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Distinct phases of relative sea level changes in the central Adriatic during the last 1500 years — influence of climatic variations?

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ABSTRACT

We present a new sea-level reconstruction for the past 1500 years based on biological indicators from the Central Adriatic islands. Biogenic littoral rims built by the coralline rhodophyte *Lithophyllum byssoides* were found on the particularly exposed sites on the rocky coasts of the islands of Vis, Ravnik and Biševo in Croatia. The presence of thick and well-developed *Lithophyllum* rims, considered to be precise (±10 cm) sea-level indicators, points directly to the rising sea-level environment. Biogenic rims were mapped, measured and sampled for ^{14}C dating. The obtained results point to four phases of sea-level changes. The sea-level was near stable from around 550 till 770 cal AD, in the Dark Ages Cold Period (DACP), then during the Medieval Climate Anomaly (MCA) (770 till 1330 cal AD) the sea-level increased at a rate of 0.71 mm/yr. During the Little Ice Age (LIA) (1330 till 1640 cal AD) it was near stable again. Later, the sea-level started to rise at a much higher rate particularly during the Current Warm Period (CWP). These data were compared with local predictions derived from a glacio-hydro-isostatic models associated with the Last Glacial cycle. If the isostatic–eustatic component is separated, this area seems to have almost stable tectonic conditions during the past 1500 years.

Our results show that the large algal rims most likely grew during near-stable sea-level conditions that occurred during two relatively colder periods in the past 1500 years. They also reveal that well-developed (up to 1.8 m wide) upper levels of algal rims were formed during ~300 years of stabilisation throughout the LIA.

1. Introduction

The study of sea-level variations today is pluridisciplinarily approached. Geomorphological, sedimentological, archaeological and biological indicators are used and combined. Within the studies of the 2 ka relative sea-level change along the Croatian Adriatic coast, different markers have been used till now. One of the first markers used to estimate the sea-level change were submerged archaeological remains (e.g. Degrassi, 1955; Vrsalović, 1979). In 1980, the study of the geomorphological markers has been introduced by Pirazzoli (1980) and numerous studies followed (e.g. Antonioli et al., 2004; Benac et al., 2004, 2008). As the available geomorphological markers (submerged tidal notches) cannot be directly dated, they were combined with archaeological markers (e.g. Fouache et al., 2000; Faivre and Fouache, 2003; Fouache et al., 2005a, 2005b; Antonioli et al., 2007; Faivre et al., 2010a; Faivre et al., 2010b). In addition, sedimentological studies have been initiated along the Istrian shores (Faivre et al., 2011) with the same purpose.

The recent use of archaeological remains as sea-level markers opened up numerous questions: the problem of the functional height of the structures (Antonioli et al., 2007; Auriemma and Solinas, 2009; Faivre et al., 2010b); the problem of the missing upper level blocks; the minimal sea depth below the structure (Carre et al., 2011; Fouache et al., 2011), the draught of the ships; and the way of measurement and the correction of tide. Still, these do not permit a sufficiently precise defining of the sea-level change.

The study of the biological sea-level markers along the eastern Adriatic coast has started just recently (Faivre et al., 2010b) with the aim of restraining the error bar and obtaining more accurate results for comparison of different sea level indicators (archaeological, geomorphological and biological). Such an interdisciplinary approach was used e.g. for the ancient harbour of Marseille by Morhange et al. (2001). In this study, sea-level reconstruction will encompass the last 1500 years in the hope of providing the context for understanding the nature and causes of past and current sea-level changes.

2. Study area

Field work started in 2008 on the islands of Vis, Ravnik and Biševo. Those are relatively close islands, situated in the central part of the eastern Adriatic (Fig. 1). They belong to the Central Dalmatian Islands

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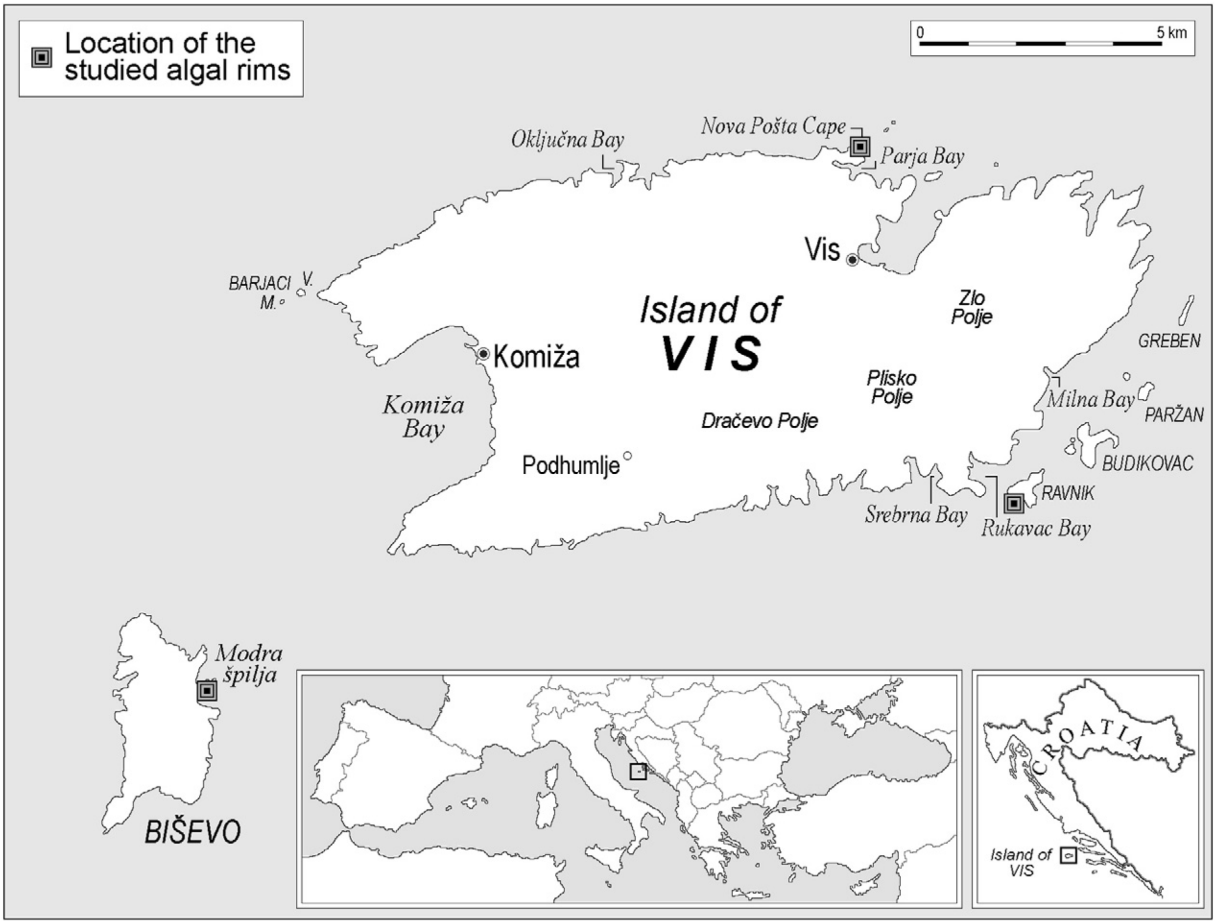

Fig. 1. Study area with the locations of the studied algal rims on Vis, Biševo and Ravnik Island.

group in Croatia. By its size, the island of Vis (89.7 km^2) is the ninth island in the Adriatic Sea (Duplančić Leder et al., 2004) while Biševo, and particularly Ravnik are much smaller. They are located around 45 km from the mainland. The geological and geomorphological properties of the island of Vis are detailed in Faivre et al. (2010b).

