ELSEVIER

Marine Geology 212 (2004) 21–33

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Submerged tidal notches in the Rijeka Bay NE Adriatic Sea: indicators of relative sea-level change and of recent tectonic movements

Čedomir Benac[a], Mladen Juračić[b,*], Tatjana Bakran-Petricioli[c]

[a]*Faculty of Civil Engineering, University of Rijeka, V. Cara Emina 5, HR-51 000 Rijeka, Croatia*
[b]*Department of Geology, Faculty of Science, University of Zagreb, Zvonimirova 8, HR-10 000 Zagreb, Croatia*
[c]*Department of Biology, Faculty of Science, University of Zagreb, Rooseveltov trg 6, HR-10 000 Zagreb, Croatia*

Received 15 July 2003; received in revised form 20 July 2004; accepted 3 September 2004

Abstract

The Rijeka Bay coast is formed predominately in carbonate rocks. Due to relatively sheltered position, processes of bioerosion dominate, while mechanical wave action has low impact.

Biological zone limits in Rijeka Bay are well expressed, and they reflect the local biological mean sea level (BMSL). Therefore, they were used as referent levels for measurement of submerged tidal notch position. These in situ biological indicators could be more useful than sea-level mareograph data.

Well developed tidal notches are permanently submerged and quite ubiquitous in the whole Rijeka Bay area; that is, they are situated in the infralittoral zone. They have elongated, asymmetric shape. Inasmuch as the roof top of the notches is well preserved, they were correlated with well defined biological zone limit [upper limit of white (WE) zone; sensu Schneider, J., 1976. Biological and inorganic factor in the destruction of limestone coast. Contributions to Sedimentology 6, 1–11].

Results of survey showed that, in most of the area, tidal notches are located 50–60 cm below BMSL. However, within the Bakar Bay, notches are from 103 to 115 cm below BMSL.

Regional occurrence of well preserved tidal notches at 0.5–0.6 m below BMSL indicates their possible coseismic origin (rapid tectonic subsidence).

Deeper positions of tidal notches in the northeastern part of Rijeka Bay and within Bakar Bay indicate enhanced subsidence of that zone which is assumed to be the most seismotectonicaly active.

Keywords: tidal notch; sea level change; biological mean sea level; subsidence; Croatia

---

1. Introduction

Marine notches are groove-like features that are formed in rocky coasts and are best developed in

---

* Corresponding author. Tel.: +385 1 460 6648; fax: +385 1 455 4960.

E-mail address: mjuracic@geol.pmf.hr (M. Juračić).

0025-3227/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2004.09.002

limestones. They develop parallel to the sea level by combination of physical and biological abrasion, and by chemical and biological dissolution (Kershaw and Guo, 2001). However, a subgroup of marine notches, the tidal notches, develop primarily by bioerosion within the tidal zone (i.e., intertidal, eulittoral, midlittoral, or mediolittoral) on relatively sheltered limestone coasts with small tidal range (Pirazzoli, 1986).

Bioerosional activities by a variety of marine organisms include biochemical and biomechanical processes (Griggs and Trenhaile, 1997). Characteristic destructional relief forms developed on limestone coasts as a result of bioerosion (biokarst forms) are arranged according to bionomic zones and have good fossilisation potential (Schneider and Torunski, 1983). Tidal notches are considered to be one of the best indicators of the local sea level change (Pirazzoli, 1986).

Intertidal zone (mediolittoral) in the Adriatic as well as in the Mediterranean is very narrow due to microtidal character of these two seas. Despite its narrowness, on the carbonate coasts, such as those of the eastern Adriatic, distinct biological zones can be observed on rocky shores (Pérès and Picard, 1964; for northern Adriatic see Schneider, 1976; Torunski, 1979), and they reflect the long time average moisture conditions. The distinctiveness of these zones is primarily based on colour due to different species of cyanobacteria and their response to particular environmental conditions (Schneider, 1977; Golubić and Schneider, 1979; Schneider and le Campion-Alsumard, 1999). As early as 1932, Ercegović (1932), in his detailed research of cyanobacteria in this zone on the eastern coasts of the middle Adriatic, reported colour zonation and indicated that lithophitic cyanobacteria are the main component of intertidal living community where they play an important role in rock destruction.

The upper limit of the biogenic notches coincides with a steep drop in the erosion rate at the upper limit of the habitat of *Patella coerulea*, while the lower limit is characterized by the first appearance of infralittoral species such as sea urchins *Paracentrotus lividus* and *Arbacia lixula*, bivalve *Lithophaga lithophaga*, clionid sponges, etc. (Schneider, 1976; Torunski, 1979; Schneider and Torunski, 1983). The upper mediolittoral zone has whitish appearance due to the colour of certain endolithic cyanobacterial species (e.g., *Mastigocoleus testarum*, light gray) as well as due to intense grazing by gastropods (primarily *Patella* spp., *Monodonta turbinata*), which prevents settlement of epilithic cyanobacteria. Also, irregular crusts of rhodophyte from genus *Lithophyllum*, which are sometimes present in this zone, add to the whitish appearance during periods of emersion. Schneider (1976) named it white (WE) zone. While the lower part of mediolittoral is in western Mediterranean and middle Adriatic characterized with the rim-building rhodophyte *Lithophyllum lichenoides*, in the northern Adriatic, it is characterized by dense populations of the phaeophyte *Fucus virsoides* (Pérès and Picard, 1964; Gamulin-Brida, 1974). In case when sea urchins remove the macrophytes, that zone has its degraded aspect, and due to the longer period of immersion as well as to the colour of lithophitic cyanobacteria, it appears green. Torunski (1979) named that zone green (GN) zone. The upper limit of the green zone, i.e., the border between the WE and GN zones, coincides with the mean sea level (MSL), while the lower limit of GN zone lacks distinct phenomenological features (Torunski, 1979). Therefore, biological zones in the intertidal zone (mediolittoral) in the northern Adriatic have specific colour, on the basis of which they can be recognized and distinguished without specialistic knowledge about species which live in them.

In the northern part of the Croatian Adriatic coast, a well developed tidal notch below mean sea level has already been recognized. Pirazzoli (1980) measured the tidal notches on two locations on the Lošinj Island, on one location in the Vinodol Channel and on two locations in the Velebit Channel. He reported that they are U- to V-shaped, and that the retreat point was approximately 0.6 m below mean sea level (MSL).

Tidal notches that are U-shaped and are fully developed only on very steep limestone coasts have already been known from the Kvarner area (Benac, 1992).

Benac and Juračić (1998) correlated U-shaped tidal notches at approximately 0.6 m below MSL, and U- to V-shaped notches at 18-m depth, with Adriatic sea level changes during the Holocene. Fouache et al. (2000) described tidal notches on Rab and Pag Islands and on the Velebit Channel coast, and they connected their position with recent sea level rise.

In the broader Mediterranean region, a lot of research on tidal notch formation has been performed, and use of tidal notches in reconstructing sea level changes has been documented (e.g., Sartoretto et al., 1996; Pirazzoli, 1986, 1996; Pirazzoli et al., 1996a; Kershaw and Guo, 2001). However, most examples from central and eastern Mediterranean reported in the literature indicate Late Holocene rapid coseismic uplift of the coastal zone due to the strong seismotectonic activity (Pirazzoli et al., 1994a, 1994b, 1996b, 1999; Laborel and Laborel-Deguen, 1994; Rust and Kershaw, 2000; Stiros, 2001; Stiros et al., 1994, 2000; Kershaw and Guo, 2001).

