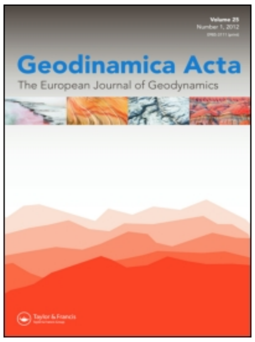

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Relative Sea-Level Change During the Late Holocene on the Island of Vis (Croatia) – Issa Harbour Archaeological Site

Sanja Faivre [1*], Tatjana Bakran-Petricioli [2], Nada Horvatinčić [3]

[1] *Department of Geography, Faculty of Science, Marulićev trg 19/II, 10 000 Zagreb, Croatia*

[2] *Department of Biology, Faculty of Science, Rooseveltov trg 6, 10 000 Zagreb, Croatia*

[3] *Institute Ruđer Bošković, Bijenička 54, 10 000 Zagreb, Croatia*

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Abstract

The 2.4 ka shoreline evolution on the Island of Vis has been investigated. It represents a particularly interesting area for this kind of investigation due to the existence of the submerged archaeological remains, the antique port of Issa, as well as to the existence of geomorphological and biological sea-level markers. The actual depths of the different parts of the submerged quay have been mapped and measured with respect to the present mean sea-level, applying corrections for tide and atmospheric pressure values at the time of the surveys. The functional heights related to the sea level at the time of construction have also been taken into account. These data were further compared with predictions derived from a glacio-hydro-isostatic model associated with the Last Glacial cycle. During the investigation of the coast, tidal notches and algal rims were found. They were mapped, measured and correlated with results of the submerged port remains, as well as with other available data along the Croatian coast.

Our results demonstrate a 199±25 cm sea-level change during 2.4 ka on the Island of Vis. Taking into account the total relative sea-level change, an average rate of around ~0.83 mm/yr is derived. If the isostatic-eustatic component is separated, a tectonic subsidence rate ranges between 0.17 and 0.3 mm/yr depending on the predicted model used. Compared to the Northern Adriatic area, the Island of Vis shows a much smaller component of tectonic subsidence.

Keywords: sea-level change, submerged Issa harbour, tidal notch, coralline algae, Adriatic Sea

1. Introduction

The evolution of the Croatian shoreline during the last 2500 years has been at the focus of our research since 1999. In our work, we have correlated geomorphological and archaeological markers all along the coast [1-4] placing them both in the geological and geomorphological regional setting. The Kvarner and Istria area has been closely studied lately [5-10]. Consequently, the Island of Vis represents a very good location for improving knowledge on factors influencing the sea-level change in the Middle Dalmatian area. We use the tidal notch for the main geomorphological marker as it is considered to be one of the best indicators of sea-level change [11], particularly in the low-tide seas such as the Mediterranean. As our archaeological marker, we used the submerged remains whose function, at the time of construction, was directly related to

* Corresponding author.
Tel : (+385) 1 4895-422 *Fax :* (+385) 1 4895-440
Email address : sfaivre@geog.pmf.hr

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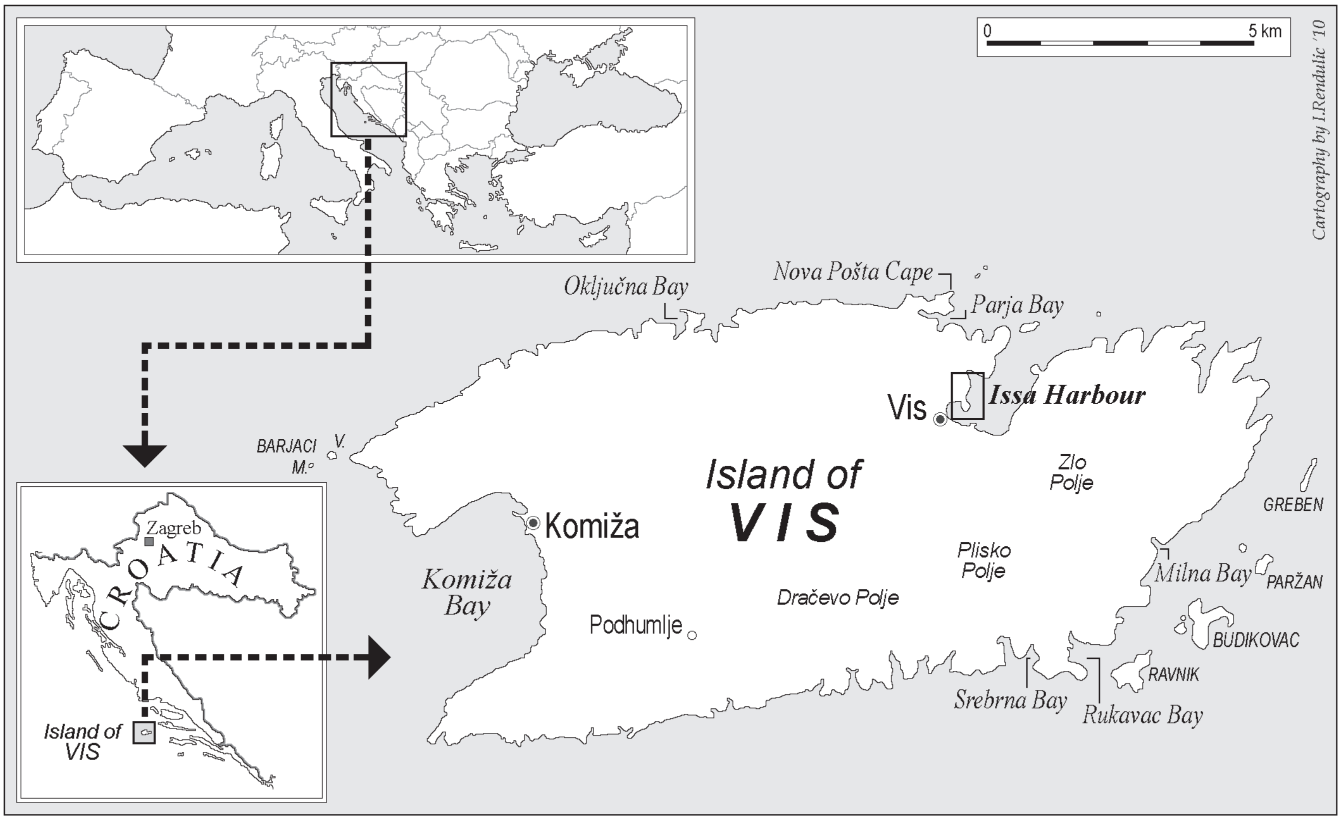

Fig. 1: Study area.

the sea, for example, port remains, fish tanks, salinas etc. In this work we also used the biological markers as indicators of recent sea-level variations. The biogenic littoral rims built by the coralline rhodophyte *Lithophyllum lichenoides* grow at around mean sea-level (MSL) and may be preserved for millennia when growing in a rising sea-level environment [12-13]. Therefore, algal rims can provide additional ^{14}C data, which can be directly correlated with the tidal notches.

2. Geological and geomorphological settings

The Island of Vis belongs to the Central Dalmatian Islands group. By its size (90.3 km^2) it is the tenth island in the Adriatic Sea, located 45 km from the mainland (Fig. 1). The relief of the Island of Vis can be simply described through three main hilly ranges, between which dry valleys and poljes are situated. They are mainly east-west oriented as a consequence of spreading of the main geological structures.

Structurally, the island represents an anticline that spreads roughly east-west and sinks 10° on average toward the east. The core of the anticline is made up of clastites with gypsum and igneous rocks, while the limbs are of Cretaceous carbonate limestone and dolomites accumulated on the ancient Adriatic Carbonate Platform [14-15]. Anhydrites can be found in the depth below the Lower Cretaceous on the larger area of the Island of Vis. The westernmost part of the island is built of magmatic and clastic rocks associated with the Komiža Bay diapire.

The anticline is completely cut by faults that are parallel with the hinge line of the anticline. The transversal orientation of the regional stress direction, which is 18-198° [16-17] in relation to the spreading of structures, points to the compressional character of the structures and to the locally expressed left horizontal movement. Under those circumstances, the reverse movements along the faults of opposite vergences occurred and pop-up like structures were formed. The horizontal movements of fault limbs took place when the fault line was 30° or less in relation to the main stress direction. The gradational change in the stress direction along the fault indicates the rotation of structures. Those conditions resulted in numerous fissures and intensive karstification [17].