3. The biological basis

The spatial distribution of the littoral fauna and flora of rocky shores shows a pattern of superimposed belts, called biological zonation (Pérès and Picard, 1964; Pérès, 1982). Three particular biological zones can be distinguished near the sea-level: the supralittoral, the mediolittoral and the infralittoral zone. The height of the first two zones: supra- and mediolittoral is defined by the micro-tidal character of the Mediterranean Sea. The supralittoral zone is occasionally wetted by surf and there the biomass is mainly represented by endolithic Cyanobacteria (Le Campion-Alsumard, 1970). In the mediolittoral zone, which is periodically submerged by waves and tides, Cyanobacteria and limpets interact on limestone shores in shaping the tidal notch. Rock-building elements such as the coralline rhodophyte *Lithophyllum byssoides* (Lamarck) Foslie (formerly known as *Lithophyllum lichenoides* Philippi; Guiry, 2011) may also be important (Pérès and Picard, 1952; Laborel et al., 1994) and, under favourable conditions, it may build up reef like bioconstructions just above the biological mean sea-level (Laborel and Laborel-Deguen, 1996). The infralittoral zone ranges from the lowest waters down to 25–35 m of depth and it is characterised with an abrupt rise of biodiversity in comparison with the first two zones (Laborel et al., 1994).

Many regional and local differences of those biological zones occur due to biogeography, tides, direction and intensity of prevailing winds, water temperature and other oceanographical factors (Laborel et al., 1994). On limestone shores these constraining actions lead to different types of vertical profiles (Guilcher, 1953; Dalongeville, 1986) in which notches alternate with bioconstructed structures that can be preserved over a prolonged period when they are uplifted or submerged, and thus, can be used for the study of past sea-levels (Pirazzoli, 1986).

The *Lithophyllum* rim, also termed corniche (Molinier, 1955; Pérès, 1968), is an organogenic calcareous protrusion that grows out from steep rocky surfaces slightly over mean sea-level (MSL) (Laborel et al., 1994). It is like a narrow pavement at the foot of marine cliffs (Trenhaile, 1987). On limestone coast, the *Lithophyllum* rim develops at the base of the mediolittoral tidal notch (Dalongeville, 1986) and may attain a maximum width of about 2 m and an average thickness of 30–40 cm (Laborel et al., 1994). The growth rate of the living thalli is relatively rapid, up to 3 cm in diameter per year (Boudouresque et al., 1972) but the evolution from an incipient algal population to a mature rim with hardened core is a long process, and it does not happen everywhere.

Lithophyllum rims are absent in the calm, sheltered areas. They develop in the less agitated parts of the exposed coasts (Pérès and Picard, 1952). Consequently, they are best developed in the inlets of exposed coasts because the organic construction needs strong mixing of water but not too strong wave impact.

Although *Lithophyllum byssoides* can survive in areas where it is subjected to direct sunshine, it prefers less insolation. This could explain why *Lithophyllum* rims develop better on very steep slopes, and particularly why they prefer north facing surfaces (Pérès and Picard, 1952).

The outer portion of a *Lithophyllum* rim consists of living algae, but diagenesis of the interior makes the formation very resistant to wave attack. According to Laborel and Laborel-Deguen (1996), the best sites for development of rims are narrow and dark canyons with vertical slopes, which provide good conditions for *Lithophyllum* growth and conservation.

The prominence of encrusting coralline ledge coatings on the exposed portions of the coast may be a result of increased nutrient supply in turbulent water, or due to the circulation of sea water trough the accretions or both (Adey and MacIntyre, 1973). The encrusting coralline algae with excrescences trap detrital material carried by the sea, which is then cemented by encrusting coralline algae like *Lithophyllum incrustants* R.A. Philippi. The biogenic structure therefore grows in a thickness always covered by another layer of encrusting coralline algae. The infralittoral part of the rim is covered by upright bushy, articulated coralline algae like *Jania rubens* and *Corallina* spp.

Well-developed fossil *Lithophyllum* formations could be preserved after submergence (Faivre et al., 2010b) despite possible strong bioerosion as evidenced by Morhange (1994) in the Western Mediterranean.

Pérès and Picard (1952) stated that *Lithophyllum byssoides* grows only in the north-western Mediterranean basin. Zimmermann (1982) later specified that *Lithophyllum* rims are limited to the Western Mediterranean basin, although the species is also present in the Eastern Mediterranean region, but not as a rim builder. Obviously, the existence of the algal rims in the Eastern Mediterranean is not well-known. The coralline alga *L. byssoides* occurs along the eastern Adriatic coast not only as single specimens but also as rim builders, which we started to study in 2008 (Faivre et al., 2010b). The presence of this species in Croatia had already been mentioned (Špan, 1969; Lovrić, 1971; Dalongeville, 1980) but the algal rims were not studied in detail.

4. Material and methods

We started this study with a survey of the coast of three islands. Up to now, six locations have been identified: 3 on the Island of Vis, 1 on Ravnik Island and 2 on Biševo Island. Three of them have been selected for detailed analyses and have been precisely measured, mapped and sampled for ^{14}C dating during 2008–2010. Vertical sections were excavated with a hammer and chisel.

Lithophyllum byssoides have a very narrow vertical range closely associated to mean sea-level (MSL). Any direct reference to the actual water level is thus unnecessary, knowing that biological sea-level markers are not perfect horizontal lines but are naturally warped even on short distances, due to the local variations of hydrodynamism and morphology. Therefore, levelling was done by direct measurements of the vertical distance between the outer edge of the upper level algal rim, taken as the reference datum, and the centre of the broken section as explained in Laborel (1986) and Laborel et al. (1994). The actual sea water level at the moment of the study was also taken into account. The studied area belongs to a micro-tidal environment with an average amplitude of 25 cm (data from the Split mareograph). The vertical range of living *Lithophyllum* thalli at the studied area is 20 cm, so the total error is estimated at ±10 cm.

Samples were labelled, cleaned and dried. They were cut with a diamond saw and then dated by ^{14}C method in Radiocarbon Laboratory at Rudjer Bošković Institute in Zagreb. Two ^{14}C techniques were used for dating algal samples: 1) liquid scintillation counting (LSC Quantulus 1220) using benzene synthesis method for sample preparation (Horvatinčić et al., 2004) and 2) accelerator mass spectrometry (AMS) using graphite sample preparation in Radiocarbon Laboratory in Zagreb (Krajcar Bronić et al., 2010a) and ^{14}C measurement of graphite targets on AMS in Scottish Universities Environmental Research Centre

Table 1

Radiocarbon dates obtained on *Lithophyllum* and shell samples. Measured ^{14}C activity is expressed as percent of modern carbon (pMC). Calibrated ranges expressed in cal BP and cal BC/AD are obtained using OxCal calibration software (Bronk Ramsey, 2011) with probability of 95.4%. Calibrated ages (cal BP and cal BC/AD) are obtained as a median values of the calibrated ranges.