2. Investigated area

The area of Rijeka Bay is approximately 450 km^2, and the length of its coast is 115 km. The Bay is quite sheltered (Fig. 1A,B). Eastern (Istrian) coast, northern coast in the Rijeka area, and southern (northern part of Cres Island) coast are not indented, whereas on northeastern and eastern coasts of Rijeka Bay, there are Bakar, Omišalj, and Malinska bays.

In the Rijeka Bay, weak to moderate winds prevail with speeds up to 10 ms^{-1}, whereas storm winds with speeds >30 ms^{-1} are rare (Fig. 1C; Benac, 1992).

Tides in the Adriatic are of semidiurnal type. In the Rijeka Bay area, tidal range is small: average amplitude is approximately 30 cm (data for Bakar Mareograph). However, sea level fluctuations are influenced also by atmospheric conditions. During north–northeast wind (Bora) and high atmospheric pressure, the sea level may be significantly lowered, and during south–southeast winds (Sirocco) and low atmospheric pressure, the sea level can rise more than 1.1 m above MSL. Calculated extreme sea level span in 100 years is more than 2 m (from −79 to +124 cm from MSL; M. Pršić, personal communication).

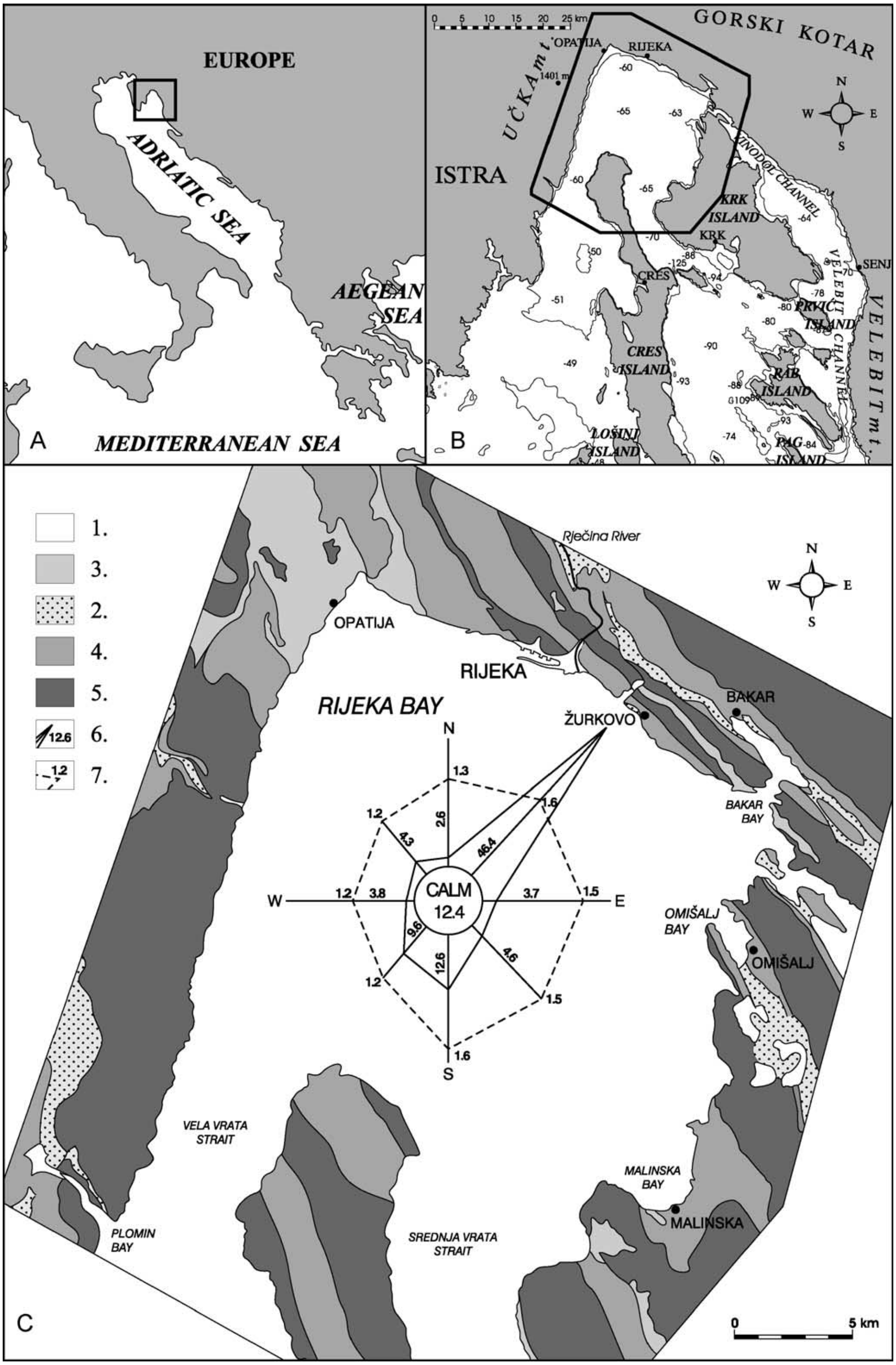
The Rijeka Bay area (Fig. 1) as a part of the Kvarner area in the northern Adriatic had a very dynamic morphologic evolution due to intensive tectonic activity and glacioeustatic sea level changes (Colantoni et al., 1979; Correggiari et al., 1996; Benac and Juračić, 1998).

The Rijeka Bay coasts are formed in Cretaceous and Paleogene carbonate and clastic sedimentary rocks. Carbonate rocks (limestones, dolomites, and carbonate breccias) predominate in the coastal area, whereas flysch sediments are of subordinate importance (Fig. 1C). Cretaceous and Paleogene rocks on land are partly covered by Quaternary sediments. Contrary to the steep rocky coast, the Rijeka Bay bottom is very flat at approximately 60-m depth and covered with Recent lithogenous muddy sediments (Juračić et al., 1999).

The prevailing limestones are quite pure (92–99% of calcite). However, dolomites and partly dolomitic limestones are also present (Benac and Juračić, 1998).

Tectogenesis of the Kvarner region reflects the subduction of Adriatic carbonate platform beneath the Dinarics. The main geodynamic processes have been subdivided in two time-defined phases: the Eocene (Pyreenean) movements, together with the subsequent ones, caused the formation of the folded and faulted structures, and the final shape was obtained by tectonic reactivation since the Upper Pliocene (Blašković, 1999). An uneven intensity of subduction of the “Istria” and “Adriaticum” geodynamic units beneath “Dinaricum” geodynamic unit (sensu Herak, 1986; units I, II, and III in Fig. 2 respectively) has been postulated. Therefore, units I and II are divided by the horizontal dextral Kvarner fault. That caused the sinusoidal twist of structures into the meridional strike in the western part of the Kvarner region (Prelogović et al., 1995) and a helicoidal fault system in the Vinodol Valley (Blašković, 1997). The main tectonic structures strike northwest–southeast (Fig. 2). The movement and the subduction of the “Adriaticum” (II in Fig. 2) towards north–northeast is presumed in such a way that, in the broader zone, horizontal displacement predominates, whereas a narrow zone, including the Vinodol Valley and Bakar Bay, is characterized by more pronounced vertical movements, causing maximal subsidence. The most intensive tectonic movements occurred during the Quaternary period, subsequent to the deposition of the upper Pliocene sediments (Blašković, 1999).