The youngest sedimentary complex is represented by the Quaternary deposits that cover a great part of the island. They are developed in several continental facies: *terra rossa,* breccia, breccia-conglomerates and eolian sands. They are primarily remains from the past glacial periods – largely Pleistocene. The oldest sequence is represented by the redistributed *terra rossa*, whose genesis, probably related to the Mindel-Riss period [18]. The thickest deposits of *terra rossa* are found in the karstic poljes. The core drilled in the Velo Polje shows that the thickness of the quaternary sediments is up to 45 m [19]. During the cold climate of the Riss period the creation of talus deposits followed, these being consolidated today in breccias. They were relatively dated at the Milna Bay and Pothumlje area [18]. The third phase is characterized by the conglomerates of fluvial origin and breccia-conglomerates in the Komiža Bay from the Riss and Würm

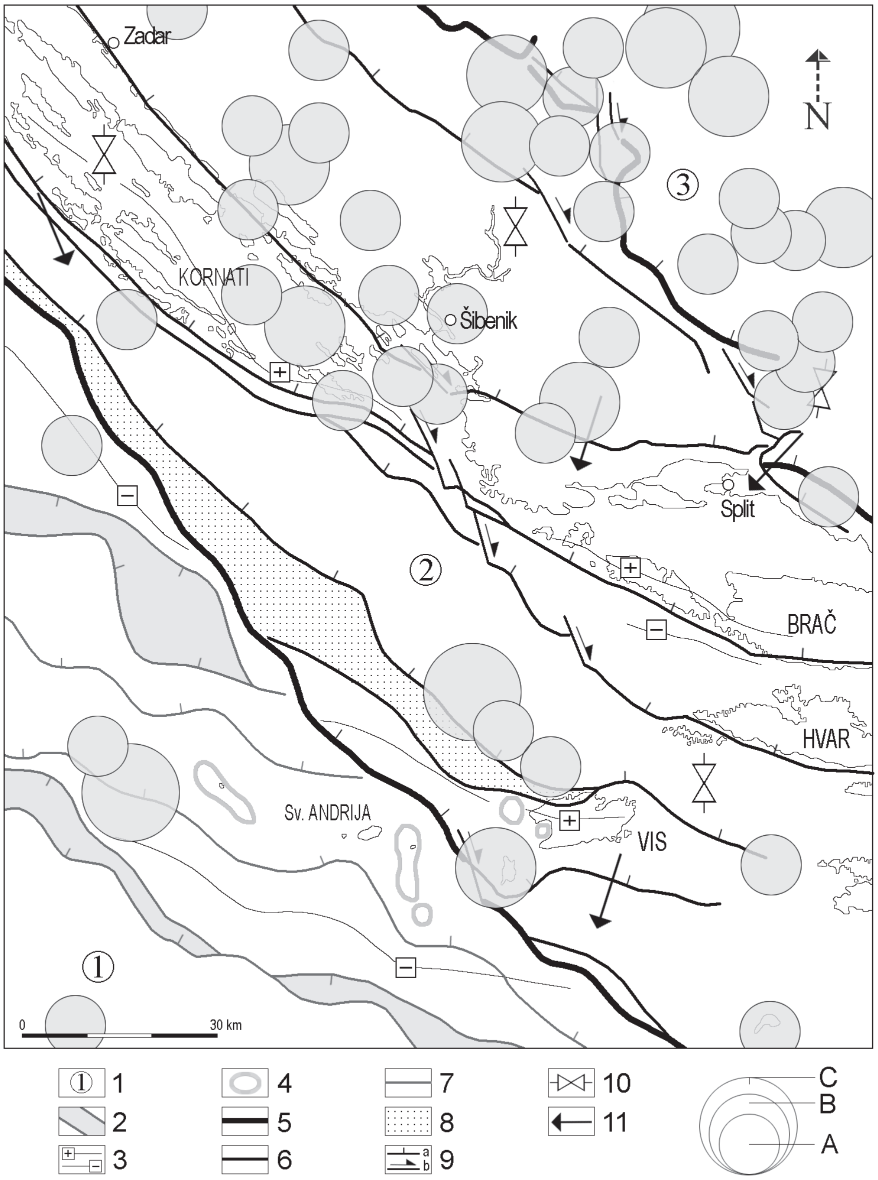

Fig. 2: Structural map of the investigated area with earthquake epicenters of magnitude larger or equal to 5.0 since 1900, according to [22]

1 - regional structural units: Adriatic microplate (1), transitional zone (2), Dinarides (3);
2 - raised structures within the Adriatic microplate bounded by the reverse faults of opposite vergence;
3 - axes of minima and maxima of the Bouguer anomalies;
4 - eruptive intrusions;
5 - boundary faults of regional structural units;
6 - boundary faults of structural units within the transitional zone;
7 - most important faults within the Adriatic microplate;
8 - fault zones;
9 - a: reverse faults, b: dextral faults;
10 -direction of maximal compressive stress;
11 - prevailing direction of displacement of structures near the surface;
ABC, Earthquake epicenters from the Croatian Earthquake Catalogue [59]. Events since 1900 with magnitude larger or equal to 5.0 (the smallest symbols correspond to magnitudes of 5.0≤M<5.5; the middle one to 5.5≤M<6.0; the largest one to 6.0≤M).

interglacial. Subsequently, the sedimentation of aeolian sands (up to 10 m thick) followed during the Würm period. They were transported from the NE sector, that is, from the areas which are under the sea today. The *Pupa muscorum* gastropod found [20] confirms its Pleistocene, continental and aeolian origin. After that came the creation of brown fossil soil, upon which sand deposits have been found again at Zlopolje. The last phase of the climate change is documented with the creation of post-Pleistocene brown soils [18] that are still forming today.

3. Geodynamic setting

The tectonic framework of the studied region is conditioned by movements of the Adriatic microplate (Adria) and by resistance of the Dinarides to those movements. Ever-present tectonic activity during the Neogene and Quaternary causes constant narrowing of the microplate area [21]. Movements of the microplate generate a broad transitional zone (2) between the Adria (1) and the Dinarides (3) (Fig. 2) that extends all along the Adriatic coast in a NW and SE direction [16,22]. This transitional zone (2) is characterized by reverse structures of the NW-SE strike. Seismic refraction profiles indicate that it is characterized by broad fault-zones in the SW, related to the Susak-Vis and Vis-Southern Adriatic faults (Fig. 2). Approaching the Dinarides, the amount of compression grows, causing the dip of faults to increase. The displacements of hanging walls also increase, and faults reach the surface between Kornati and Vis [2,16,23]. Consequently, the Island of Vis is situated right on the edge of this transitional zone (2) toward the Adria (1).

A very strong earthquake that took place on the Island of Vis on 15th August 1956 was analyzed by numerous authors [24-26]. The earthquake considered was of M_L=5.75 magnitude. Its fault-plain solution represents a strike-slip faulting with a small normal component, although data do not rule out strike slip dominated reverse faults [27]. This is an important event that contributed to the knowledge of the tectonics of the active region in the Central Adriatic Sea [22].

Several intrusions of evaporites and igneous rocks represent a peculiarity found only in this area of the microplate, that is, between the islands of Jabuka and of Vis. Maximal compressive stress and measured displacements of structures at the surface are consistent with prevailing compression of the area. The regional compressive stress is oriented nearly N-S and varies between directions of 15-195° and 340-160º [17,28,29,30].