Lab. No	Site	Sample	Depth below MSL (cm)	^{14}C activity (pMC)	^{14}C age (yr BP)	Calibrated range (cal BP)	Calibrated age (cal BP)	Calibrated range (cal BC/AD)	Calibrated age (cal BC/AD)	Note
Z-4298	Vis–Nova Pošta	1a (2008)	0.0	103.7 ± 1.21	Modern	–	–	–	–	Recent
Z-4301	Vis–Nova Pošta	1X (2008)	20 ± 10	92.5 ± 0.7	620 ± 60	660–550	600	1280–1420	1350	
Z-4302	Vis–Nova Pošta	3 (2008)	20 ± 10	93.4 ± 0.4	545 ± 35	640–510	560	1310–1440	1400	
Z-4303	Vis–Nova Pošta	8 (2008)	20 ± 10	96.8 ± 0.7	255 ± 60	490–0	310	1460–1950	1640	
Z-4848	Vis–Nova Pošta	1a (2009)	20 ± 10	95.0 ± 0.6	345 ± 50	500–310	400	1450–1640	1550	
Z-4849	Vis–Nova Pošta	1b (2009)	20 ± 10	91.4 ± 0.7	660 ± 60	690–540	620	1260–1410	1330	
Z-4850	Vis–Nova Pošta	1c (2009)	20 ± 10	95.1 ± 0.5	400 ± 40	520–320	460	1430–1630	1490	AMS, $\delta^{13}C = 2.5$‰
Z-4851	Vis–Nova Pošta	2a (2009)	20 ± 10	95.8 ± 0.5	345 ± 40	490–310	400	1460–1640	1550	AMS, $\delta^{13}C = 2.7$‰
Z-4852	Vis–Nova Pošta	2b (2009)	20 ± 10	96.5 ± 0.5	285 ± 40	470–150	380	1480–1800	1580	AMS, $\delta^{13}C = 2.3$‰
Z-4507	Vis–Nova Pošta	1 (2009)	60 ± 10	85.1 ± 1.0	1290 ± 95	1370–980	1210	575–970	745	
Z-4508	Vis–Nova Pošta	2 (2009)	60 ± 10	85.6 ± 0.5	1250 ± 45	1280–1070	1190	670–880	760	
Z-4509	Vis–Nova Pošta	3 (2009)	60 ± 10	83.4 ± 0.5	1460 ± 50	1510–1290	1350	535–665	600	
Z-4510	Vis–Nova Pošta	4 (2009)	60 ± 10	83.2 ± 0.4	1470 ± 40	1480–1300	1360	535–655	590	
Z-4511	Vis–Nova Pošta	5 (2009)	60 ± 10	83.1 ± 0.9	1490 ± 85	1570–1270	1400	385–685	555	
Z-4512	Vis–Nova Pošta	6 (2009)	60 ± 10	85.3 ± 0.3	1270 ± 25	1280–1170	1220	670–780	725	Shell, AMS, $\delta^{13}C = 2.9$‰
Z-4642	Vis–Nova Pošta	7 (2009)	60 ± 10	84.9 ± 0.3	1310 ± 25	1290–1180	1260	655–770	690	Shell, AMS, $\delta^{13}C = 3.0$‰
Z-4693	Biševo-Modra Špilja	8a (2010)	15 ± 10	91.6 ± 0.6	640 ± 50	670–540	610	1280–1410	1340	
Z-4694	Biševo-Modra Špilja	8b (2010)	15 ± 10	94.8 ± 0.6	370 ± 55	510–310	410	1440–1640	1540	
Z-4685	Biševo-Modra Špilja	3a (2010)	65 ± 10	82.9 ± 0.6	1440 ± 55	1420–1280	1340	530–675	610	
Z-4686	Biševo-Modra Špilja	3b (2010)	65 ± 10	85.0 ± 0.6	1240 ± 60	1290–1050	1170	660–895	775	
Z-4692	Biševo-Modra Špilja	4 (2010)	90 ± 10	71.9 ± 0.5	2590 ± 55	2800–2490	2720	850–540 BC	770 BC	More data needed
Z-4687	Biševo-Modra Špilja	5a (2010)	140 ± 10	75.6 ± 0.6	2190 ± 60	2340–2040	2200	390–90 BC	255 BC	More data needed
Z-4688	Biševo-Modra Špilja	5b (2010)	140 ± 10	81.4 ± 0.6	1590 ± 55	1610–1350	1470	345–595	480	Probably contaminated with recent material
Z-4689	Biševo-Modra Špilja	7a (2010)	150 ± 10	91.2 ± 0.6	675 ± 55	690–540	630	1255–1405	1320	Probably contaminated with recent material
Z-4690	Biševo-Modra Špilja	7b (2010)	150 ± 10	90.2 ± 0.7	765 ± 65	800–560	700	1155–1390	1245	Probably contaminated with recent material
Z-4691	Biševo-Modra Špilja	7c (2010)	150 ± 10	91.4 ± 0.6	665 ± 55	650–490	620	1265–1405	1330	Probably contaminated with recent material
Z-4695	Ravnik-Zelena Špilja	1a (2009)	15 ± 10	93.1 ± 0.6	510 ± 50	650–490	540	1305–1460	1415	
Z-4696	Ravnik-Zelena Špilja	1b (2009)	15 ± 10	92.7 ± 0.6	545 ± 50	650–510	570	1300–1440	1385	

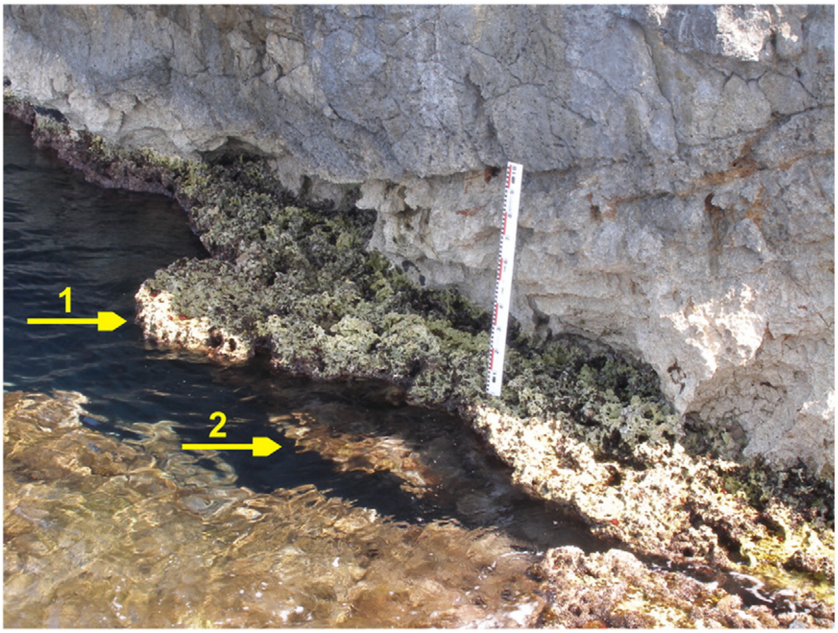

Fig. 2. Morphology of the *Lithophyllum* rim at Nova Pošta, Vis Island with two dominant pronounced levels: the upper one (1) with a maximal extension of 140 cm and the lower one (2) with a maximal extension of 40 cm.

(SUERC), East Kilbride, Scotland. Twenty-three samples of algal formation were dated by the LSC method and three samples of algal formations along with two shell samples were dated by the AMS method. The results were reported as ^{14}C activity ($a^{14}C$) in percentage of modern carbon (pMC) which relates the ^{14}C content of a sample to the ^{14}C content of a modern standard normalized for isotope fractionation. The ^{14}C age was expressed in conventional ^{14}C years BP.

The ^{14}C activity of the recent sample was 103.7 pMC (Table 1) indicating that algae used CO_2 from the atmosphere. The mean ^{14}C activity of atmospheric CO_2 in Zagreb for 2010 was 102.0 pMC (Krajcar Bronić et al., 2010b) and this was also close to ^{14}C activity of recent molluscs from the Adriatic Sea (107.5 and 106.9 pMC; Surić, 2002). Consequently we did not apply any ^{14}C age correction for the reservoir effect. $\delta^{13}C$ values of the biogenic rims for five samples (3 algal and 2 shell samples, Table 1) were between 2.3 and 3.0‰VPDB indicating marine origin. Similar values were determined for the recent shells (from −1.1‰ to 1.6‰) and marine biogenic overgrowth (from −2.6‰ to 2.5‰) on submerged speleothems in the Adriatic Sea (Surić et al., 2005). The control dating on living algal thalli effectuated by Laborel et al. (1994) indicated that *Lithophyllum byssoides* does not appear to be subject to any kind of reservoir effect (Stuiver et al., 1986). Laborel et al. (1994) also found that *Cliona* perforations filled up with younger materials are the commonest cause of contamination. A special cause of error that could not be eliminated nor quantified at the moment is the presence of inner deposited cement, which cannot be separated from imbedded calcified algal thalli. For the calibration of ^{14}C ages we used OxCal calibration software (Bronk Ramsey, 2011).