Geomorphologic characteristics of the relief and terra rossa distribution (Benac and Durn, 1997) and high seismicity indicate very active recent tectonic activity in the Kvarner area (Del Ben et al., 1991; Prelogović et al., 1995; Herak et al., 1996) and


A
EUROPE
ADRIATIC SEA
AEGEAN SEA
MEDITERRANEAN SEA
B
0 5 10 15 20 25 km
GORSKI KOTAR
UČKA mt.
1401 m
OPATIJA
RIJEKA
ISTRA
VINODOL CHANNEL
KRK ISLAND
KRK
CRES
CRES ISLAND
LOŠINJ ISLAND
SENJ
PRVIĆ ISLAND
RAB ISLAND
PAG ISLAND
VELEBIT CHANNEL
VELEBIT mt.
N
W
E
S
-60
-65
-63
-60
-65
-64
-70
-50
-88
-125
-94
-70
-51
-78
-80
-80
-90
-49
-93
-88
-109
-93
-74
-84
-48
C
1.
3.
2.
4.
5.
12.6 6.
1.2 7.
Rječina River
OPATIJA
RIJEKA
RIJEKA BAY
ŽURKOVO
BAKAR
BAKAR BAY
OMIŠALJ BAY
OMIŠALJ
MALINSKA BAY
MALINSKA
VELA VRATA STRAIT
PLOMIN BAY
SREDNJA VRATA STRAIT
N
S
W
E
CALM 12.4
1.3
2.6
1.6
46.4
1.2
4.3
1.2
3.8
3.7
1.5
9.6
12.6
4.6
1.2
1.5
1.6
0
5 km

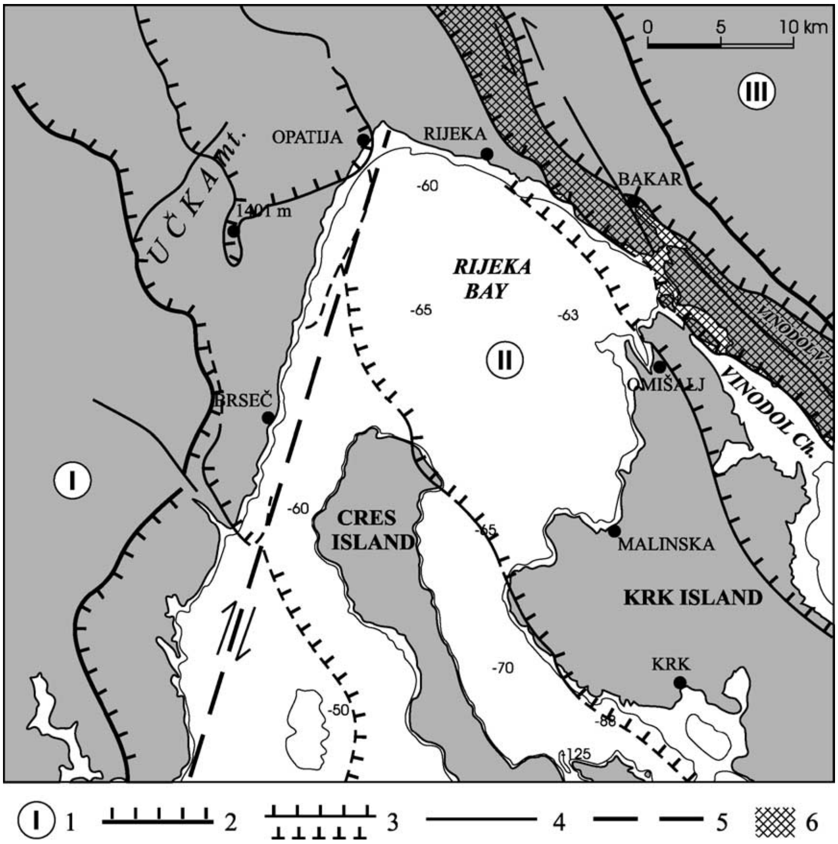


Fig. 2. Structural-tectonic map of Rijeka Bay area (simplified and modified; after Prelogović et al., 1995). 1—regional geodynamic units: I—Istria, II—Adriaticum, III—Dinaricum; 2—regional reverse faults bordering geodynamic units; 3—reverse faults and presumed fault sections; 4—faults without surely defined character; 5—horizontal dextral Kvarner fault; 6—the zone of maximal recent subsidence (Vinodol Valley, Bakar Bay and northeastern coast of Rijeka Bay; Blašković, 1999).

especially in the Bakar Bay and Vinodol Valley (Blašković, 1999).

3. Methods of investigation

During a detailed survey of the Rijeka Bay coast, including Bakar and Omišalj Bays, zones with relatively compact carbonate rocks were selected for measurements. On these rocky parts of the coast, a detailed search has been performed by snorkelling and scuba diving in order to find tidal notches. Geographic locations of 32 measured notches are reported as Gauss–Krueger coordinates with an accuracy of ±25 m.

Measurements were done according to Pirazzoli (1986). Biological zone limits in Rijeka Bay are well expressed, reflecting the local BMSL (biological mean sea level, see Discussion; Figs. 3 and 4). In the Rijeka Bay, in the intertidal zone (mediolittoral), two distinct zones could be recognized: the white (WE) zone (Schneider, 1976) and, below it, the green (GN) zone (Torunski, 1979; see Introduction). Measurements of the tidal notch position were done

---

Fig. 1. (A) Location map of Kvarner region. (B) The research area (Rijeka Bay) and the locations mentioned in the text. (C) Lithology map of the Rijeka Bay coast and hydrographical conditions in the Bay. 1—Quaternary and Recent sediments; 2—Eocene–Oligocene carbonate breccias; 3—Eocene flysch; 4—Cretaceous and Paleogene pure limestones; 5—Cretaceous dolomites and dolomitized limestones; 6—wind direction mean frequency distribution (in %); 7—sea state.