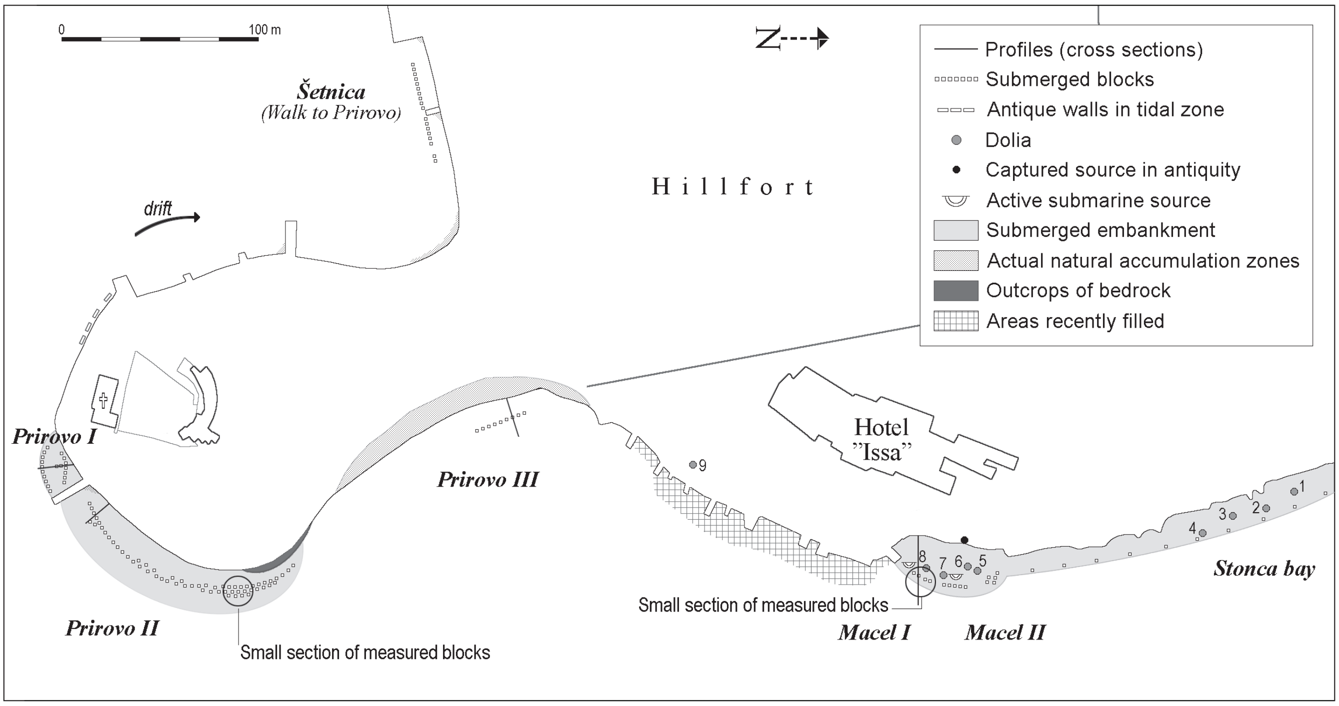

Fig. 3: General ground plan of the Issa harbour with studied locations.

4. Methods

Taking into account the methodology developed by Flemming, Flemming and Webb, and Pirazzoli [31-34], the remains of the submerged harbour, undoubtedly related to the ancient marine environment, have been selected. Due to the existence of the submerged antique port of Issa that is very well preserved, the island of Vis represents a particularly interesting area for that kind of investigation. After careful survey of the area, the blocks missing on previous maps have been mapped and the depths of all the blocks have been measured on three sections of the ancient port: the Walkway to Prirovo, Prirovo I and Prirovo III (Fig. 3). On the other two sections of the port, Prirovo II and Macel, the depth was measured on selected segments. 2-4 points were measured on the blocks and 2-4 points under the blocks, depending on the dimensions or position of the blocks. All the measurements were corrected to the MSL according to the relevant mareograph data (Split Station) obtained from the Hydrographical Institute in Split. The studied area belongs to a micro-tidal environment with an average amplitude of 25 cm (data from the Split mareograph).

The functional height was added to the obtained mean depth values of the representative segments to allow comparisons of the data in general [8]. Functional height is considered as measure of the emerged part with respect to the average sea level [35]. It depends on the typology of the archaeological evidence, its use and the local tide amplitudes.

A series of dives has been also carried out, looking for potential geomorphological sea-level markers, that is, for tidal marine notches in the areas of the limestone cliffs, which are considered to be good indicators of coastal tectonic movements [9].

Lithophyllum rims have been found at several localities during the survey of the coast. After the measurement of the width of the fossil and present rim, a vertical section was excavated. Levelling was done by direct measurements of the vertical distance between the outer edge of the recent rim, taken as the reference datum, and the centre of the broken section as explained in [13, 36]. Total error is estimated at ±20 cm.

Two samples of algal formation were dated by the radiocarbon dating method as described in [37]. The results were reported as ^{14}C activity in percentage of modern carbon (pMC) and as ^{14}C age in yr BP. The results were not corrected for initial ^{14}C activity, that is, reservoir effect. The unknown initial ^{14}C activity of the calcified samples, but also possible contamination with the allochthonous calcareous deposits, could have influenced the accuracy and reliability of the ^{14}C age of the dated samples.

5. Results

5.1. Archaeological markers at Issa harbour

The well-preserved submerged remains of the Issa harbour are located in the bay of Vis. They spread from the current petrol station, all around the peninsula of Prirovo including the Bay of Stonca in a length of 1.5 km (Fig. 3). Detailed mapping of the Issa harbour was started in 1989 by Radić I., Orlić M., Jurišić M. and Dijaković D., but their work was not published [38]. Later in 1992, Gluščević and Brusić have mapped two sites, the area near the recent pier with a sea light (called Prirovo I later in the text) and in front of the beach (called Prirovo III). They also took soundings on six sites

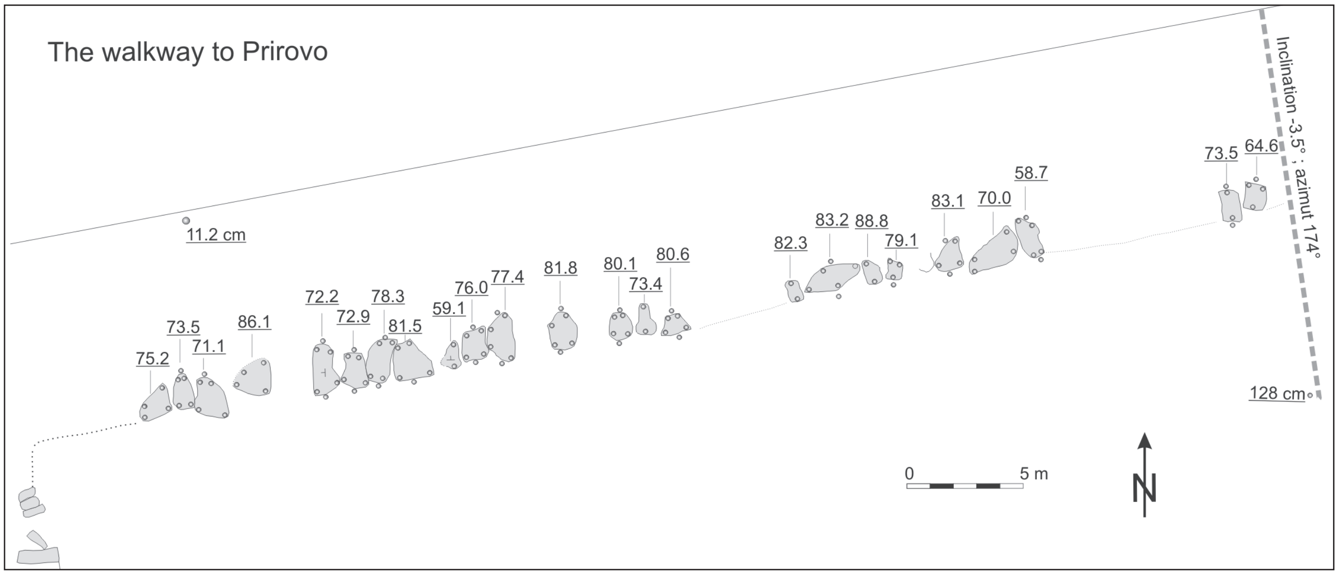

Fig. 4: Mean depth values of each block below the MSL with points of measurements (values corrected for tide, pressure and wind of the walkway to Prirovo). Ground plan after [38].

along the huge ancient port [39]. Čargo started the new, more complete, geodetic measurement in 2003 [38].

The port was built on the edge of the embankment made of different sized stones but also of ceramic fragments, which are submerged today and strongly calcified [39]. Some sections of the port were built on the embankment. This bank largely follows the actual coast line. It is gently inclined and of different widths. Unfortunately, some locations have been partly covered recently by filling and some segments have also been filled with concrete. More or less dislocated, large stone blocks can be seen along this ancient sea shore. However, they are *in situ* at several sites.

The building technique and the size of the blocks seem to be the same as those used for the construction of the nearby walls of the Hellenistic city. This suggests that the harbour was built at the same period of time as the walls of the town, that is, in the 4th century BC [38,40,41]. Kirigin suggested that the northern part of the harbour from the end of Prirovo III to Stonca Bay was built later by the Romans [42]. Gabričević had also written earlier that the Greek harbour of Issa extended along the southern part of Issa with Prirovo, without mentioning the Macel area and Stonca Bay at all [43]. The remains of the Issa harbour are among the oldest known port remains in Croatia [38]. Its characteristics will be presented according their geographical location and not according to their relative importance.