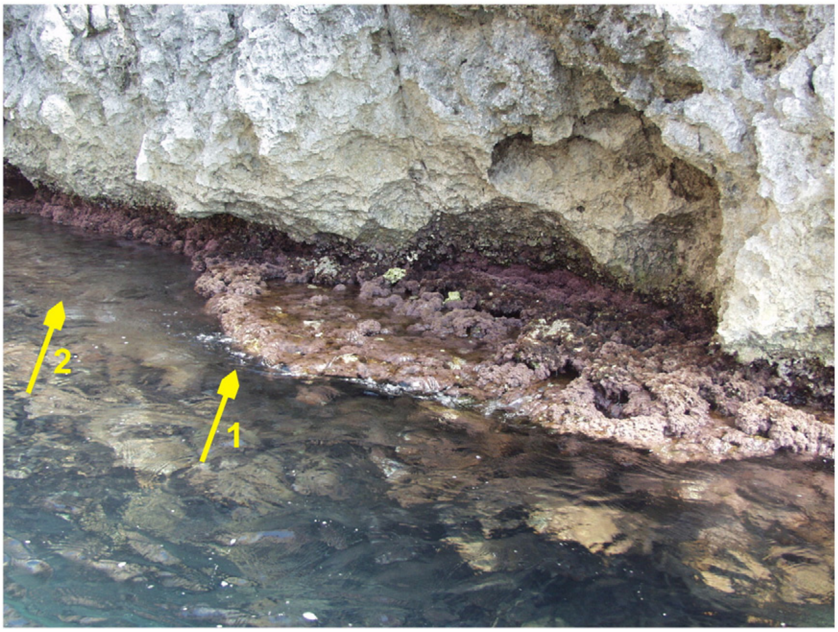

Fig. 3. Morphology of the *Lithophyllum* rim (section A; see Fig. 5) at Biševo Island with two dominant levels: the upper one (1) with a maximal extension of 180 cm and the lower one (2).

5. Results

Two of the three studied algal structures – Nova Pošta on the Island of Vis and Modra Špilja on the island of Biševo – represent thick and well-developed *Lithophyllum* rims (Figs. 2, 3). They both have similar morphology, i.e. they have two pronounced levels. The *Lithophyllum* rim at Zelena Špilja on Ravnik Island has only one pronounced level, the upper one. The thickness of each level at its most protruding part is around 15 cm at all three locations. The *Lithophyllum* rims that we studied are developed on limestone, although, generally their development is not restricted to calcareous substrates (Barbaza, 1970). Consequently, a recent notch, directly connected with the formation of

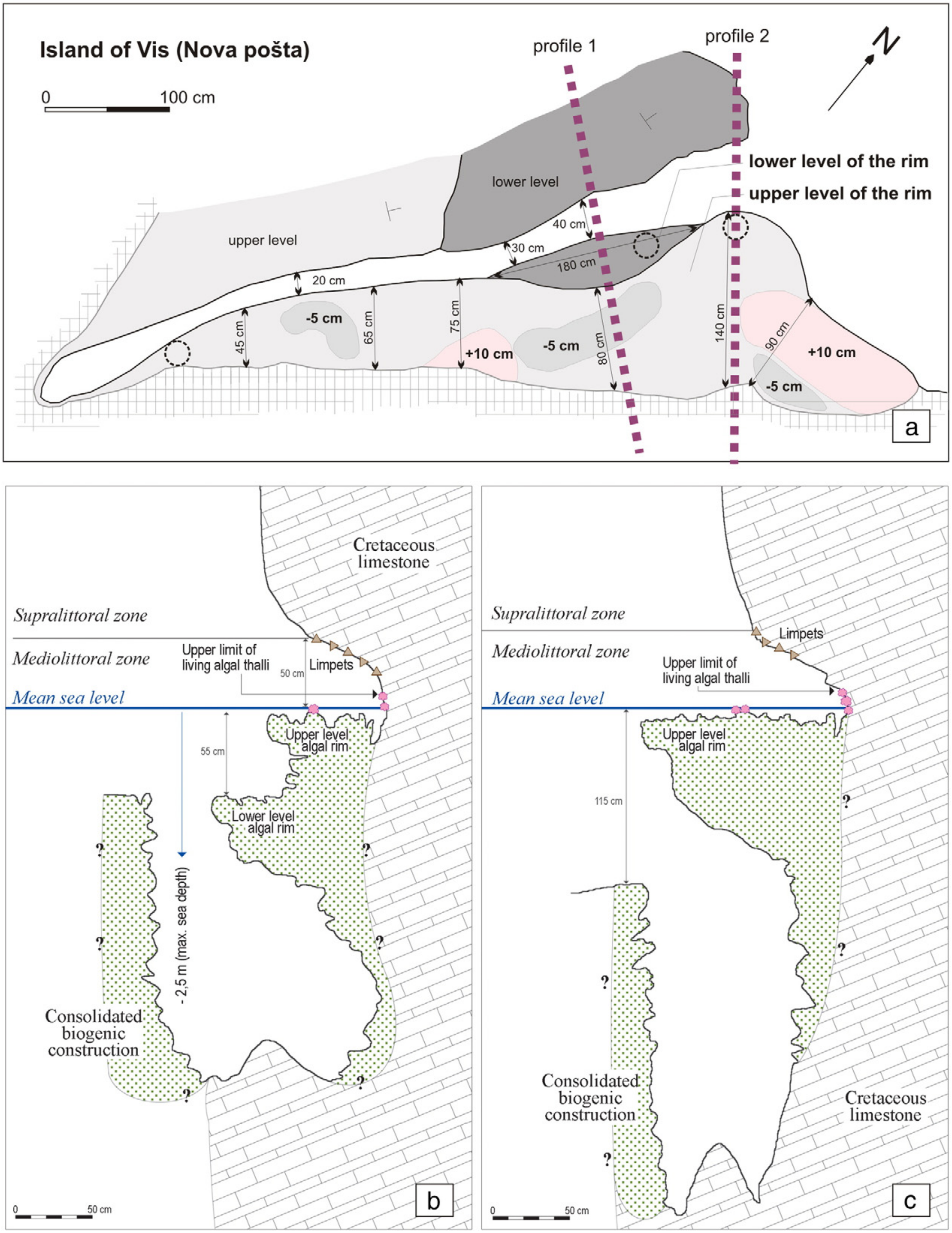

Fig. 4. The Nova Pošta algal rim, Vis Island; a) ground plan, dashed circles represent sampling locations; b) profile 1; c) profile 2. Position and upper limit of living *Lithophyllum* thalli are marked in the figure.

biogenic littoral rim, has been identified systematically. All the studied algal rims are located in the shady coves and cliffs exposed to surf action. They developed under the influence of different frequent winds in the area, the north-western, the north-eastern and the south-eastern winds.

The whole algal rim at Nova Pošta on the northern shore of Vis Island begins between −100 cm and −75 cm below the recent MSL, depending on the micro location (Fig. 4). It has two clearly differentiated levels: the upper one around 7 m long and 40 to 140 cm wide, and the lower one whose protruding part has a maximal extension of 40 cm. The upper level of the algal rim is −20 ± 10 cm below the recent MSL, while the surface of the lower level is −60 ± 10 cm below the recent one.

Sixteen samples from Vis Island have been dated, eight samples from the upper level of the algal rim, seven samples from the lower level of the algal rim and one recent sample of coralline algae (Figs. 2 and 4).

