Geomorphological and archaeological indicators of Croatian shoreline evolution over the last two thousand years

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Abstract

The authors seek to correlate geomorphological and archaeological markers in order to trace the evolution of the Croatian shoreline over the past two thousand years. In the limestone along the Adriatic Sea coast of mainland Croatia from Porec to Zadar as well as on the islands of Cres, Rab and Pag, a submerged tidal notch between 0.5 m and 0.7 m below sea-level exists. The only exception is in Bakar Bay, where the notch reaches 1.15 m below present sea-level. Numerous archaeological remains in the same area indicate a sea-level change of 1.0-1.5 m during the past two millennia. In the Zadar-Šibenik region, archaeological remnants reveal a submersion of at least 1.5 m. At numerous sites, no notches were found; therefore, in that part of the coast the obtained results could not be correlated with a geomorphological marker. As far south as Korcula and Dubrovnik, notches occur only sporadically and unfortunately no appropriate archaeological markers were found there. Data were further correlated with recent tectonic movements and tide gauge measurements.

Keywords: Sea-level, Notch, Archaeological remnants, Croatian coast

Introduction

The Croatian shoreline was recognized long ago as one that has undergone submergence at an earlier date (Gnirs, 1908; Andrijaševic, 1909). Late Pleistocene-Holocene sea-level rise preoccupies numerous authors, such as Šegota (1982), Benac and Juracic (1998), and Suric *et al.* (2005). Many historians and archaeologists have attempted to estimate the degree and rate of the two millennia of sea-level change from submerged archaeological remains. For example, Degrassi (1955) estimated a change of at least 1.5 meters. Vrsalovic (1979) and later Kozlicic (1986) proposed a change of 2.0 m. Šegota and Filipcic (1991) calculated that Iron Age sea level was 3.1 to 1.96 m below the present level. The study of tidal notches as indicators of sea level change along the Croatian coast was initiated by Pirazzoli (1980). Later, Benac (1989, 1992, 1994) studied the presence of a notch in Rijeka Bay. Pirazzoli (1980) and Benac *et al.* (2004, 2008) mentioned the possible coseisimic submergence of the notches. Submerged marine notches, as well as, the archaeological remains along the Istrian coast also recently have been studied by Antonioli *et al.* (2004, 2007).

Since 1999, we have been gathering data concerning the evolution that has occurred in the Croatian shoreline over the last two thousand years. In our work we seek to systematically correlate geomorphological and archaeological markers from various points along Croatia's Adriatic coast (Fouache *et al.,* 2000, 2004, 2005; Faivre and Fouache, 2003). The main geomorphological marker used is the tidal notch, which is considered one of the best indicators of sea-level change (Pirazzoli, 1986), particularly in low-tide seas such as the Mediterranean. Such a geomorphological marker can be correlated with man-made shore-front structures found in the archaeological record. Combined, the history of sea level change can be deduced.

Methods

A series of dives have been carried out to detect potential fossil submerged notches in limestone cliffs. The creation of such notches primarily is due to bioerosion at the tidal zone, which reveals where shorelines existed in the past. Following the methodology developed by Flemming (1979-80)

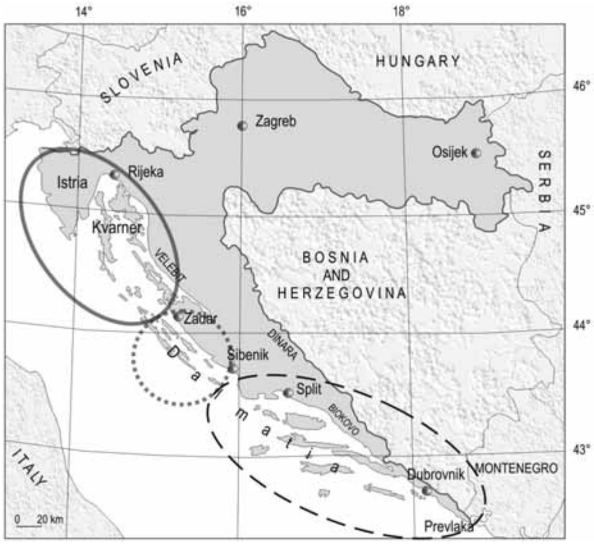


Fig. 1 - Study Area.