5.1.1. The walkway to Prirovo

This part of the Issa remains located near the petrol station was mapped for the first time by Čargo [38]. It consists of a 59m-long row of aligned stone blocks. In the western part of the site, the walls run about 90° toward the south. The actual quay also follows these antique lines. 24 blocks have been measured, those aligned in the E-W direction (Fig. 4). They are 7 to 7.5m away from the today's quay and 49m long. The average depth of those blocks is -76 cm below present MSL, corrected for tide, pressure and wind (Table 1). As observed from the measurements of the block bases, as well as from the slope gradient, which is very low – 3.5°, this area of the antique port is buried to a great extent, due to the sediment drift that comes from the south and southeast directions (Fig. 3). The blocks are relatively spaced one from another; thus it is difficult to establish their exact use.

5.1.2. Prirovo I

The second investigated area is located near the monastery at the Prirovo Peninsula, more precisely, on the western side of the today's pier with a sea light. The submerged quay follows the natural roundness of the peninsula, as does the recent one. Past research has shown that the ancient harbours were built similarly to present-day ones, and that the way of conception and construction has not basically changed from that time [44]. In ancient times, as well as today, the construction of the port equipment was adjusted to the geographical particularity of the site, that is, according to the indentation of the coast and the degree of its natural protection. The port of Issa is an example of ports which do not have headmost piers. Their operative shores follow the configuration of the land. This way of building can be explained by the fact that the complete functional coast was in a naturally sheltered bay, protected from all winds, which ensured the safety of docking and anchoring.

The first ground-plan of this section of the port, which consists of 13 major blocks, was done by Gluščević and Brusić in 1992 [39]. It was later completed by Čargo in 2002 and enlarged to 26 blocks. This work has been continued and a ground plan of the site now includes 50 blocks (Fig. 5, Fig. 6).

Prirovo I, as well as the entire Issean harbour, is made of great stone blocks built without mortar. Two overlapping arched

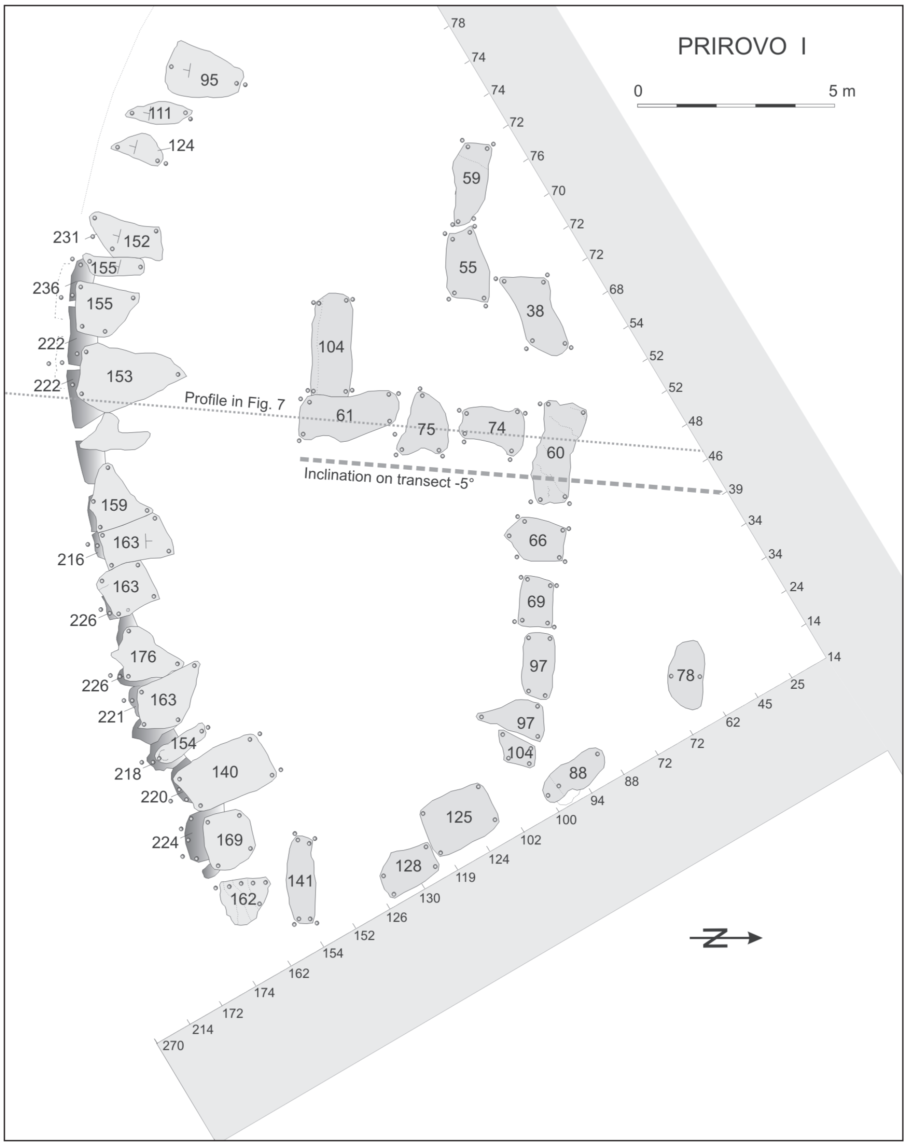

Fig. 5: Ground plan of Prirovo I with mean depth values of blocks below the MSL (values corrected for tide, pressure and wind) with points of measurement.

layers of blocks are preserved today in a length of 24 m (Fig. 5, Fig. 6). The preserved stone blocks border the plateau-like surface, built of smaller rock fragments and ceramic sherds (tegulae and amphora). The embankment slopes southwards at an inclination of 5° measured on the transect marked in the Fig. 5. At the maximum curvature, it is 17 m away from the today's quay. The facade of the ancient harbour is made of opus quadratum with 1-3 m long blocks joined (in places) by transverse blocks. The blocks are mainly of irregular shape but have a regular carved front.

After careful survey of the area, the missing blocks have been mapped and the depths of all the blocks have been measured (Table 1), as explained in Chapter 4. These two main rows of blocks represent the ancient quay (Fig. 6). The inner side of the embankment (behind the quay) lies between -137 and -150 cm below the recent MSL. The upper surface of the quay is -159 cm below the present-day MSL (corrected for tide, pressure and wind). The second layer is situated -222 cm below, and often protrudes roughly 30-40 cm beneath the upper layer. The base is at -287 cm. So, the foundation of the quay is 128 cm below its upper surface. This means that the blocks are 64 cm thick on average. The slope further southwards is represented by two major steps (Fig. 7). The sea bottom reaches a depth of 5 m at a distance of 4 m from the quay.

If the functional height of the quay [8] is determined at 40 cm due to the small tide amplitude of the area, and to the fact that during meteorological events the top of the surface of small piers or docks can be nearly submerged during maximum tides, the relative sea-level has risen by (159 cm + 40 cm) 199 ±25 cm from the time of its construction. Even today, the sections of the actual Vis harbour are nearly submerged during extremely high tides. The possible existence of a former third layer is excluded, because there are no other large blocks that can be seen nearby.

In the northern (landward) section of the investigated area, the blocks are placed on the embankment. The 9 highest blocks lie -64 cm below the present-day MSL (on average). Further eastwards, another group of blocks can be distinguished that are situated at -106 cm below the MSL and probably represents the base of the previous one. The underlying block can be clearly seen in the Fig. 7. These two rows of inside blocks can be well observed in profile.

5.1.3. Prirovo II

Beyond today's pier with a sea light, which was built at the beginning of the 20th century, the antique remains continue all around the Prirovo Peninsula. This is where the long embankment starts, which follows the natural line of the Prirovo Peninsula (Fig. 3). Between numerous blocks, some scattered, some aligned, while one principal row of different sized stone blocks can be discerned, nevertheless, on several segments. Many of them are not *in situ* today, but several segments still are. The way of conception seems different here, because the blocks are placed on the embankment and not on its edge as in the previous section. The embankment slopes more gradually than at Prirovo I.