The results of ^{14}C dating of Vis Island — Nova Pošta (Table 1) suggest that the upper level of the rim (20 ± 10 cm below MSL) was formed between 600 cal yr BP and 310 cal yr BP, while the lower level of the algal rim (60 ± 10 cm below MSL) was formed between 1400 cal yr BP and 1190 cal yr BP (Fig. 6). Within the lower level of the algal rim, two

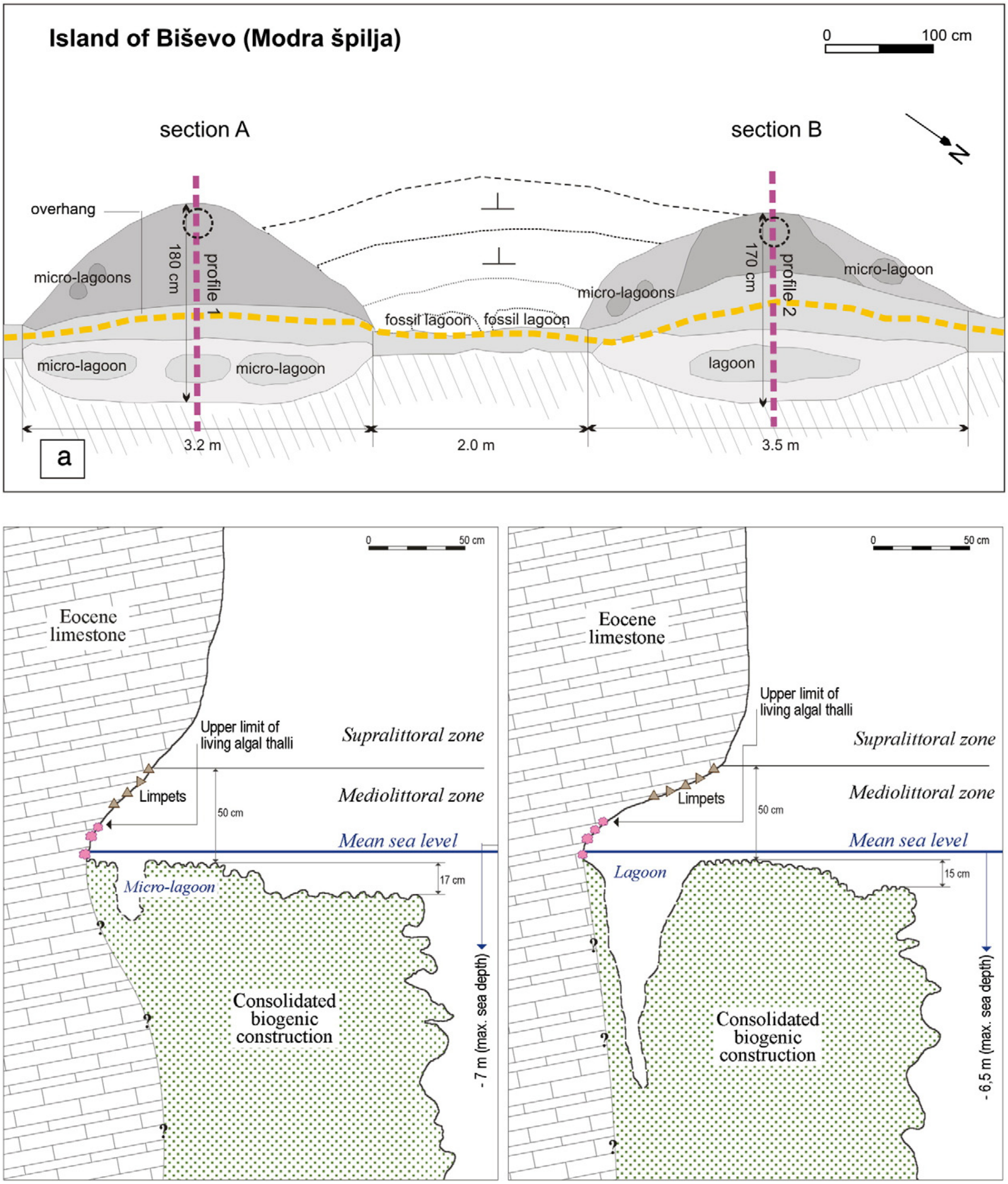

Fig. 5. The Modra Špilja algal rim, Biševo Island; a) ground plan, dashed circles represent sampling locations; b) profile 1; c) profile 2. Position and upper limit of living *Lithophyllum* thalli are marked in the figure.

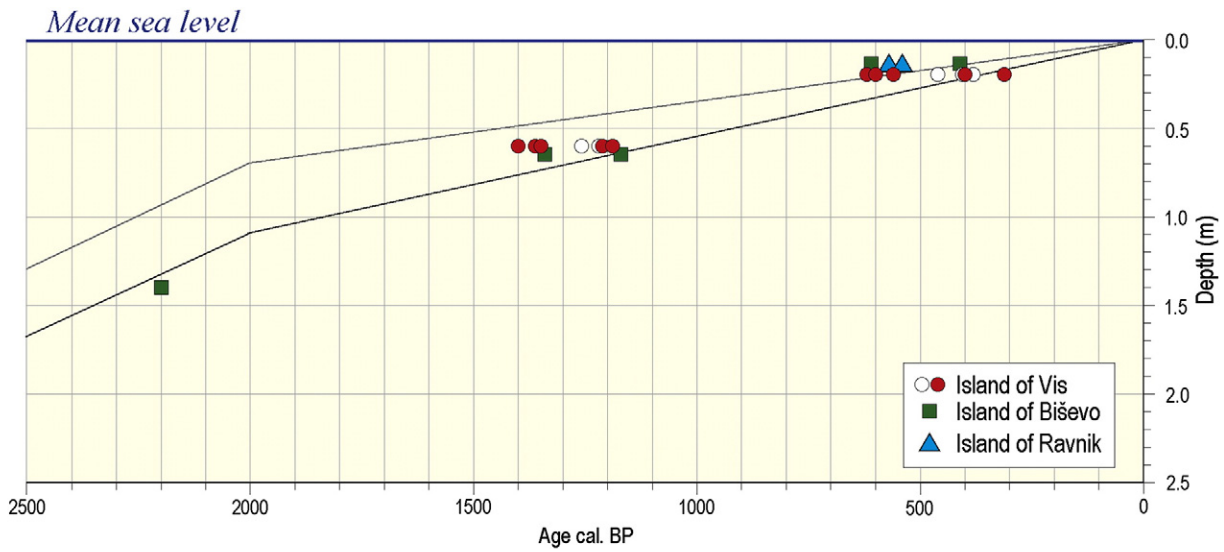

Fig. 6. Comparison between the predicted models of relative sea-level change for the Central Adriatic, black line – Lambeck et al. (2004), grey line – Lambeck and Purcell (2005), and the ^{14}C dated algal rim samples from the Vis, Biševo and Ravnik Islands. Empty circles indicate results obtained with AMS technique and full symbols by LSC technique.

mollusc shells have been found which were dated by AMS. Those two results perfectly fit in the other results obtained with *Lithophyllum* dating (Table 1).

The algal rim studied on Biševo Island (Modra Špilja) can be divided in two sections: A and B (Fig. 5). The upper level of the algal rim is particularly wide in both sections. In the A section it reaches 180 cm at its maximal protrusion and 170 cm in the B section. The upper level of the rim at both sections has general step-like morphology, slightly rising towards the notch vertex, with small but sometimes very deep lagoons (Figs. 3, 5). The lower level of the rim is best visible between the mentioned two dominant sections (A and B) of the upper rim level. Below the rim, thick consolidated biogenic construction continues downwards. The same morphology with pronounced two rim levels can be well observed on the other side of this particular small bay, but there the rim starts at around −1 m. According to our results (ten samples), the upper level of the algal rim on Biševo Island (15 ± 10 cm below MSL) has grown in the time span between the 610 cal yr BP and 410 cal yr BP, while its lower level (65 ± 10 cm below MSL) was formed between 1340 and 1170 cal yr BP (Table 1, Fig. 6). The results obtained for the samples of the deeper portion of the rim (0.9 m, 1.4 m and 1.5 m below MSL) (Table 1; Fig. 6) need further more detailed studies. Consequently, they will not be discussed here.