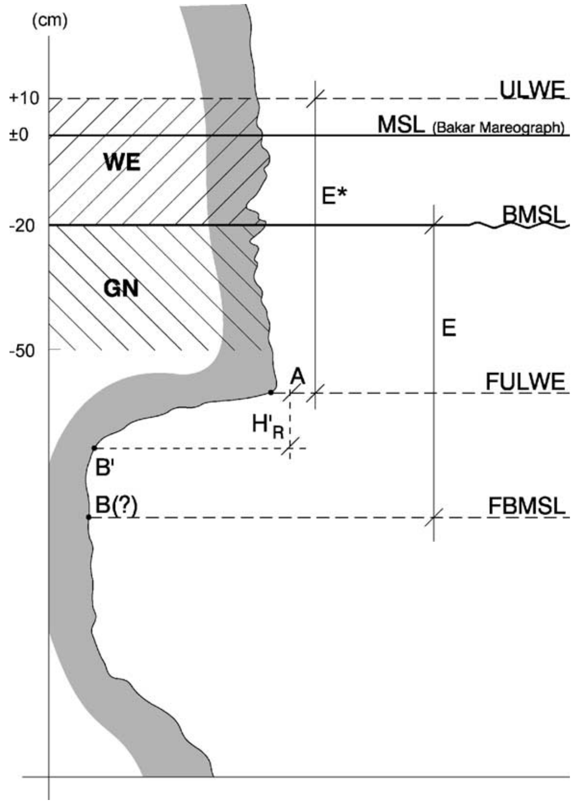


Fig. 3. Submerged tidal notch profile with correlation between biological zone limits, water level marks, and notch points. Due to ill defined retreat point B(?) of the notch the roof top, A was used as a measurement point. The upper limit of WE zone (ULWE, which is biologically and phenomenologically defined) corresponds to the roof of recent tidal notch formation (Schneider, 1976). WE—white zone (Schneider, 1976); GN—green zone (Torunski, 1979); ULWE—upper limit of WE zone; FULWE—former upper limit of WE zone; A—point of roof top of the notch (Pirazzoli, 1986); B—retreat point (Pirazzoli, 1986); B'—apparent retreat point; H'_R—apparent roof height; E—elevation (Pirazzoli, 1986); E^*—measured elevation; MSL—hydrographic mean sea level (Bakar Mareograph); BMSL—biological mean sea level; FBMSL—former biological mean sea level.

from the upper limit of the WE zone to the roof top of tidal notch (point A, Pirazzoli, 1986). The white zone is usually clearly visible. However, on the exposed coasts, the upper limit of the WE zone is expanded, and in those cases, the upper limit of the GN zone, which coincides with BMSL, was used. The vertical distance between the upper WE and GN zone limits in Rijeka Bay was approximately 30 cm, which is in accordance with the average tidal amplitude (18 year mean range of high and low water is 47 cm, whereas the range of high and low water during the spring tides is 61.7 cm; Bakar Mareograph, M. Pasarić, personal communication). Metal bars with centimeter division and in-built spirit level were used for measurements in order to achieve better vertical and horizontal accuracy. Only tidal notches with horizontal extension larger than 1 m were measured. On each location, several measurements were performed, and the means are reported in Results. Relatively often, there were visible fractures in the rock, which deformed the tidal notch, and by multiple measurements, the accuracy was improved.

In order to determine the relationship between hydrographic MSL as recorded at Bakar Mareograph and BMSL (sensu Schneider, 1976), a set of sea-level measurements at Žurkovo were performed and compared to the Bakar Mareograph data (Table 1; position of measurement locations indicated in Fig. 1C).

4. Results

Preliminary results suggesting that BMSL in the Rijeka Bay is 20 cm below hydrographic MSL (as recorded at Bakar Mareograph) are shown in Table 1.

The roof of a well expressed tidal notch was always at least 20 cm below recent BMSL. Tidal notches had asymmetric shape, height (H) between 55 and 330 cm, and depth (D_R) between 18 and 150 cm (Table 2; Fig. 5). Characteristic profile of the tidal notch (Fig. 6) indicates the complexity of determination of retreat point (B; Pirazzoli, 1986). Therefore, the apparent retreat point B' (Fig. 3) was introduced as a characteristic measurable point. Measurement from B' to the roof top (point A) is reported as the roof height (H_R') in Table 2; it was from 0 to 20 cm.

On the west coast of Rijeka Bay (Istria Peninsula), the position of tidal notches was between 50 and 57 cm below BMSL. On the northeast coast, west of Rječina River mouth, the position of notches was 52 to 56 cm, while east from Rječina River mouth, the position was from 60 to 75 cm below BMSL. Within the Bakar Bay, it was between 103 and 115 cm. Southeast from the entrance to the Bakar Bay, the position of notches was between 55 and 75 cm, and on the east coast of the Rijeka Bay (on the Krk Island),

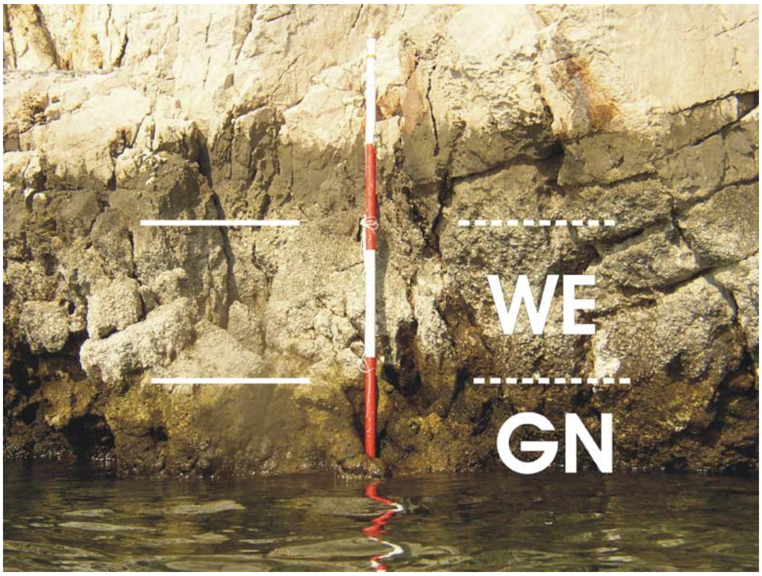


Fig. 4. Vertical biozonation in Cretaceous rudist limestones on the northeastern coast of Rijeka Bay, used here as a sea level indicator. Local tidal range is approximately 0.5 m (location *N*=501250; *E*=546700; Photo: C. Benac, Feb. 2003).

the actual position of the tidal notch was between 50 and 60 cm below BMSL (Fig. 5; Table 2).

5. Discussion

The sea level at a given place and time is not a measurable entity but the statistical result of highly complex movements of the water surface under the influence of a number of factors: tides, winds, atmospheric pressure, currents, shoreline morphology, etc. Therefore, the use of mareograph data in research of sea level changes is insufficient, and it is much better to use biological mean sea level (BMSL) based upon biological zonation in the intertidal zone, which is the measure of long-term average moisture conditions (Laborel, 1986). In accordance with this, the border between white (WE) zone and green (GN) zone used here, which actually corresponds to the vertex of the tidal notch, should be considered as BMSL. Laborel and Laborel-Deguen (1994) defined BMSL as the limit between mediolittoral and infralittoral zones because they were able to connect that limit to certain fixed species with a narrow depth range located just over or just under it. In our research, we could not use the usual BMSL indicator rhodophyte *L. lichenoides*. This species is present in the mediolittoral zone of the Rijeka Bay, but it does not build rims like in southern Adriatic (Zavodnik and Zavodnik, 1985).

BMSL does not necessarily correspond to the hydrographic mean sea level (MSL) (Laborel, 1986; Stiros et al., 1994). Our attempt to correlate hydrographic MSL in the area and BMSL indicates that actual BMSL is approximately 20 cm below hydrographic MSL in Rijeka Bay (Table 1). Further research is needed in order to understand the relationship between BMSL and hydrographic MSL.