On the maximal curvature of Prirovo II, 17 m from the shore, the blocks gain in size, because it is the most exposed part of the Issa harbour. The five largest blocks on this section

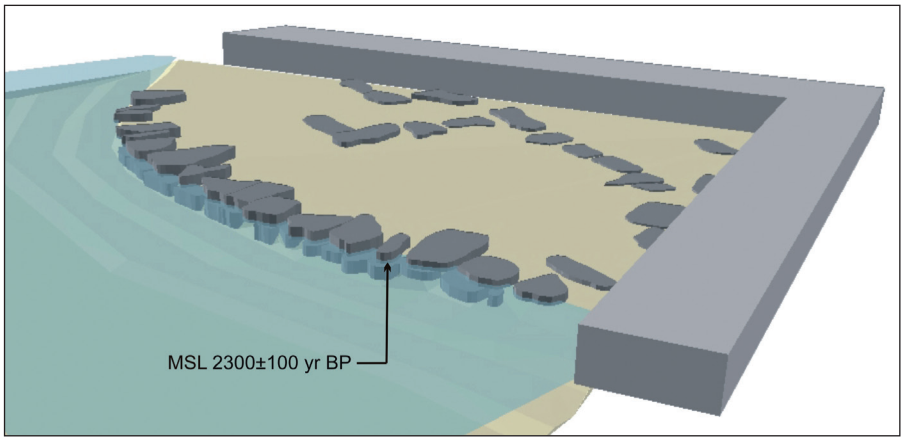

Fig. 6: 3D view of the Prirovo I section with a sea level at the time of construction.

have been selected and precisely measured (Fig. 3). Today, the mean depth (the upper level) of those blocks is -110 cm below the recent MSL. Generally, one layer of blocks has been observed, these being 40-50 cm thick. The depth of the sea in front of the blocks (toward the open sea) is actually -156 cm. The slowly dipping embankment ends 24 m from the shore. The slope becomes steeper, reaching more than 4 m in depth. It is difficult to draw conclusions on this section because the different sized blocks are spread all around and most of the frontal blocks are no longer *in situ*.

A segment of a well-preserved pavement has been observed 20 m from today's pier with a sea light. These paving stones (which close a 45° angle with today's quay) formed the ancient walking surface of the port. They are cut and fitted together tightly. Just below today's quay the pavement is -68 cm below recent MSL (Fig. 14). This part was definitely on land at the time of construction.

5.1.4. Prirovo III

The third investigated section of the Issa harbour is situated in front of today's beach, which was artificially filled very recently with terrigenous river sediments. Here, 16 m from the sea shore, another section of the Issa harbour is again well preserved. A row of 26 aligned *in situ* blocks is located there. The ground plan was drawn up by Gluščević [39]. Only a few blocks were added (Fig. 8). This measured part of the structure is 28.5 m long. The size of the blocks varies again from 1 to 3 m. This row of blocks is preserved principally in one layer, but a few segments with two and three layers have been also found. Based on the section with three rows of blocks, the structure was 80 cm high, which corresponds to today's height of the quay in the vicinity. The blocks are around 25 cm thick (much thinner than in the Prirovo I section). Thin foundation blocks can be observed in a few places. The sea bottom below this structure is -204 cm deep and it slowly dips toward the northeast (Fig. 9). It differs from Prirovo I by the numerous large blocks that have fallen along both sides of the structure, often leaning on the main row, on its inner and external part. Consequently, a virtual reconstruction could be done in the future.

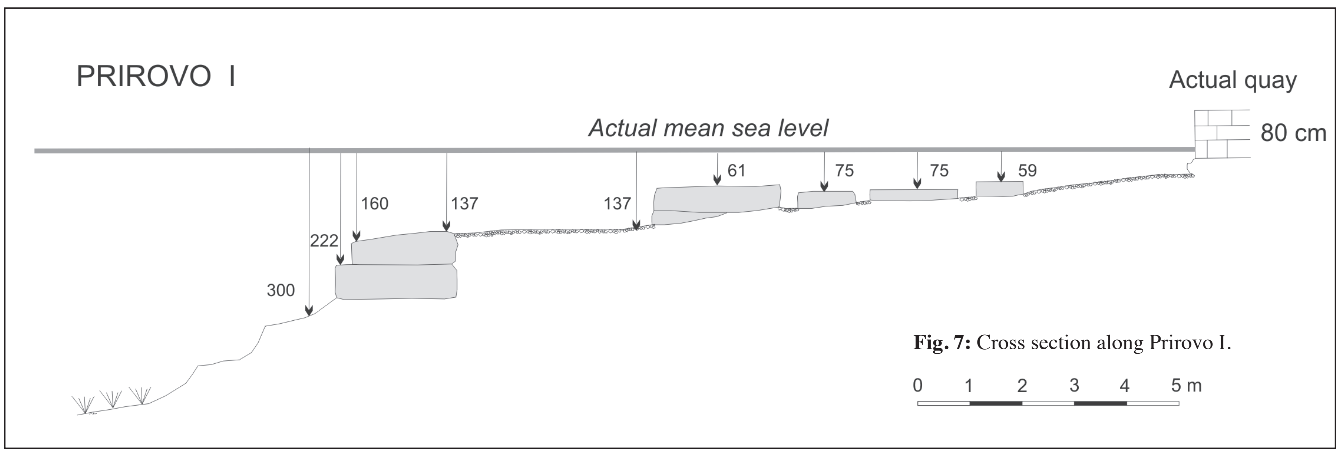

Fig. 7: Cross section along Prirovo I.

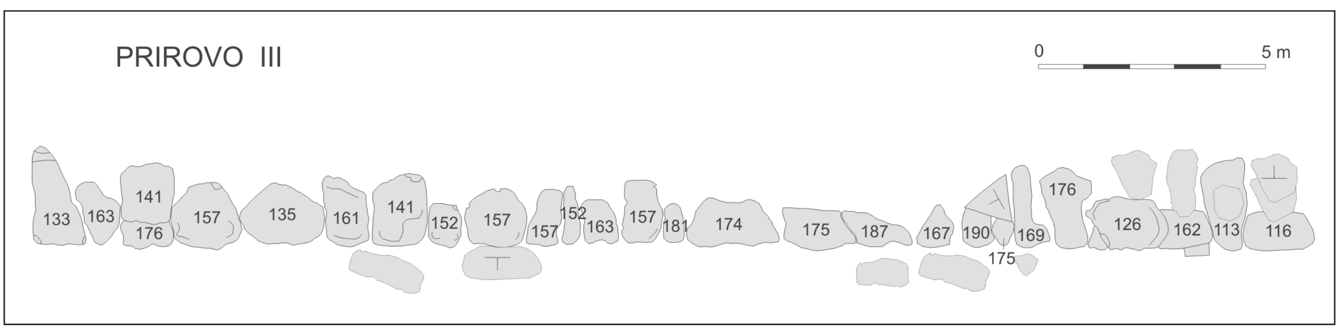

Fig. 8: Mean depth values of each block below the MSL (values corrected for tide, pressure and wind) on the ground plan of Prirovo III, slightly modified after [39].

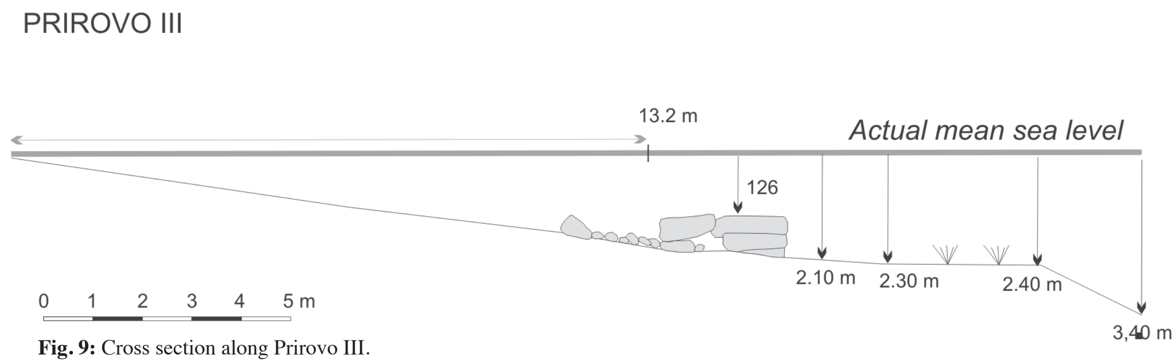

Fig. 9: Cross section along Prirovo III.