Fig. 2 - Submerged notch in Porozina Bay, Cres Island.

and Pirazzoli (1980), from Degrassi (1955) and Vrsalovic (1979) submerged archaeological remains were selected which were related to the ancient marine environment, such as jetties, harbours, and fish-ponds and referring whenever possible to archaeological sources. The areas concerned then were surveyed and evidence of ancient sea-levels was sought. In order to correct our measurements to present mean sea-level, daily tidal range curves were used.

Results

About seventy locations along Croatia's Adriatic coast were explored. As a result of those investigations, we roughly divide the Croatian coast into three major regions: the Istrian Peninsula and Kvarner coastal regions from Porec to Zadar (Istria-Kvarner); the coastal region between Zadar and Šibenik (Zadar-Šibenik); and the coastal region between Šibenik and the Prevlaka Peninsula (Fig. 1). This paper will address each of these areas in turn and discuss our findings in each.

The Istria-Kvarner region

Work began at Catoro Peninsula on the Istrian Peninsula in 1999. A submerged notch 0.5 to 0.7 m below present sea-level was found at many dive sites between Porec and Zadar, as well as on the islands of Krk, Cres (Fig. 2), Lošinj, Rab and Pag. In the Istria-Kvarner region the submerged notch is quasi-continuous. The only exception is the area between Kostrena and Bakar Bay where the notch is 0.7 to 1.1 m deep (Benac *et al.,* 2004). It is important to note that the notches display different morphologies depending on exposure and lithology.

Fortunately, the Istrian Peninsula is characterized by numerous Roman-era archaeological remains. The most important for sea-level investigations are those which have a direct connection with the sea, such as remnants of ports and fish ponds. The remains of the Roman harbor at Sveti Ivan Bay (Fig. 3) reveal that the foundations of the Roman jetties go down more than five meters. Their top parts are now at 1.0 m below sea-level. It is particularly important that the connections of these jetties to the mainland, a few meters away from the present shore, are now beneath 0.4 m of water. It is possible to infer from this that the average sea level rise from the first century C.E. cannot have highly exceeded 1.0 m.

The situation is similar in Valeta Bay (Fig. 4). Despite drastic human reshaping of the shoreline, following Degrassi's (1955) descriptions we identified one submerged Roman-era jetty consisting of large limestone blocks totaling 35.0 m in length and 10.0 m in width. It begins 5.0 m from the shore at a depth of -0.75 m. These stone blocks probably represent the basement; of course, the jetty was higher.

The third jetty was discovered in Busuja Bay (Fig. 5). It is 27.0 m in length and only the basement blocks are preserved today. Their upper portions are now -1.4 m below sea level (Fouache *et al.,* 2004).

The second type of archeological remains present in the area is fish ponds. In 2002 the Kupanja fish pond, which consists of a few basins, was investigated. The *in situ* blocks closest to the shore were -0.6 m below sea level (Fig. 6). The deepest point did not exceed -2.7 m. The same values were obtained at the Katoro fish pond (Fouache *et al.,*

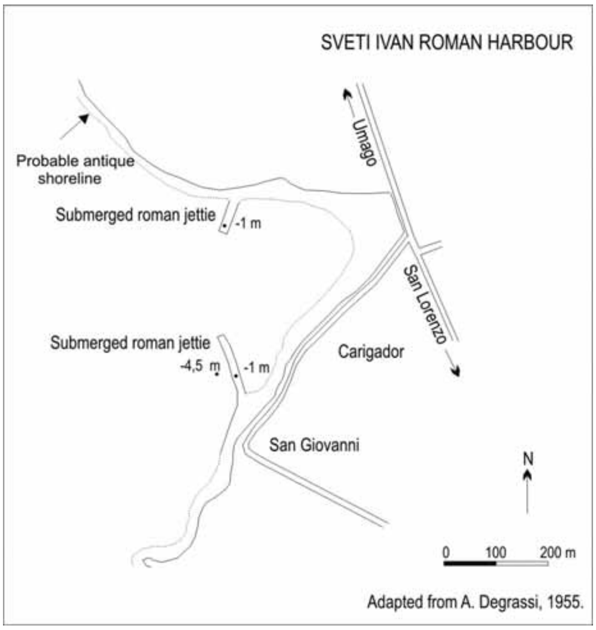


Fig. 3 - Submerged jetties in Sveti Ivan Bay.