On Ravnik Island (Zelena Špilja), only the upper level of the algal rim is developed (15 ± 10 cm below MSL) and it is around 550 cal yr BP old (Table 1; Fig. 6) (two samples). The rim is relatively narrow there, with maximal protrusion of about 1 m, but continuous.

Today, on the relatively horizontal surfaces of upper level of all the studied algal rims, processes of biodestruction prevail over bioconstruction. The most of these surfaces, especially on Nova Pošta on Vis, are heavily bioeroded, mostly by gastropods. The rest of the surfaces are covered with various soft algae. In small depressions, filled with water almost all the time, numerous beadlet anemones (*Actinia equina*) are present, signalizing that most of the upper level of the rims are below biological mean sea-level today. Living thalli of the coralline alga *Lithophyllum byssoides* were found only on small patches at the highest position on the horizontal surface of the rim and along

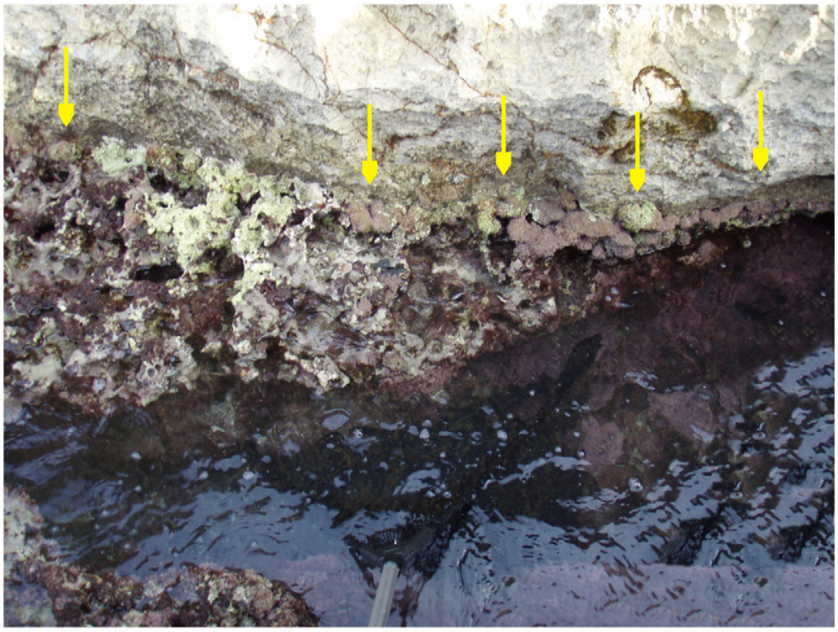

Fig. 7. Living thalli of *Lithophyllum byssoides* coralline algae along the upper limit of the algal rim on Nova Pošta, Vis Island.

the upper limit of the rim (Fig. 7), that is, up to the vertex of the recent notch (Figs. 4, 5).

The inner structure of the studied algal rims revealed the consolidated layers of dead thalli that are the result of deposition processes i.e. filing up of the interstices between fronds with a hardened sedimentary matrix. The core has a multilayered structure with numerous discontinuities. The lower surface of all the rims is strongly bioeroded by *Lithophaga* and boring sponges, and covered by the different species of shade loving algae.

6. Discussion

The thick and well-developed *Lithophyllum* rims point directly to the rising sea-level environment. Laborel et al. (1994) suggested that the building of a well-developed rim requires a near-stable or slowly rising sea-level, allowing a continuous superposition of new layers upon the dead core that buttresses and strengthens the rim. Too rapid sea-level rise would not allow the vertical development of the rim. Therefore, the presence of a thick and well-developed *Lithophyllum* rim generally corresponds to a gentle rise of relative sea-level. Consequently, the protruding morphology of the algal rims in the Central Adriatic area points to the slowing of sea-level rise, which started at around −1.0 m below the recent mean sea-level (MSL), when the algal rims began to develop.

The obtained ^{14}C dating results of the algal rims at particular depth on the islands of Vis, Ravnik and Biševo show that their growth was generally synchronous (Table 1; Fig. 6). Two periods of relatively stable sea-level relations have been observed: the first period between the 1400 cal yr BP and 1170 cal yr BP and the second, longer period, which started at around 610 cal yr BP and lasted till the 310 cal yr BP. These relatively stable periods are directly reflected particularly well in the algal rim morphology (two pronounced levels) on the islands of Vis and Biševo (Figs. 2–5). The lower and smaller level of algal rims (~60 cm below MSL) corresponds to the relatively stable period of ~200 years, while the larger and upper level of algal rims (~20 cm below MSL) corresponds to ~300 years of relatively stable period (Fig. 6).

The algal rims could be further related to the fossil notches (probably tidal) in the studied area (Fig. 8, b). The widespread well-developed notches can be found at around 30 ± 10 cm below MSL and sporadically at 70 ± 10 cm below MSL (Faivre et al., 2010b). Consequently, the notches could be correlated to the algal rim formations (Fig. 8) and can be explained by the phases of near stable sea-level conditions as well.

On the basis of algal rim morphology, their ^{14}C dating, and the tidal notch positions (depth below MSL), four distinct sea-level phases can be distinguished (Fig. 9) during the last 1500 years. The time will be expressed hereafter as calibrated age BC/AD to simplify comparison with other data (Table 1). The first period of relatively stable sea-level started at around 550 cal AD, which corresponds to the Dark Ages Cold Period (DACP). From around 770 till 1330 cal AD the rate of sea-level rise accelerated at ~0.71 mm/yr (Table 1), roughly corresponding to the Medieval Climate Anomaly (MCA) (also called Medieval Warm Period). That period was followed by the second relatively stable sea-level period which, according to our results in the studied area, started at around 1330 cal AD and lasted till around 1640 cal AD, coinciding with the coldest part of the Little Ice Age (LIA) period. The most recent phase is marked by a higher value of relative sea-level rise with the major impact on the biological systems still effective today, which is clearly documented by the abrupt change in the algal rims morphology on all three studied locations (Figs. 2–5; Fig. 7). Probably due to strong bioerosion of the youngest *Lithophyllum* rim upper level, it is currently hard to uncover the precise timing of transition from LIA to Current Warm Period (CWP) by ^{14}C dating.

On all the researched rims today, as described in the Results, regression dominates. This situation could clearly be connected with the recent acceleration of sea-level rise as mentioned by Laborel et al. (1994).

Guilcher (1953) found that the metabolism of the calcareous algae is considerably higher during winter. We noted that living thalli of *Lithophyllum byssoides* on the researched sites looked much healthier during winter in comparison with summer months. Although Laborel (1986) stated that *Lithophyllum* in warmer waters gradually loses its building abilities, we still do not know the temperature optima necessary for rim formation. Therefore, it is hard to say how much obviously cooler temperatures during these two relatively stable sea-level periods