According to the measurements in this section, several depth levels appear. Calculated on the 7 highest blocks, the upper surface stands today at -130 cm below MSL (Table 1). The next depth level is calculated at -160 cm below MSL (based on 13 blocks). The foundation blocks are at -179 cm today (based on 8 blocks). If the functional height is added to the highest reference surface, the sea-level at the time of construction was (130 cm measured below MSL + functional height of 40 cm) = -170 ±25 cm below MSL.

5.1.5. Macel and the Stonca Bay

During the construction of the Hotel Issa (1983/84), a large part of the ancient embankment has been filled in (Fig. 3). Therefore, the next sequence can be found near the building called – Macel. This section is characterized by a small number of large scattered blocks, some of them particularly thick. The first blocks can be found at the distance of 13 meters from the sea shore. They are small and -68 cm below the recent MSL. At the time of construction, they were a part of the walking surface. The embankment at the Macel section is particularly long, twice as long as at Prirovo I & II.

On the northern part of the Macel section 18.5 m from the shore, 8 m of continuous large thick blocks lie in a transversal position in relation to the shoreline. This is a unique location at Issa harbour with a continuous row of transversal blocks. These are the lateral blocks of the quay. The embankment's inclination increases 30 m from the shore and the bottom quickly reaches a depth of 4 m below MSL, after which the sea bottom drops to around 8 m.

The lateral remains of the Macel structure consist of particularly large blocks. They are 2-3 m long, 90-120 m wide and 60-80 cm thick. Compared with the sea level, they are also significantly higher than all the other blocks. The transversal side blocks are located at the adjusted height of -49 cm below the present day MSL, which could not be correlated with any other depth level of the nearby blocks. These side blocks are the largest and the thickest blocks found at the Issa harbour.

Near the recent small pier there are also a few preserved frontal blocks at a depth today that is -132 cm below the present MSL. Seawards to them at a distance of 27 m from the shore, the sea is -210 cm deep today. If the functional height is added to the highest reference surface, the sea-level at the time of construction was (132 cm - measured + 40 cm - functional height) = -172 ±25 cm below MSL.

Fortunately, the *dolia* bases at the Macel area and in the Stonca Bay have been found by Abramić, Jurišić and Gluščević [45,46,39]. They have originated precisely from the Roman period [47]. Those big ceramic vessels, known as *dolia*, were built at the same time as the port [48]. Consequently, this section of the port was constructed in Roman times. It could possibly have also been used before then, but the actually observable remains are from Roman times. They were at least 9 *dolia* in this area [47].

The lower parts of the *dolia* (up to 60 cm in height), have been built into the shore and have been preserved until today,

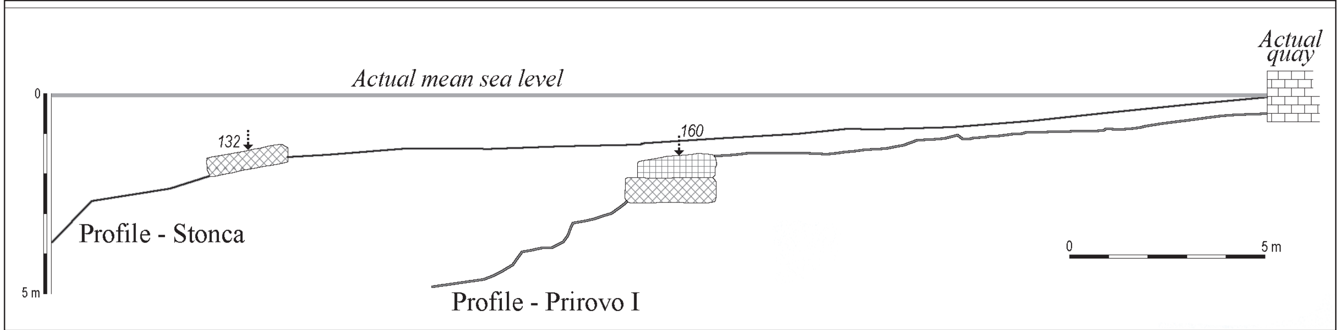

Fig. 10: Comparison between the Prirovo I, II and Macel profiles (the mean depth values are indicated on the blocks).

while the upper parts have been destroyed by the sea or by the human factor. The material found in the *dolia* can be dated only generally, due to the extensive time span, as being from the 1st or 2nd century AD [49]. The part of the embankment around the *dolia* was also examined, but the beginning of the vessels' use could not be precisely determined [47]. According to Matijašić, the main function of the *dolia* was to preserve food [50]. *Dolia* have been found at numerous places along the Croatian coast. Their standard size is about 160 cm in height and 140 cm in width, including the aperture at 70 cm of height on its edge, with 5 cm thick walls. The perforations have given the *dolia* from Vis a completely different function that has not been fully defined up to now. The actual depths of the half-buried *dolia* are -80 cm and -110 cm below the MSL. According to the depth of the frontal blocks of the quay, *dolia* bottoms were placed precisely at the MSL at the time of construction; however it is difficult to determine if they could have been in contact with the sea in that position.

This section of the port is also specific due to the numerous sources of freshwater, which are submerged today (submarine springs) (Fig. 3). Although we do not know the exact use of the *dolia* at the investigated area, due to the thickness of the blocks, the embankment that is almost twice as long (Fig. 10), the sources of freshwater and the particularly sheltered position of this section of the port for which a different function is assumed. Consequently, Macel and Stonca Bay probably had an important economic function in the Issa harbour.

Fig. 11: Submerged notch at Parja Bay.

5.2. Geomorphological and biological markers

During investigation of the coast of the Island of Vis, submerged tidal notches were sporadically found. Generally, the notches are better expressed on the northern shores of the island. A good example is found in Parja Bay, where the notch is -30 cm below the MSL, corrected for tide, pressure and wind (Fig. 11). Along the former Rogačić Island, which was transformed into a peninsula by anthropogenic filling, the notch is also -30 cm deep. Furthermore, two notches were found in Oključna Bay, one below the other. The lower one can be followed only in a very short section. The upper submerged notch can be well followed on the western side of the bay, standing at -20 cm below the MSL, while the deeper notch is located at -75 cm below MSL. The notches are rare on the southern shores of the island and can be

Table 1: Measurements of the Issa harbour sections

Location	Section<	Number of measured blocks	Number of measurements on the section	Length of measured structure (m)	Depth of the reference surface (cm below MSL)	Structure height (cm)	Number of observed superposed blocks	Distance from the shore (m)
Walkway to Prirovo	Half buried blocks	24	110	49	-76	16 (buried)	1	7,7
Prirovo I	Inner blocks	17	110	-	-69	-	2	-
Prirovo I	Frontal structure	33	94	24	-159	128	2	17
Prirovo II	Frontal structure	5	40	8	-110	58	1	17
Prirovo III	Frontal structure	26	155	28,5	-130	80	3	16
Macel	Frontal structure	3	24	5	-132	78	3	27
Macel	Side blocks	4	14	8	-49	78	1	-

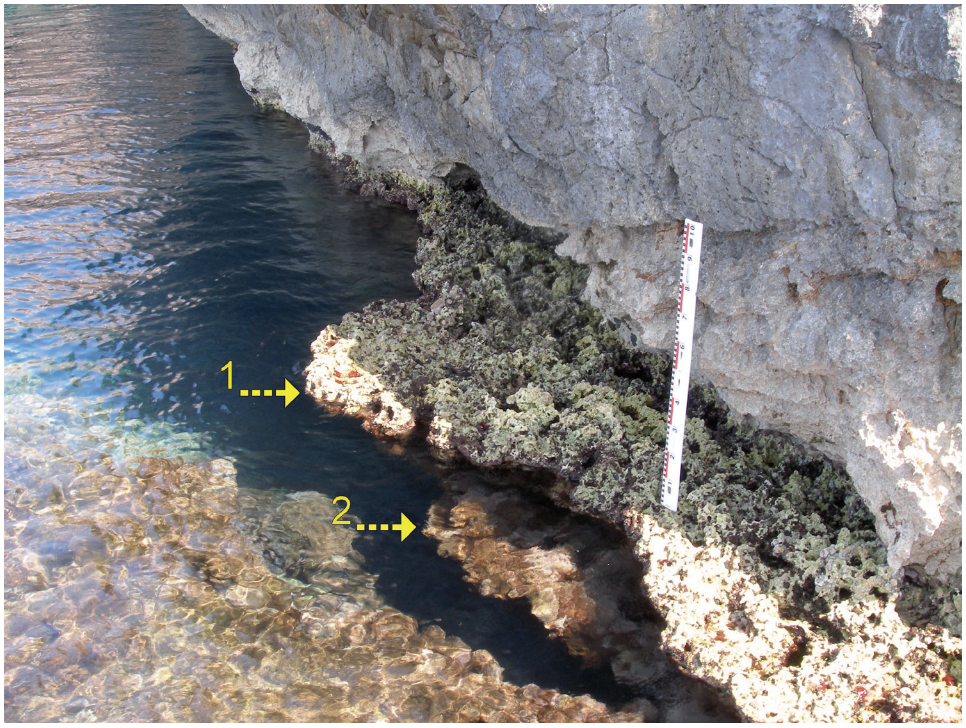

Fig. 12: Morphology of the *Lithophyllum* rim at Nova Pošta - two dominant pronounced levels: the upper one (1) with a maximal extension of 130 cm and the lower one (2) with a maximal extension of 40 cm are clearly visible.

found only on some short segments in the bays. This is not unexpected, because these southern shores of the island are highly exposed to southern winds. At Srebrena Bay, the notch is again located at around -30 cm below MSL.