The mediolittoral zone in carbonate rocks (i.e., zone of rapid tidal notch development due to maximum abundance of grazing organisms feeding primarily on lithophitic cyanobacteria) is well defined in the Rijeka Bay, although recent tidal notches were not observed in it. In future research, this phenomenon as well as biodestruction/bioconstruction ratio in the intertidal zone in the Rijeka Bay remains to be elucidated. The mediolittoral zone is approximately 60-cm high (Fig. 4), and within it, recent bioerosion is forming irregular pits 5- to 10-cm deep.

On the walls of boreholes produced by endolithic cyanobacteria, substrate grains become loosened by biological corrosion. The grazers feed on the epilithic and endolithic cyanobacteria together with the loosened carbonate grains (Schneider, 1976).

Table 1
Relationship between hydrographic mean sea level (MSL, calculated from 18 years of measurement at Bakar Mareograph, M. Parsić, personal communication) and biological mean sea level (BMSL, border between WE and GN zones sensu Schneider, 1976 and Torunski, 1979—see text for explanation) in Rijeka Bay

Date	Time	Sea level in Bakar reduced to hydrographic mean sea level (cm)	Sea level in Žurkovo reduced to biological mean sea level (cm)	Difference between HMSL and BMSL (cm)
05 11 03	09:25	9	−6	15
05 11 03	10:00	6	−15	21
05 11 03	13:05	−17	−40	23
05 11 03	13:45	−20	−43	24
05 11 03	17:05	−5	−23	18
06 11 03	09:00	11	−5	16
06 11 03	11:16	−12	−34	22
06 11 03	15:40	−11	−27	16
06 11 03	17:10	−2	−18	16
21 11 03	05:50	24	3	21
21 11 03	08:25	10	−13	23
21 11 03	13:00	−36	−56	20
29 11 03	12:55	17	−2	19
			Average	19.6
			Median	19.9

This process of biogenic carbonate removal is synergistic and has cumulative effect. Cyanobacteria, as light dependent photosynthetic organisms, are limited to relatively thin surface layer of carbonate rock. Removal of a thin layer of substrate results in a deeper light penetration, and therefore, the continuation of algal penetration depends on the continuous removal of rock by grazers (Schneider, 1977; Golubić and Schneider, 1979; Schneider and Torunski, 1983). Dalongeville et al. (1994) experimentally showed that littoral bioerosion exceeds bioconstruction on naturally colonized rock containing endolithic microorganisms, covered by algal turf. On the other hand, increased macroalgal abundance in the intertidal zone corresponds with reduction in bioerosion (Naylor and Viles, 2002).

In the eastern part of the northern Adriatic, the most pronounced part of notch (i.e., the vertex) developed at the limit between the white (WE) zone and the green (GN) zone, around the mean sea level where population densities of *P. coerulea* (species which had by far the highest abrasion potential) were the highest (Torunski, 1979). Bioerosion rates estimated for the white zone was 0.7 mma^{-1} and for the green zone was 0.9 mma^{-1}.

Although tidal notches at the recent sea level were not observed at the coasts of the Rijeka Bay area, notches with well developed roof top are quite ubiquitous in the infralittoral zone (Fig. 5). They have irregular elongated shape and appear to be similar to the types “e” and/or “i” notches according to Pirazzoli (1986) (our Fig. 6). Their height was up to several times larger than the recent tidal range (Table 2; Fig. 6). Therefore, the position (elevation) of the retreat point (point B after Pirazzoli, 1986) of the notches could not be compared. Inasmuch as the upper limit of the WE zone corresponds to the roof of the recent tidal notch formation (Schneider, 1976), we consider the distance E^* (Fig. 3), between the upper WE zone limit and the well defined roof top of the notch (point A, Pirazzoli, 1986), as the most reliable distance for measurement. For a formation of an almost horizontal roof, quite a long time with stable relative sea level was necessary. We also presume that the tidal range in the Rijeka Bay has not changed drastically in the last few millennia due to the fact that the shape of the Rijeka Bay and the Adriatic basin has not changed substantially (Benac and Juračić, 1998). Therefore, we argue that the distance between the upper WE zone limit and the roof top of the notch corresponds to the distance between the recent BMSL and the former BMSL during the formation of the notch (distance/elevation E; Fig. 3).

Our results indicate the existence of a pronounced tidal notch in the wider Rijeka Bay area. In the largest part of the area, this notch is located 50–60 cm below the BMSL. This is in accordance with earlier results obtained along the larger part of northeastern coast of the Adriatic Sea (Schneider, 1976; Torunski, 1979; Pirazzoli, 1980; Fouache et al., 2000). The results are similar, although the former authors measured the elevation E, while we measured E^* (Fig. 3).

In order to explain the elongated shape of the notches, their excellent preservation (especially the notch roofs), and their present location, we propose that there was a slow relative gradual change (rise) of the sea level prior to the quick tectonic (coseismic?) subsidence.

Fouache et al. (2000) suggested that it took at least 500 years in Roman antiquity to form a 50-cm-deep

Table 2
Location and measurements of tidal notches on 32 locations in the Rijeka Bay (see also Fig. 5)

No. of measured point	Gauss–Krueger coordinates		Coast slope	Lithology	Geological age	Tidal notch measures (cm)			
	N	E				E[a] (vertical position)	H'_R[b] (roof height)	D (notch depth)	H (notch height)
1	50 00 34	54 39 36	75°	Limestone	$K_2^{1,2}$	−57	10	70	200
2	50 04 60	54 40 90	90°	Limestone	$K_2^{1,2}$	−55	8	65	260
3	50 10 72	54 42 06	45°	Dolmitized limestone	$K_2^{1,2}$	−55	0	150	170
4	50 14 00	54 43 03	80°	Dolmitized limestone	$K_2^{1,2}$	−56	10	55	230
5	50 15 95	54 43 37	35°	Limestone	$K_2^{1,2}$	−50	20	120	70
6	50 19 65	54 45 12	80°	Limestone	K_1	−56	10	60	210
7	50 23 30	54 48 06	45°	Limestone	K_1	−52	10	46	60
8	50 22 67	54 49 47	40°	Carbonate breccia	E_3Ol_1	−55	8	40	55
9	50 22 65	54 50 26	40°	Carbonate breccia	E_3Ol_1	−55	10	50	58
10	50 19 65	54 58 07	80°	Rudist limestone	$K_2^{2,3}$	−75	15	43	330
11	50 19 28	54 58 55	80°	Rudist limestone	$K_2^{2,3}$	−77	20	50	205
12	50 17 76	54 60 20	70°	Rudist limestone	$K_2^{2,3}$	−75	8	56	170
13	50 17 15	54 60 64	90°	Rudist limestone	$K_2^{2,3}$	−67	10	60	190
14	50 16 80	54 61 01	40°	Rudist limestone	$K_2^{2,3}$	−70	15	60	60
15	50 16 14	54 62 42	70°	Rudist limestone	$K_2^{2,3}$	−70	20	80	120
16	50 15 44	54 66 38	60°	Rudist limestone	$K_2^{2,3}$	−105	10	25	275
17	50 15 38	54 66 55	60°	Rudist limestone	$K_2^{2,3}$	−103	10	80	190
18	50 15 15	54 67 26	45°	Rudist limestone	$K_2^{2,3}$	−115	5	45	60
19	50 15 11	54 66 25	70°	Dolmitized limestone	$K_2^{1,2}$	−75	10	90	80
20	50 13 50	54 66 01	70°	Carbonate breccia	$K_{1,2}$	−62	7	30	105
21	50 13 25	54 66 37	60°	Carbonate breccia	$K_{1,2}$	−57	7	30	55
22	50 12 95	54 66 65	45°	Dolmitized limestone	$K_2^{1,2}$	−55	10	54	90
23	50 11 90	54 66 84	45°	Dolmitized limestone	$K_2^{1,2}$	−62	5	18	82
24	50 12 03	54 65 48	70°	Foraminiferal limestone	Pc_3E_1	−65	5	40	120
25	50 08 66	54 65 07	30°	Foraminiferal limestone	Pc_3E_1	−57	10	40	60
26	50 09 43	54 64 92	80°	Foraminiferal limestone	Pc_3E_1	−60	10	60	180
27	50 02 90	54 64 63	40°	Limestone	$K_2^{1,2}$	−58	8	40	60
28	50 00 45	54 63 20	80°	Foraminiferal limestone	Pc_3E_1	−60	10	45	120
29	50 00 01	54 63 25	80°	Rudist limestone	$K_2^{2,3}$	−55	10	120	155
30	49 99 40	54 63 16	75°	Rudist limestone	$K_2^{2,3}$	−55	10	120	120
31	49 97 07	54 61 35	80°	Foraminiferal limestone	Pc_3E_1	−56	10	45	120
32	49 94 64	54 56 28	45°	Limestone	$K_2^{1,2}$	−63	10	40	60

