS 3 was probably not connected with submergence. MIS 3 U-Th ages for the speleothem L-10 are quite confusing, indicating the unsuitability of coralloids (popcorn speleothems) for dating. The majority of ^{14}C results from the previous study (SURIĆ et al., 2005a) from the Cave in Tihovac Bay (Pag Island), Zmajevo uho Pit, and Pit in Lučice Bay (Brač Island) also fit into MIS 3 period. Five of them fit into the LGM (30–19 BP).

No reliable results were obtained from **MIS 2** (22–11.5 ka BP). Stalagmite Z-41, with one part dated to 21.9 ka BP, showed significant stratigraphic inversion of U-Th ages, which could be expected owing to its obvious contamination with clay-rich material.

The sea-level rise associated with **MIS 1** (11.5 ka BP – Present) terminated the growth of speleothem Z-41 from Vrulja Zečica at 9.2 ka BP, probably by a rise in groundwater level. So, after the subaerial phase, this void became a coastal spring, and subsequently a submarine one. The ^{14}C age of the youngest part of speleothem L-10 possibly indicates cessation of growth ca. 7 ka BP, while the speleothem L-1 at –1.5 m was in vadose conditions, with needle-like deposits on its surface ca. 3350 years BP. As expected, all the ages of marine overgrowth samples also fall into the MIS 1 period.

Although the examined speleothems cover the last 220 ka, only a partial sea-level curve for the Eastern Adriatic could be constructed (Fig. 3) but it shows good correlation with the global sea-level curve. The few discrepancies in recorded elevations probably result from long-term regional tectonics.

7.2. Palaeoenvironmental changes

Sea-level changes have significantly changed the palaeogeographic scenery of the Eastern Adriatic region, but not evenly in all its parts. Relatively shallow parts of the northern Adriatic and southern Dalmatia experienced substantial shifts in shoreline during low sea levels, whilst numerous regions with steep, even sub-vertical coasts remained almost unchanged even during sea-level fall of as much as 50 m (PIKELJ et al., 2009). Along with sea-level changes, coastal hydrology was considerably transformed, especially in terms of submergence of coastal springs and the activation of new ones at higher elevations during sea level rise, and their drying up during sea-level fall. Lowering of the absolute erosional base level resulted in river incision far below present sea level. Emergence during regressional phases enabled not only deeper karstification but also migration of Pleistocene fauna whose remnants can be found on today's islands that are presently too small to sustain large Pleistocene animals (PAUNOVIĆ et al., 2001). Fossil remnants from the northern part of the Adriatic basin (Druška Peć Cave, Mošćenička Draga) consist exclusively of an alpine faunal assemblage found at a relatively low elevation (335 m), suggesting substantial climatic cooling (MALEZ et al., 1979). However, within the southeastern Adriatic region (Vela Spila on Korčula Island), there are no fossil remnants of Upper Pleistocene animals adapted to colder conditions (ČEČUK & RADIĆ, 2005), meaning that even during the cold MIS 2, climate-driven environmental changes were not so significant as in the northern region. Apart from the faunal migrations, emergent continental regions presented refuge areas for plant species that could not adapt to glacial conditions. Thus, during the climate cooling in Europe, vegetation zones did not move as a whole to the south and there was no forest belt; forests could not be maintained in southern Europe, either in lowlands which were too dry, or in higher parts of mountain ranges where it was too cold. Steppe vegetation dominated and forests survived in narrow zones with appropriate moist conditions (ZAGWIJN, 1992). According to palynological research, one such zone spread along the Eastern Adriatic region as a refuge area for plant species from the north – coniferous forest interspersed with deciduous trees (ZAGWIJN, 1992). Aside from migrating floral and faunal species, conditions were probably also appropriate for early humans.

Abundant moisture and forest cover provided the soil and groundwater conditions ideal for dissolution and depositional karstification during the LGM, and probably also during previous glacial periods. Speleothem deposition and vegetation that requires damp conditions suggest that during the LGM the Eastern Adriatic coast was a border between a relatively temperate Mediterranean zone and the periglacial part of Europe to the north. Along with geographic position (latitude), the Adriatic Sea and the Alps and Dinarides were the key climate modifiers that mitigated the influence of climate changes, which were very severe throughout most of Europe. Namely, mountain ranges partly alleviated cold influences from the north, while the Adriatic Sea to the south ensured sufficient humidity. During the LGM, the average annual temperature in the coastal area was probably 10 ± 5 °C lower than today (PEYRON et al., 1998), so the idea of speleothem deposition in such an environment [e.g., LGM temperature in Hvar was estimated to be 7.5 °C by MIRACLE (1995)] can be supported by recent speleothem growth in the region where temperatures are similar [e.g. in Gorski Kotar with annual average temperature of 7 °C (CASALE et al., 2004)].

The similarity between LGM and Holocene $\delta^{18}O$ values (–6.7‰ to –4.1‰ and –6‰ to –3.5‰, respectively) suggests similar climatic conditions during these two periods. But, prior to carbonate deposition, the $\delta^{18}O$ signal in meteoric water is influenced not only by temperature but also by the transport pathway of the water vapour, distance from the coast, amount of rainfall, etc. Therefore, different coastline positions during the LGM and Holocene could induce $\delta^{18}O$ signal changes that would produce similar values for the two periods despite the temperature difference of 10 ± 5 °C.

8. CONCLUSIONS

Climate changes associated with the Late Pleistocene-Holocene period had considerable influence on the Eastern Adriatic region, in both the palaeogeographic and palaeoenvironmental sense. According to U-Th and ^{14}C ages, and mineralogical composition of 16 submerged speleothems, the curve of relative sea-level changes during the last 220 ka has been partially constructed for the Eastern Adriatic coast, and it generally corresponds to the global sea-level curve. Some sea-level stands are better resolved: sea level lower than –23 m during MIS 7b (202 ka BP), the *double peak* during the MIS 5a (84 ka and 77 ka BP) with sea level above –14 m and low sea-stand in-between at ~80 ka BP, and rapid Holocene sea-level rise with sea level lower than –41.5 m (9.2 ka BP), –10 m (7.8 ka BP) and –1.5 m (3.4 ka BP). The ages of other dated samples correspond to periods with sea-level lower than present. Speleothem growth cessations were not caused by climate changes – if so, simultaneous terminations should have been noticed. Moreover, several speleothems grew even during the LGM. Growth cessation was probably caused by infilling of the feeder channels, changes in groundwater flow paths, or by submergence of the speleothems in fresh water or sea water.

$\delta^{18}O$ signals could not be interpreted as a proxy for temperature due to kinetic fractionation during speleothem deposition. But speleothem growth during cold phases, preconditioned by adequate humidity and vegetation cover, suggests that the Eastern Adriatic area was transitional between periglacial Europe and the temperate Mediterranean zone, with favourable conditions not only for karstification, but also for migrating plants and animals, and most probably for early humans.

To obtain more precise records of palaeoenvironmental changes in the Croatian coastal zone, future studies should encompass not only submerged speleothems from a wider range of depths and locations, but should also compare similar inland features and coastal sea-level markers below and above the present sea level.

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