A recent notch has also been identified on the Island of Vis in the areas where the biogenic littoral rims have been found, at the Nova Pošta and Bili Bok locations. Those recent notches are directly connected with the formation of biogenic littoral rims built by the coralline rhodophyte *Lithophyllum lichenoides*. The *Lithophyllum* rims develop in close connection with the sea level and represent another precise (±10 cm) sea-level indicator [12,13].

The algal rim at Nova Pošta on the northern shore of the Island of Vis has been studied. The whole rim begins at between 1 m and 0.75 m below the recent MSL, depending on the micro location. It has two dominant levels: the upper one (arrow 1 in Fig. 12) around 6 m long and 40 to 130 cm wide, and the lower one (arrow 2 in Fig. 12) with a maximal extension of 40 cm. The surface of the lower level is 60 cm below the recent one. The thickness of each level at its most protruding part is around 15 cm.

The presence of a thick and well-developed *Lithophyllum* rim generally corresponds to a gentle rise of relative sea-level. The composed algal rim at the Nova Pošta location represents thick buttress rim by its morphology [13] and points directly, therefore, to the rising sea-level environment. Two samples were dated from the upper level of algal rim (arrow 1 in Fig. 12), 1X (inner part) and 8 (external part) (Table 2). The sample 8 from the external part seems to have been contaminated and will not, therefore, be discussed at all. Our preliminary results of ^{14}C dating suggest that the upper level of the present rim was formed around 400 yr BP (Table 2). Today, processes of biodestruction prevail over the bioconstruction on the relatively horizontal surface of the algal rim upper level. Living talli of the coralline alga *Lithophyllum lichenoides* were found only on small patches at the highest position on the horizontal surface of the rim and along the upper limit of the rim (arrows in Fig. 13), that is, up to the vertex of the recent notch. Such a situation could clearly be connected with the recent acceleration of the sea-level rise.

6. Discussion

The preserved parts of the ancient harbour on the Island of Vis show that it was a well-built harbour and that its constructors were familiar with techniques of building in the sea with large stone blocks [40]. This research of Issa harbour allows the distinction of several types of blocks in the studied area. According to their actual disposition, inner, frontal and side blocks can be distinguished. The inner blocks are in all sections, except the Prirovo III area. They were on land at the time of construction and cannot be directly used for the sea-level reconstruction. The frontal structures can be found 16-17 m from the recent shore all around the Prirovo Peninsula (Prirovo I, II and III sections). Analogous structures are found 27 m from the shore only in the Macel area. From this analysis, two main structure heights can be distinguished at Prirovo I, where the frontal structure is 128 cm high, and at Prirovo III and the Macel section, where they are 80 cm high. The thickness of the frontal blocks also differs, from 64 cm at Prirovo I to 25 cm in the Prirovo III and Macel. Consistently with the actual disposition of the blocks, the main row of blocks supports the embankment at Prirovo I, while they were constructed on the top of the embankment at Prirovo II, III and Macel.

The most important finding of this study considering sea-level research is the difference in depths of the measured sections. Two main depth levels have been shown: –159 cm at Prirovo I and –130 cm and –132 cm below the MSL at Prirovo III and Macel.

These differences in the depth levels lead us toward the consideration of the different ages of the port sections. The *dolia* buried in the embankment give the age of 1st or 2nd century AD for the Macel section, where the frontal structures are –132 cm below the recent MSL (corrected for tide, pressure and wind). Consequently, the Prirovo I section (–159 cm below MSL) must have been built earlier, during

Table 2: Results of ^{14}C dating of the upper part of the algal rim. ^{14}C results are expressed as ^{14}C activity of percentage of modern carbon (pMC) and as ^{14}C age in yr BP (uncorrected radiocarbon years)

Sample No.	Sample name	pMC	^{14}C age BP
Z-4301	1X	95.1 ± 0.7	404 ± 56
Z-4303	8	99.0 ± 0.7	78 ± 55

Fig. 13: Living talli of *Lithophyllum lichenoides* coralline algae along the upper limit of the algal rim.

Greek times. This could also be argued by the mentioned differences in the construction types (the difference in structure height, block thickness and the disposition of blocks in relation to the embankment). This opinion can also be corroborated by the earlier statements of Gabričević, who wrote that the Greek harbour of Issa extended along the southern part of Issa with Prirovo [43] and those of Kirigin, who agreed with Gabričević, and added that the section from the end of Prirovo III including Macel and Stonca Bay was built later by the Romans [42].

To make those results comparable with other worldwide measurements, we have added the functional height. It can be simply said that this functional height allows the structure to be usable or, in other words, to work. As the submerged remains represent an ancient quay and the tide is low, the functional height was determined at 40 cm. Consequently, we come to the depth of -199 cm ±25 cm for the Greek period based on the Prirovo I section, along with -170 cm ±25 cm and -172 cm ±25 cm for the Roman period, based on the Prirovo III and Macel sections (Fig. 14).

The position of the perforated *dolia* according to the MSL also raises a very interesting issue. The obtained results show that the bases of the *dolia* were placed at around the MSL at the time of construction. Despite this, it is difficult to conclude if they really were in contact with the sea. Nevertheless, according to their position in relation to the sea-level, this contact was possible. As this section of the port has numerous sources of freshwater, the use of *dolia* could also have been connected with this abundance.

Geomorphological markers on the Island of Vis are situated much higher in comparison with the archaeological remains. Consequently, tidal notches are much younger than the archaeological remains. They are mainly -30 cm below the MSL today. Since tidal notches are hard to date, we decided to study the coralline algae rims that could help us to estimate the age of the notches. At the moment, we are in the early

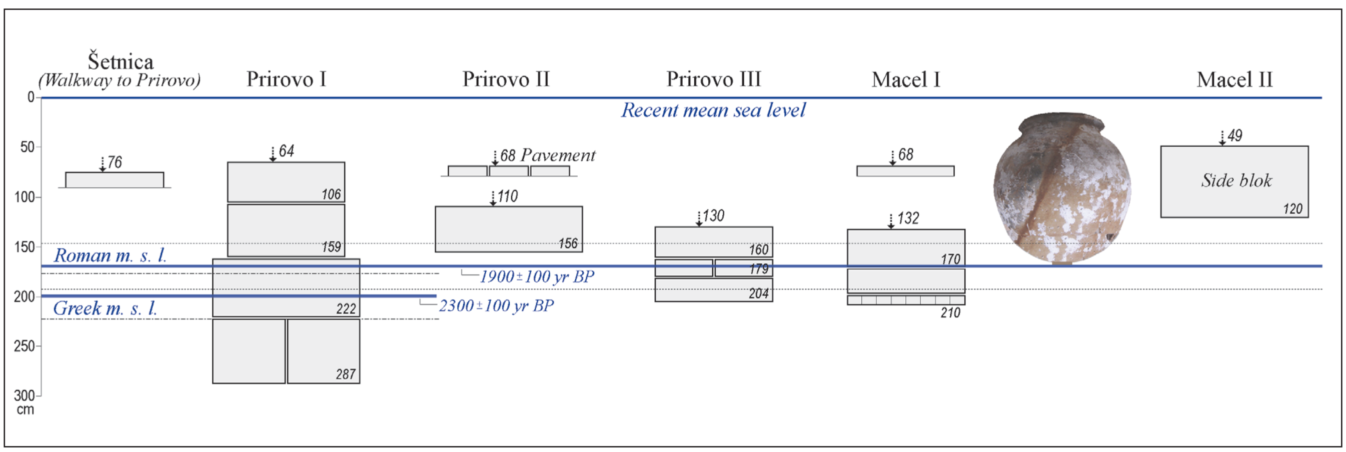

Fig. 14: Summary of all investigated sections of the Issa harbour with the corresponding MSL obtained from the submerged archaeological remains.