[a] Vertical position (elevation) of the notch was measured from the upper limit of the white zone (WE; Schneider, 1976) to the roof top (point A; Pirazzoli, 1986; see Fig. 3).

[b] Apparent roof height, height between roof top (A) and apparent retreat point (B') (see Fig. 3).

notch found on submerged Roman jetties and at other shores in the northern Adriatic. The well preserved notch, on the other hand, presumes a rapid rise of the MSL. Already, Pirazzoli (1980) inferred that the submersion of the notches on various spots along the North Dalmatian shore took place after the Roman antiquity and suggested that the submersion had seismic origin. Fouache et al. (2000) opened the question whether the notches observed at the same depth (0.5–0.6 m) in Istria, on the North Dalmatian

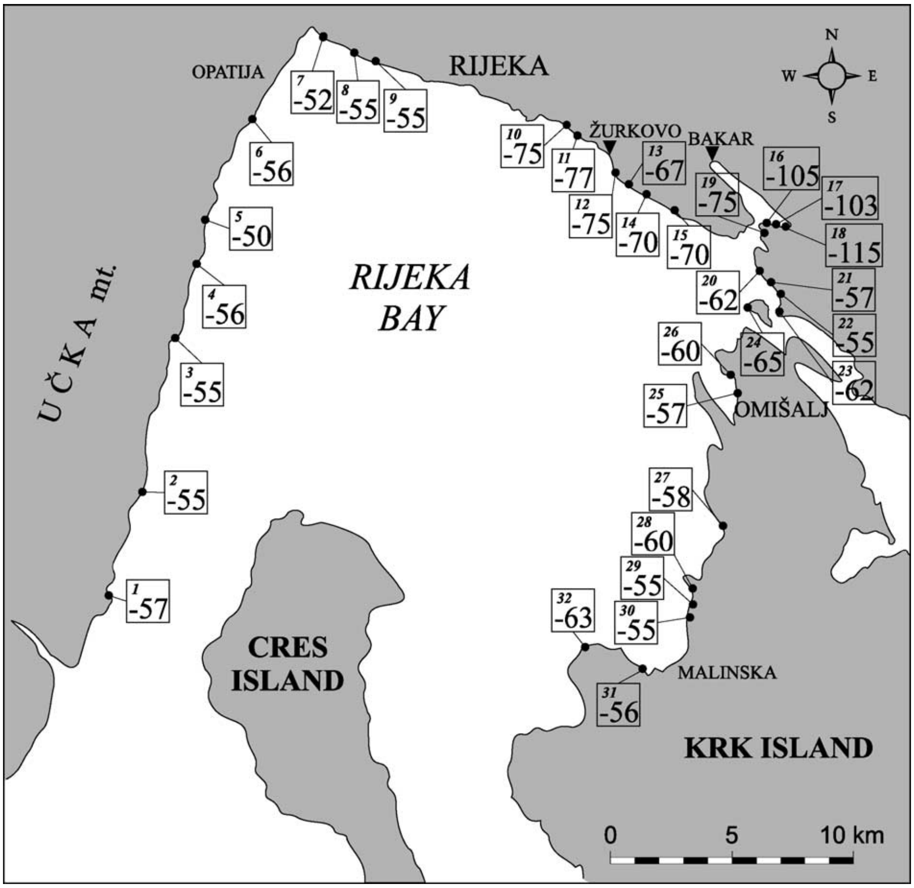


Fig. 5. Location and vertical position (negative elevation, cm) of tidal notches in the Rijeka Bay (see also Table 2).

(Kvarner) islands, and on the eastern edge of Velebit range mean that there was a particular quick eustatic rise or a tectonic subsidence (necessarily on a regional scale).

However, contrary to most of our results and to literature data, well preserved tidal notches in the northeastern part of Rijeka Bay and in Bakar Bay are distinctively deeper (i.e., 67–115 cm below BMSL; Table 2; Fig. 5).

Given the structural framework of the area, consisting of northwestern to southeastern striking, east-dipping thrust sheets (Fig. 2), and that points 16–18 are located on the footwall of the reactivated Vinodol thrust, we propose that reactivation of this thrust led to higher amplitude subsidence in the Bakar Bay. This is consistent with the requirement of the elastic dislocation theory (e.g., Kontogianni et al., 2002) and with the long-term tectonics of the area (subsidence of the Bakar Bay–Vinodol Valley; Blašković, 1999). Coastal data therefore provide evidence of reactivation of this thrust, most likely after the drowning of the notches farther southwest, as the absence of signs of a second notch reveals.