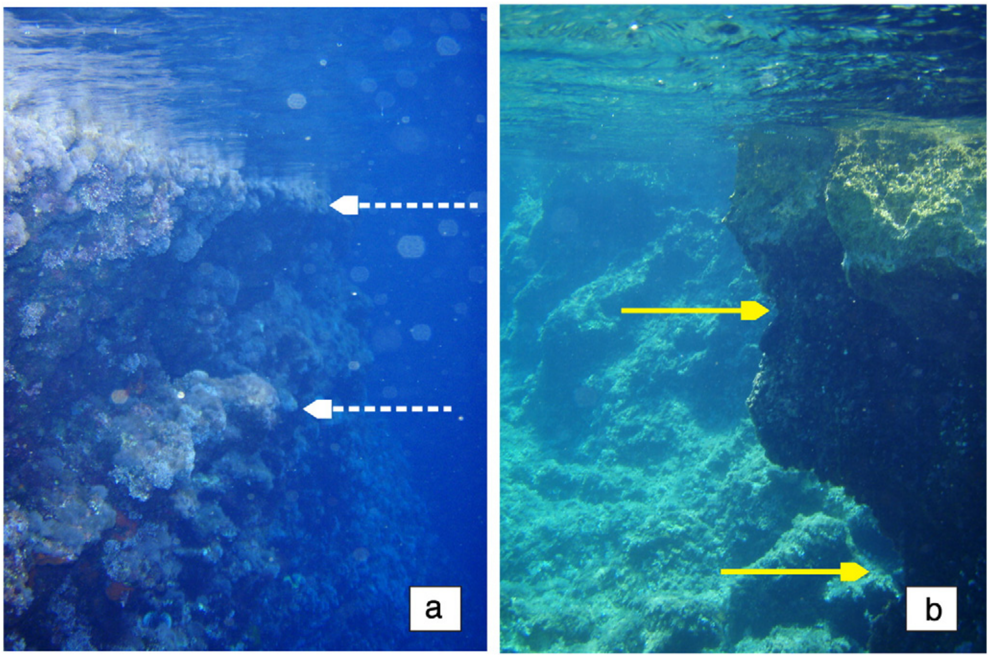

Fig. 8. Comparison between a) the two dominant levels of algal rim at Modra Špilja, Biševo Island and b) the submerged fossil notches, most probably tidal, on the Vis Island.

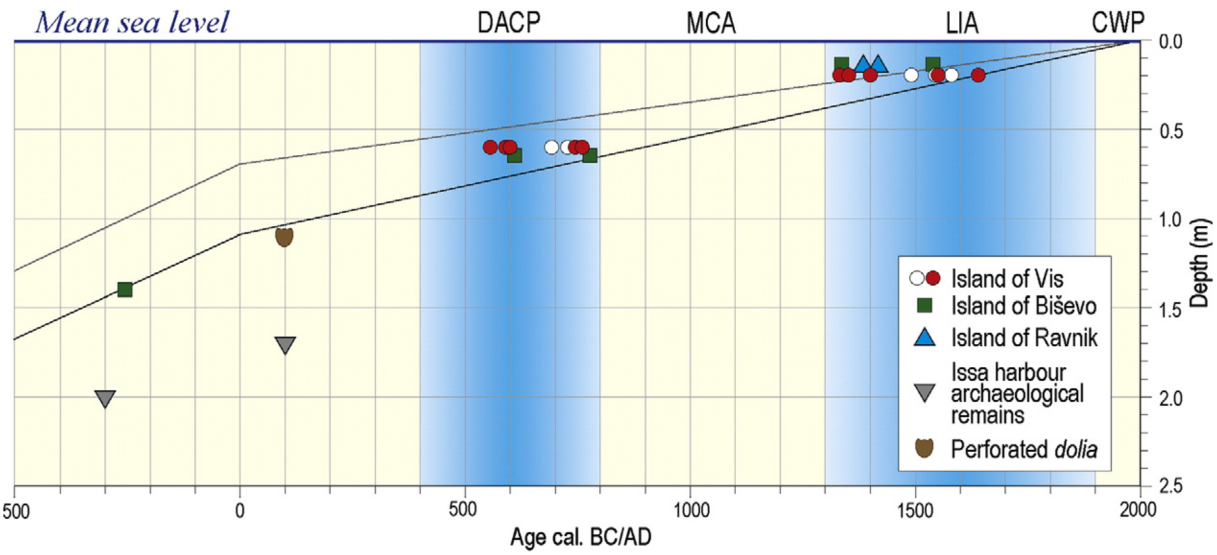

Fig. 9. Comparison between the predicted models of relative sea-level change for the Central Adriatic, black line – Lambeck et al. (2004), grey line – Lambeck and Purcell (2005), the ^{14}C dated algal rim samples from the islands of Vis, Ravnik and Biševo and different climatic periods in the last 1500 years: Dark Ages Cold Period (DACP), Medieval Climate Anomaly (MCA), Little Ice Age (LIA) and Current Warm Period (CWP); the onset of DACP and CWP by Hass (1996) and MCA by Trouet et al. (2009). Sea level reconstructed from the Issa harbour archaeological remains and perforated *dolia* (Faivre et al., 2010b) are also noted on the graph. Empty circles indicate results obtained with AMS technique.

that we found contributed to the rim building in the researched locations.

The obtained results were further compared with the local predictions derived from two glacio-hydro-isostatic models associated with the Last Glacial cycle (Lambeck et al., 2004; Lambeck and Purcell, 2005) (Figs. 6, 9), the second model (Lambeck and Purcell, 2005) includes also the Alpine deglaciation model. The accuracy of these predicted values is a function of the model parameter's uncertainties (of the earth response function and the ice load history).

As our results are in relatively good agreement with the curves, the assumption of almost stable tectonic conditions or weak subsidence could be proposed for the last 1500 years (Fig. 9). The records of sea-level change in the Central Mediterranean are mostly based on archaeological evidence that provides depth values for certain periods (e.g. for the Roman time) based on submerged fish ponds, piers or quays (Fouache et al., 2000; Lambeck et al., 2004; Fouache et al., 2005a, 2005b; Antonioli et al., 2007; Faivre et al., 2010a, 2010b). However, this kind of indicator could not provide data on sea-level fluctuations.

The four phases of the distinguished sea-level changes in the studied area for the last 1500 years generally agree with the Kemp et al. (2011) results based on salt-marsh sedimentary sequences from the US Atlantic coast where, between 850 and 1080 AD, the rate of sea-level rise increased to 0.6 mm/yr and lasted till around 1250 AD. The second change point, which happened between 1270 and 1480 AD, marked a return to stable or slightly negative sea-level until the end of the 19th century. Between 1865 and 1892 AD sea-level rise increased to a mean rate of 2.1 mm/yr (Kemp et al., 2011). Numerous records from the Atlantic coast of North America, the Gulf of Mexico and New Zealand (Gehrels et al., 2008) show stable or falling sea-level between 1400 and 1900 AD at the time of the Little Ice Age. A record from Connecticut (Donnelly et al., 2004) shows stable sea-level between 1300 and 1800 AD. All of the above indicates that sea-level changes in the central Adriatic area in the last 1500 years could also be consistent with the global temperature (climatic) variations.

Global temperatures over the European and North Atlantic sectors are known to have varied over the past 1500 years. Four climatic periods are generally distinguished which timing is every day more accurate. The DACP between ~400 and 700 AD (Hass, 1996) is well documented. MCA is approximately dated between 1080 and 1350 AD (Hass, 1996; Linge et al., 2001). Mann et al. (2009) recently defined MCA as having been in the 950–1250 AD period, while Trouet et al. (2009) defined this relatively warm period as between 800 and 1300 AD. The cold climatic interval, the LIA, has usually been dated from the middle of the 15th century to the 19th century (e.g. Mann et al., 1998). However, numerous recent records show that this period started earlier. Many records from the North Atlantic reveal that LIA commenced mainly between 1300 and 1400 AD (Andersson et al., 2003; Berstad et al., 2003; Eiríksson et al., 2006). The onset of the LIA at around 1350 AD has been suggested e.g. by Hass (1996), Sicre et al. (2008), Werner et al. (2011), the coldest temperatures occurring over the interval from 1400 to 1700 AD (Mann et al. 2009). After the LIA the warming trend is observed from 1900 AD at the onset of the Current Warm Period (CWP) (e.g. Hass, 1996; Antonioli et al., 2000–2003).

In the regional context, around the studied area, there is much evidence that the periods of rapid climate changes are generally synchronous. The available data for the 1.5 ka period are dispersed from Italy to Romania.