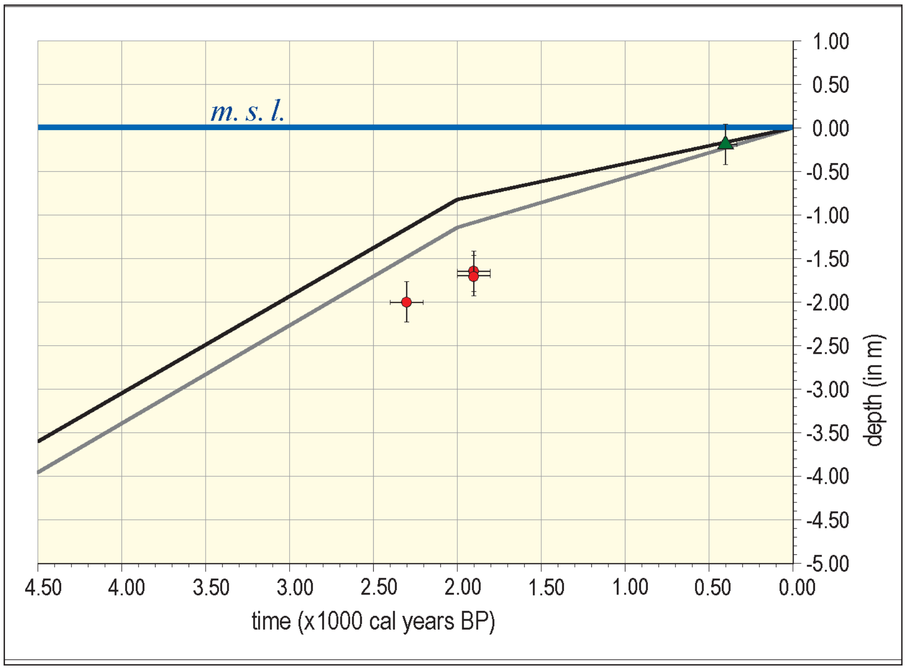

Fig. 15: Comparison between the predicted models of relative sea level change for the Central Adriatic, grey line [55], black line [56], and our observational evidence for the Vis area: Prirovo I, III and Macel (red dots) and the ^{14}C dated algal rim (green triangle).

phase of the study of the algal rims along the Croatian coast; therefore, we have obtained only preliminary results to date, which indicate that the upper level algal rim at the Nova Pošta area is 404 ± 56 yr BP old.

Taking into account the morphology of the mentioned algal rim, it seems that the slowing of the sea-level rise starts at around -1m below the MSL, when the algal rims begin to develop. Correlating the position of the tidal notches with the algal rim morphology, two clear younger periods of very slow sea-level rise have been discerned, between which a speedier relative sea-level change could have occurred. Only small sections of the upper algal rim are alive today, the highest parts on the horizontal surface of the rim, as well as single talli in an interrupted line along the recent notch wall, slightly above the vertex. The clear change in coralline algae growth, up to the recent notch vertex, points to a very young relative sea-level rise as also noted in [51].

Northward from the studied area, in the central part of the Adriatic, the archaeological remains indicate a submersion of at least 1.5 m in 2 ka [3,4]. The influence of tectonic subsidence has been also indicated at the area of Pakoštane [52]. According to the archaeological remains and to the core evidences in the Istria and Kvarner area, the sea-level was defined at around -1.7 m at 2000 years BP [8,10,53]. Based on the new calibrated model results [8], which allow the separation of the isostatic from the tectonic contribution, the Adriatic coast, from the Gulf of Trieste to the southern end of Istria, has tectonically subsided by ~1.5 m since Roman times at an average rate of ~0.75 mm/a.

The Northern Adriatic area is characterised by development of the tidal notch that is particularly widespread – from the Gulf of Trieste to the shores of the southern Velebit Mt. [2,4,7,8,9]. It is regionally developed. Based on the core evidence, it is considered that the tidal notch on the Istrian Peninsula and the Kvarner area could have been formed between 1000 yr and 500 yr BP in an environment of very slow sea-level rise or during almost stable conditions. After the date of 500 yr BP, the subsidence started at different speeds in different structural units [10]. The Northern Dalmatian area has little evidence of submerged notches while the southern Dalmatian sector is marked with their sporadic development, generally in higher positions (-30 to -40 cm below MSL) in relation to the notches at the Northern Adriatic, which vary between (-45) cm and (-110) cm below MSL at the Kvarner and Istria area. Southwards, development of the recent notch becomes increasingly more frequent [4]. Reaching the coast of Montenegro, the recent notch is becoming particularly well developed [54].

Sea-level change is the sum of the eustatic, glacio-hydro-isostatic and tectonic factors. The first is global- and time-dependent, while the other two also vary according to local setting [8]. There are several predicted sea-level rise curves for the Mediterranean coast, e.g. Lambeck *et al*. [55], Lambeck and Purcell [56]. The latest one is more accurate because of the inclusion of the Alpine deglaciation model. As obtained by Lambeck and Purcell [56] through the geophysical model, the predicted sea-level along the coasts of Vis was between -5 and -6 m at 6 ka BP, and between -1 and -0.75 m at 2 ka BP, which is well above our results obtained from the archaeological remains of Issa harbour; therefore, this difference could be attributed to the tectonic subsidence of the area (Fig. 15).

The interpretation of the young algal rim indicator is more complex due to its position between the two curves and therefore it depends on the used model. If we take into account the Lambeck and Purcell [56] model, as probably a more accurate one, a small amount of subsidence is revealed, as well (Fig. 15).

Taking into account the total amount of relative sea-level change of 199 cm during 2.4 ka at the Island of Vis, an average rate of around ~0.83 mm/yr is derived. If the isostatic-eustatic component is separated, according to Lambeck *et al*. [55] and Lambeck and Purcell [56], we come to the tectonic subsidence rate of ~0.17 and ~0.3 mm/yr respectively (Fig. 15). However, compared to the subsidence rate of the Northern Adriatic area (whichever model is used – Lambeck *et al*. [55], from which it stands at 0.55 mm/yr, or a new one – Antonioli *et al*. [8], in which the average rate of subsidence comes to 0.75 mm/yr), the Island of Vis probably has a much smaller component of tectonic subsidence.

Similar data on the relative sea level change in different parts of the Eastern Mediterranean was obtained for the same time period, e.g. 0.9 mm/yr in [57] and 0.7-2.7 mm/yr in [58].

7. Conclusion

The archaeological remains of the Issa harbour provide two good reference levels for the definition of the relative sea level during the Greek and the Roman times on the island of Vis. For the period of 2300±100 yr BP, the sea-level was defined at -199±25 cm while later, the 1900±100 yr BP sea-level comes to -170±25 cm below the recent MSL. The geomorphological and biological markers are much younger and show the more recent slowing down of the sea-level change. The sporadically developed tidal notches and the large algal rim show two main periods of slower and two periods of speedier sea-level change. As the study of algal rims has just started, we expect much more data about the younger sea-level changes in the studied area in the future.

This work demonstrates the importance of the functional height definition as a function of the type of the archaeological structure and the tidal range of the investigated area. The definition of the functional height at MSL+ 40 cm for the remains in the Issa harbour seems to correspond well to the analysed port structures and local tide amplitudes.

The new data for middle Dalmatia (Island of Vis) obtained in this research gave further evidence of the complexity of the sea-level change across the Adriatic area. They provide new estimations of the relative sea-level change and vertical land movements on the island of Vis, based on archaeological, geomorphological and biological data.

Taking into account the total amount of relative sea-level change of 199 cm during 2.4 ka, we obtained an average rate of around ~0.83 mm/yr. The discrepancy between the obtained data, particularly those older than 1600 years PB, and the models [55,56] can be attributed to the active tectonics, as the southern Croatian coast is an area with recorded seismicity [22,23,59] and to active deformation as measured by geodetic methods [60,61]. The results, which range between 0.17 and 0.3 mm/yr, show much smaller average rates of subsidence compared to the Northern Adriatic. Furthermore, the submerged tidal notches and large algal rim point to periods of slower and speedier sea-level changes.

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