An open question remains: when did this presumed fast regional subsidence occur? It must have happened after Roman times because the deep notches have been found also on Roman jetties (Fouache et al., 2000). A potential trigger could have been one of the earthquakes connected with the presumed 4th–6th century strong paroxysmic seismicity, which resulted with tectonic uplifts of unprecedented scale in the eastern Mediterranean (Pirazzoli et al., 1996b; Stiros, 2001). Kišpatić (1891) mentioned a very strong

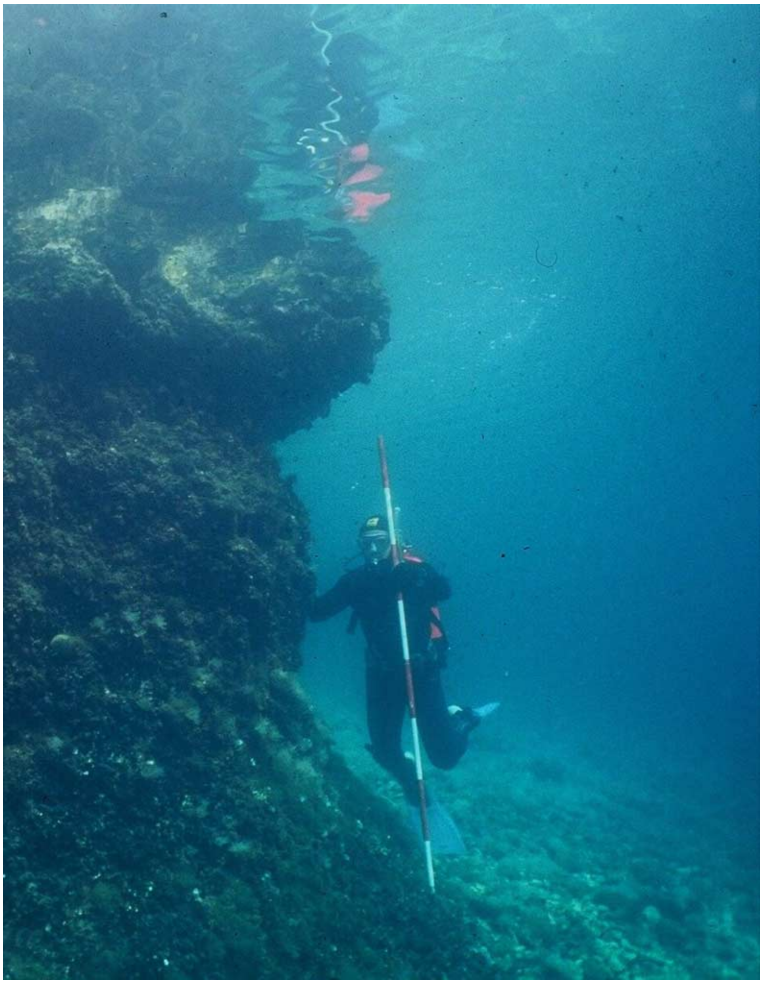


Fig. 6. Tidal notch formed in Cretaceous rudist limestones on the northeastern coast of Rijeka Bay, the roof is 0.37 m below BMSL, local tidal range is approximately 0.5 m (location 13, *N*=501715; *E*=546064; Photo: D. Frka, Sept. 1998).

earthquake, presumably in A.D. 361, which drowned the Roman town Cissa on Pag Island (southeast of Rijeka Bay in the Kvarner region) and was also felt in a large part of the Mediterranean (Shebalin et al., 1974).

6. Conclusions

The mediolittoral zone in carbonate rocks in the Rijeka Bay, which is approximately 60-cm high, is biologically well defined. Although recent tidal notches were not observed in the zone, irregular pits 5–10-cm deep are forming within it. Lack of tidal notches at the recent sea level in the Rijeka Bay remains to be elucidated.

Well developed submerged notches are quite ubiquitous in the Rijeka Bay. They have elongated asymmetric shape. The roof top of the notches is well preserved, and their position was correlated with well defined upper limit of white zone (WE zone sensu Schneider, 1976), inasmuch as the upper limit of the WE zone corresponds to the roof of the recent tidal notch formation. We argue that the distance between the upper WE zone limit and the roof top of the notch corresponds to the distance between the recent BMSL and the former BMSL during the formation of the notch.

Our preliminary results suggest that BMSL in the Rijeka Bay is 20 cm below hydrographic MSL. Further research is needed in order to understand the relationship between BMSL and hydrographic MSL inasmuch as BMSL does not necessarily correspond to the hydrographic mean sea level (MSL).

Regional occurrence of well preserved tidal notches at 0.5–0.6 m below BMSL (Rijeka Bay, Istrian Peninsula, Kvarner islands, and Velebit Channel) indicates their possible coseismic origin (rapid tectonic subsidence). It is possible that this regional coseismic subsidence occurred in the 4th century A.D., which is simultaneous with the presumed uplift in the eastern Mediterranean.

Deeper positions of tidal notches in the northeastern part of Rijeka Bay and within Bakar Bay (from 103 to 115 cm below BMSL) indicate enhanced subsidence on the footwall of the reactivated Vinodol thrust. This zone was assumed to be the most seismotectonicaly active.

Acknowledgements

Ministry of Science, Education and Sport of Republic of Croatia supported this research (Project 0119402, Sediments from the Adriatic Sea and the coastal zone). We would like to thank P.A. Pirazzoli for useful suggestions in an earlier version of the MS and our referees, S.C. Stiros and C. Vita Finzi, whose comments and suggestions greatly improved the paper. Moreover, we thank I. Blašković for critical remarks, M. Pršić and M. Pasarić for useful hydrographic data, R. Košćal for drawings, and D. Frka for the submarine photo (Fig. 6).

References

Benac, Č., 1992. Recent geomorphological processes in the area of the Rijeka Bay (in Croatian). Geografski Glasnik 54, 1–18.

Benac, Č., Durn, G., 1997. Terra rosa in the Kvarner area—geomorphological conditions of formation. Acta Geographica Croatica 32, 7–19.

Benac, Č., Juračić, M., 1998. Geomorphological indicators of the sea-level changes during upper Pleistocene (Wuerm) and Holocene in the Kvarner region. Acta Geographica Croatica 33, 27–45.

Blašković, I., 1997. The helicoidal fault system of Vinodol (Croatia) and their genesis. Geologia Croatica 50 (1), 49–56.

Blašković, I., 1999. Tectonics of part of the Vinodol Valley within the model of the continental crust subduction. Geologia Croatica 52 (2), 153–189.

Colantoni, P., Galignani, P., Lenaz, R., 1979. Late Pleistocene and Holocene evolution of the North Adriatic Continental Shelf (Italy). Marine Geology 33, M41–M45.

Correggiari, A., Roveri, M., Trincardi, F., 1996. Late Pleistocene and Holocene evolution of the north Adriatic Sea: Il Quaternario. Italian Journal of Quaternary Science 9 (2), 697–704.

Dalongeville, R., le Campion, T., Fontaine, M.F., 1994. Bilan bioconstruction–biodestruction dans les roches carbonatées en mer Méditerranée: étude expérimentale et implications géomorphologiques. Zeitschrift für Geomorphologie 38 (4), 457–474.

Del Ben, A., Finetti, I., Rebez, A., Slejko, D., 1991. Seismicity and seismotectonics at the Alps—Dinarides contact. Bollettino di Geofisica Teorica ed Applicata XXXIII (130–131), 155–176.

Ercegović, A., 1932. Ecological and sociological studies on lithophytic cyanophytes of the Adriatic coast (in Croatian). Jugoslavenska Akademija Znanosti i Umijetnosti (Rad JAZU), Zagreb 244, 129–220.

Fouache, E., Faivre, S., Dufaure, J.-J., Kovačić, V., Tassaux, F., 2000. New observation on the evolution of the Croatian shoreline between Poreč and Zadar over the past 2000 years. Zeitschrift für Geomorphologie 122, 33–46.

Gamulin-Brida, H., 1974. Biocoenoses benthiques de la mer Adriatique. Acta Adriatica 15 (9), 3–103.

Golubić, S., Schneider, J., 1979. Carbonate dissolution. In: Trudinger, P.A., Swaine, D.J. (Eds.), Biogeochemical cycling of mineral forming elements. Elsevier, Amsterdam, pp. 107–129.