Proxy measures are often available for comparison from speleothem carbonate, yielding high-resolution palaeoclimatic data. The climate records from the alpine stalagmites from Spannagel Cave in Austria (Vollweiler et al., 2006) reveal similar timing of rapid climate change periods for MCA (1200–700 yr BP) and LIA (600–150 yr BP).

The analyses of a stalagmite from the Grotta Savi (Frisia et al., 2005) located at the SE margin of the European Alps in Italy also demonstrated that the cool phase (DACP) happened between 450 and 700 AD. The MCA, reconstructed by Mann and Jones (2003) as the 800 to 1400 AD period, is characterised by climate instability. The authors stated that the LIA stands out as one of the coldest periods of the Holocene, with estimated mean annual temperatures of ~1 °C cooler relative to today, the LIA being defined from 1450 to 1800 AD.

The study of a Holocene Italian speleothem in Grotta Verde in Sardinia based on variations in $\delta^{18}O$ ratios (Antonioli et al., 2000–2003) also revealed the MCA and LIA periods and that the LIA cooling started between the 1300 and 1400 AD.

Similar timing of rapid climate change periods is also found e.g. in the Eastern Carpathians, where Popa and Kern (2009) demonstrated that the LIA extended from 1370 to 1630 AD. This early LIA, or LIA I period, has also been observed by Johnston et al. (2010) in the Măgurici Cave of NW Romania where, after the MCA dated from 1049 to 1298 AD, the LIA started and lasted till 1647 cal AD, when the relatively milder climatic conditions returned.

The most appropriate data for use in comparison with our results comes from the Central and Southern Adriatic Sea — the closest locations to our study area. Studying the late Holocene climate variability from the set of sediment cores Piva et al. (2008) proposed the base of the LIA at around 550 yr BP. Their results overall define LIA from 582 yr BP till 110 yr BP. Within that period two main phases have been distinguished: the first period, LIA I, starting at 547 ± 97 yr BP, and the second, LIA II period, which is centred around 125 yr BP. According to this study the LIA was the coldest period in the Central and Southern Adriatic since 5500 yr BP.

These findings clearly correspond to our results. The relatively long cold period is marked by sea-level stabilisation due to which a significant growth of the upper level of the algal rim occurred at the onset of the LIA, around 1330 cal AD (Fig. 10). At the beginning of the CWP, the rims development stopped. This probably happened due to the acceleration of the sea-level rise and resulted in the abrupt change of the algal rim morphology (Figs. 7, 10).

Recent investigations propose general correspondence between climate records during the last two millennia in the wider context; e.g. Magny (2004) for the south-western Mediterranean region and central Europe. This global simultaneity is suggested by Trouet et al. (2009) who find a persistent positive NAO (North Atlantic Oscillation) during the MCA and a clear shift to weaker NAO conditions into the LIA.

Our study concludes on the rise of a relative sea-level of about 60 ± 10 cm since 1500 years ago in the studied area, which seems to be climatologically controlled. Thus our results cast new light on the sea-level of Vis Island during Antiquity, which was higher than previously reconstructed. This reconstruction was based on existing submerged archaeological remains of the Issa harbour (Fig. 9; Faivre et al., 2010b). Consequently, this means that the most of the upper level blocks of the submerged Issa quays are missing. From the other side, the perforated *dolia* found in situ (Gluščević, 2006; Pešić, 2008; Radić Rossi, 2008; Faivre et al., 2010b) perfectly fit in the new biologically defined sea-level, allowing them to function with the tide (−110 ± 25 cm) (Fig. 9).

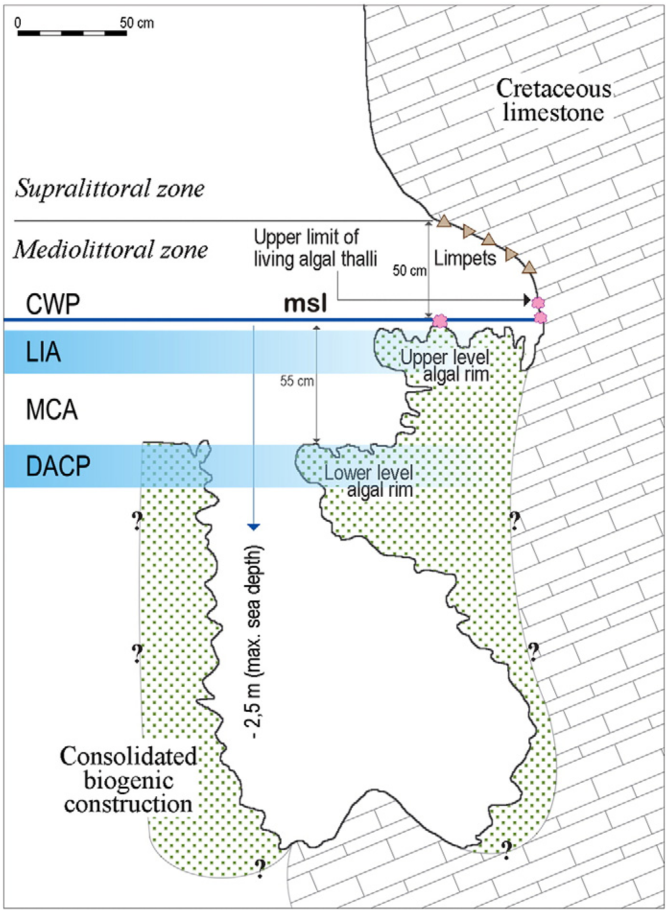

Fig. 10. Comparison between morphology of the algal rim on the Nova Pošta, Vis Island, and different climatic periods in the last 1500 years: Dark Ages Cold Period (DACP), Medieval Climate Anomaly (MCA), Little Ice Age (LIA) and Current Warm Period (CWP). The relation is shown on the profile 1. Position and upper limit of living *Lithophyllum* thalli are marked in the figure.

7. Conclusion

The study *of Lithophyllum* rims reveal four distinct phases of relative sea-level changes. As it is most likely that there is no significant tectonic subsidence during the last 1.5 ka in the studied area, the algal rim morphology also provides information about spatial and temporal ranges of climatic variations. Two cold periods with near stable sea-level relations coincided with the algal rims development, which was particularly stressed during the relatively long LIA period. During the two warm periods, the higher rates of sea-level rise are evident in the interruption of the algal rim growth. Therefore, the algal rim morphology seems to be in direct relation with the rate of relative sea-level change. Our results clearly demonstrate the relationship between biological sea-level markers and environmental conditions during the last 1.5 ka.

The 1.8 m wide upper levels of the algal rims developed during around 300 years of near stable sea-level. Lower level of the rims, around 0.5 m wide, probably developed during a shorter period of around 200 years. So, the width and size of the algal rims are generally in concordance with the length of the relatively stable sea-level periods. The rate of sea-level rise has direct impact on biological systems i.e. after it exceeds a certain rate, the *Lithophyllum* cannot build rims. Thus, our results also show the clear relative sea level acceleration in transition from LIA to CWP. Consequently, results obtained from marine biological indicators are very applicable for relative sea-level reconstruction and are also interesting for palaeoclimate estimations.

The records obtained with algal rim analyses for the Central Adriatic region seem to be reliable not only for the local analyses but they can also be used for the analyses of regional scale environmental changes, as the phases of relative sea-level changes in the studied area also coincide with the global climatic behaviour. Recent climate records in the wider context demonstrate a general correspondence between records during the last two millennia.

This research contributes to a better understanding of natural climate variability and sea-level changes in the Central Adriatic during the past 1500 years, as the knowledge of the sea-level variability during this period is limited, and the response to known climate deviations such as the Dark Ages cold period, Medieval Climate Anomaly and Little Ice Age was unknown. The presented data provide new findings of past sea-level variability that is essential for understanding current and future sea-level trends in the Central Adriatic.

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