Griggs, G.B., Trenhaile, A.S., 1997. Coastal cliffs and platforms. In: Carter, R.W., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 425–450.

Herak, Mi., 1986. A new concept of geotectonics of the Dinarides. Acta Geologica 16 (1), 1–42.

Herak, Ma., Herak, D., Markušić, S., 1996. Revision of the earthquake catalogue and seismicity of Croatia, 1902–1992. Terra Nova 8, 86–94.

Juračić, M., Benac, Č., Crmarić, R., 1999. Seabed and surface sediments map of the Kvarner Bay, Adriatic Sea, Croatia (Lithological map, M 1:500,000). Geologia Croatica 52, 131–140.

Kershaw, S., Guo, L., 2001. Marine notches in coastal cliffs. Indicators of relative sea-level change, Perachora Peninsula, central Greece. Marine Geology 179, 213–228.

Kišpatić, M., 1891. Earthquakes in Croatia (in Croatian). Rad Jugoslavenske Akademije Znanosti i Umjetnosti (Yugoslav Academy of Science and Art Zagreb) 107, 81–164.

Kontogianni, V., Tsoulos, N., Stiros, S., 2002. Coastal uplift, earthquakes and active faulting of Rhodes Island (Aegean Arc):

modelling based on geodetic inversion. Marine Geology 186, 299 – 317.

Laborel, J., 1986. Vermetid gastropods as sea-level indicators. In: van de Plassche, O. (Ed.), Sea-level research: a manual for the collection and evaluation of data. Geo Books, Norwich, pp. 281 – 310.

Laborel, J., Laborel-Deguen, F., 1994. Biological indicators of relative sea-level variations and co-seismic displacements in the Mediterranean region. Journal of Coastal Research 10 (2), 395 – 415.

Naylor, L.A., Viles, H.A., 2002. A new technique for evaluating short-term rates of coastal bioerosion and bioprotection. Geomorphology 47, 31 – 44.

Pérès, J.M., Picard, J., 1964. Noveau manuel de bionomie benthique de la mer Méditerranée. Recueil des Travaux de la Station Marine d'Endoume 31 (47), 1 – 137.

Pirazzoli, P.A., 1980. Formes de corrosion marine et vestiges archeologiques submergés: interprétation néotectonique de quelques exemples en Grèce et en Yougoslavie. Annales de l'Institut Oceanographique 56, 101 – 111.

Pirazzoli, P.A., 1986. Marine notches. In: van de Plassche, O. (Ed.), Sea-level Research: A Manual for the Collection and Evaluation of Data. Geo Books, Norwich, pp. 361 – 400.

Pirazzoli, P.A., 1996. Sea Level Changes. The Last 20 000 Years. John Wiley and Sons, Chichester, New York. 211 p.

Pirazzoli, P.A., Stiros, S.C., Arold, M., Laborel, J., Laborel-Deguen, F., Papageorgiou, S., 1994a. Episodic uplift deduced from Holocene shorelines in the Perachora Peninsula, Corinth area, Greece. Tectonophysics 229, 201 – 209.

Pirazzoli, P.A., Stiros, S.C., Laborel, J., Laborel-Deguen, F., Arold, M., Papageorgiou, S., Morhange, C., 1994b. Late-Holocene shoreline changes related to palaeoseismic events in the Ionian Islands, Greece. The Holocene 4, 397 – 405.

Pirazzoli, P.A., Laborel, J., Stiros, S.C., 1996a. Coastal indicators of rapid uplift and subsidence: examples from Crete and other eastern Mediterranean sites. Zeitschrift für Geomorphologie 102, 21 – 35.

Pirazzoli, P.A., Laborel, J., Stiros, S.C., 1996b. Earthquake clustering in the Eastern Mediterranean during historical times. Journal of Geophysical Research 101, 6083 – 6097.

Pirazzoli, P.A., Stiros, S.C., Arold, M., Laborel, J., Laborel-Deguen, F., 1999. Late Holocene coseismic vertical displacements and tsunami deposits near Kynos, gulf of Euboea, central Greece. Physics and Chemistry of the Earth (A) 24, 361 – 367.

Prelogović, E., Kuk, V., Jamičić, D., Aljinović, B., Marić, K., 1995. Seismotectonic activity of the area of Kvarner (in Croatian). Proceedings of the 1th Croatian Geological Congress, Opatija 1995, Institute of Geology and Croatian Geological Society, Zagreb, pp. 487-490.

Rust, D., Kershaw, S., 2000. Holocene tectonic uplift patterns in northeastern Sicily: evidence from marine notches in coastal outcrops. Marine Geology 167, 105 – 126.

Sartoretto, S., Verlaque, M., Laborel, J., 1996. Age of settlement and accumulation rate of submarine "coraligène" (−10 to−60 m) of the northwestern Mediterranean Sea; relation to Holocene rise in sea-level. Marine Geology 130, 317 – 331.

Schneider, J., 1976. Biological and inorganic factor in the destruction of limestone coasts. Contributions to Sedimentology 6, 1 – 112.

Schneider, J., 1977. Carbonate construction and decomposition by epilithic and endolithic microorganisms in salt- and freshwater. In: Flügel, E (Ed.), Fossil Algae: Recent Results and Developments. Springer Verlag, Berlin, pp. 248 – 260.

Schneider, J., Torunski, H., 1983. Biokarst on limestone coasts, morphogenesis and sediment production. P.S.Z.N. I, Marine Ecology 4 (1), 45 – 63.

Schneider, J., le Campion-Alsumard, T., 1999. Construction and destruction of carbonates by marine and freshwater cyanobacteria. European Journal of Phycology 34, 417 – 426.

Shebalin, N.V., Karnik, V., Hadžievski, D. (Eds.), UNDP/UNESCO Survey of the Seismicity of the Balkan region, Skopje, Catalogue of Earthquakes, vol. I–III.

Stiros, S., 2001. The AD 365 Crete earthquake and possible seismic clustering during the 4–6th centuries AD in the Eastern Mediterranean: a review of historical and archaeological data. Journal of Structural Geology 23, 545 – 562.

Stiros, S.C., Pirazzoli, P.A., Laborel, J., Laborel-Deguen, F., 1994. The earthquake in Cephalonia (Western Hellenic Arc): coastal uplift and halotectonic faulting. Geophysical Journal International 117, 834 – 849.

Stiros, S.C., Laborel, J., Laborel-Deguen, F., Papageoriou, S., Evin, J., Pirazzoli, P.A., 2000. Seismic coastal uplift in a region of subsidence: Holocene raised shorelines of Samos Island, Aegean Sea, Greece. Marine Geology 170, 41 – 58.

Torunski, H., 1979. Biological erosion and significance for the morphogenesis of limestone coasts and for nearshore sedimentation (Northern Adriatic). Senckenbergiana Maritima 11, 193 – 265.

Zavodnik, N., Zavodnik, D., 1985. On the occurrence of *Lithophyllum tortuosum* (Esper) Foslie in the North Adriatic sea. Rapports Commission Internationale pour l'Exploration Scientifique de la Mer Méditerranée 29 (5), 273 – 274.