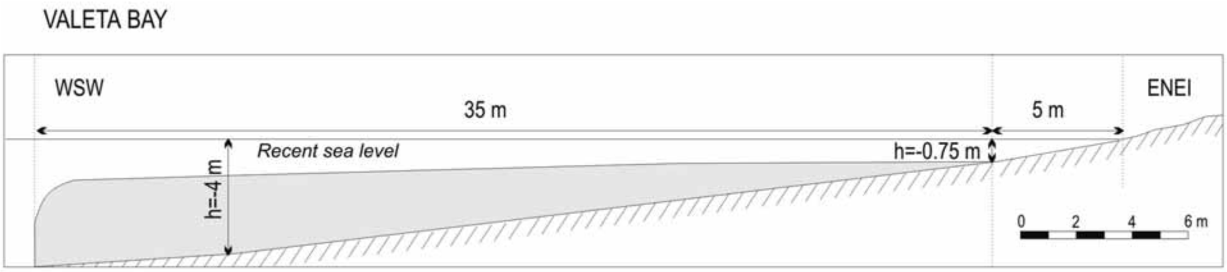


Fig. 4 - Submerged jetty in Valeta Bay.

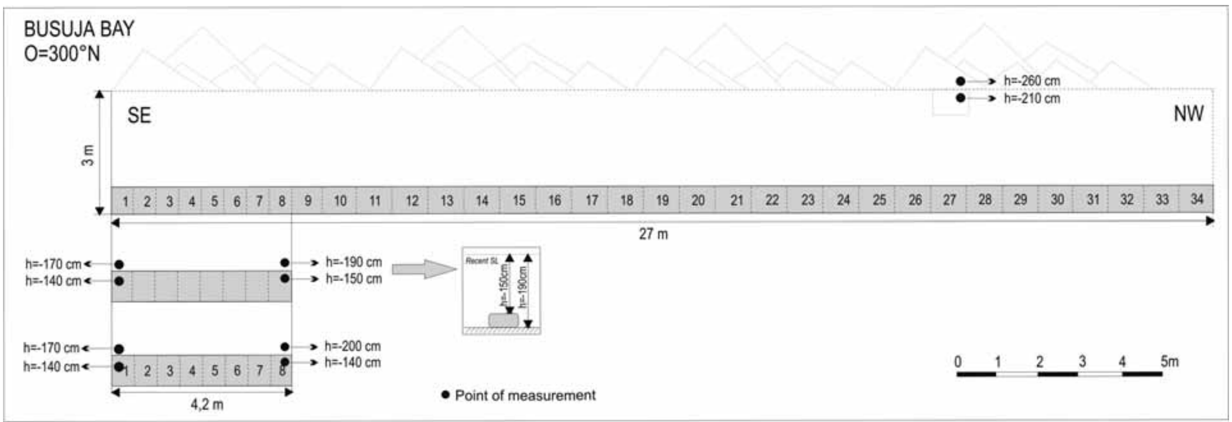


Fig. 5 - Submerged jetty in Busuja Bay.

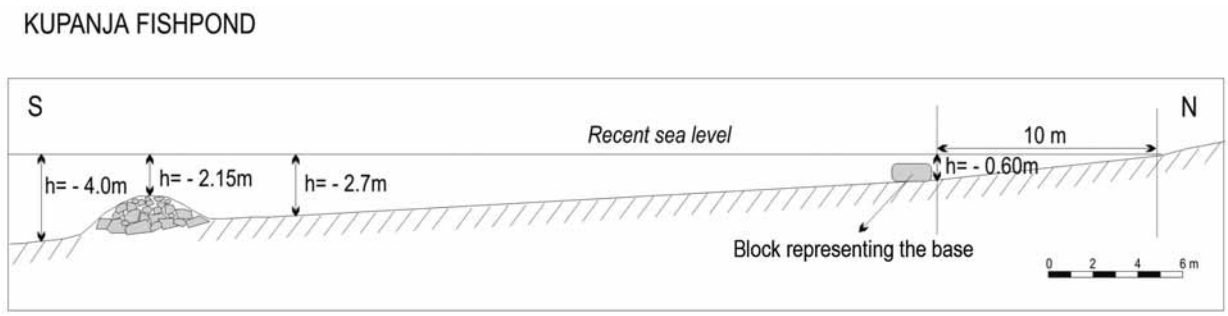


Fig. 6 - Submerged remains of the Roman fish pond in Kupanja Bay.

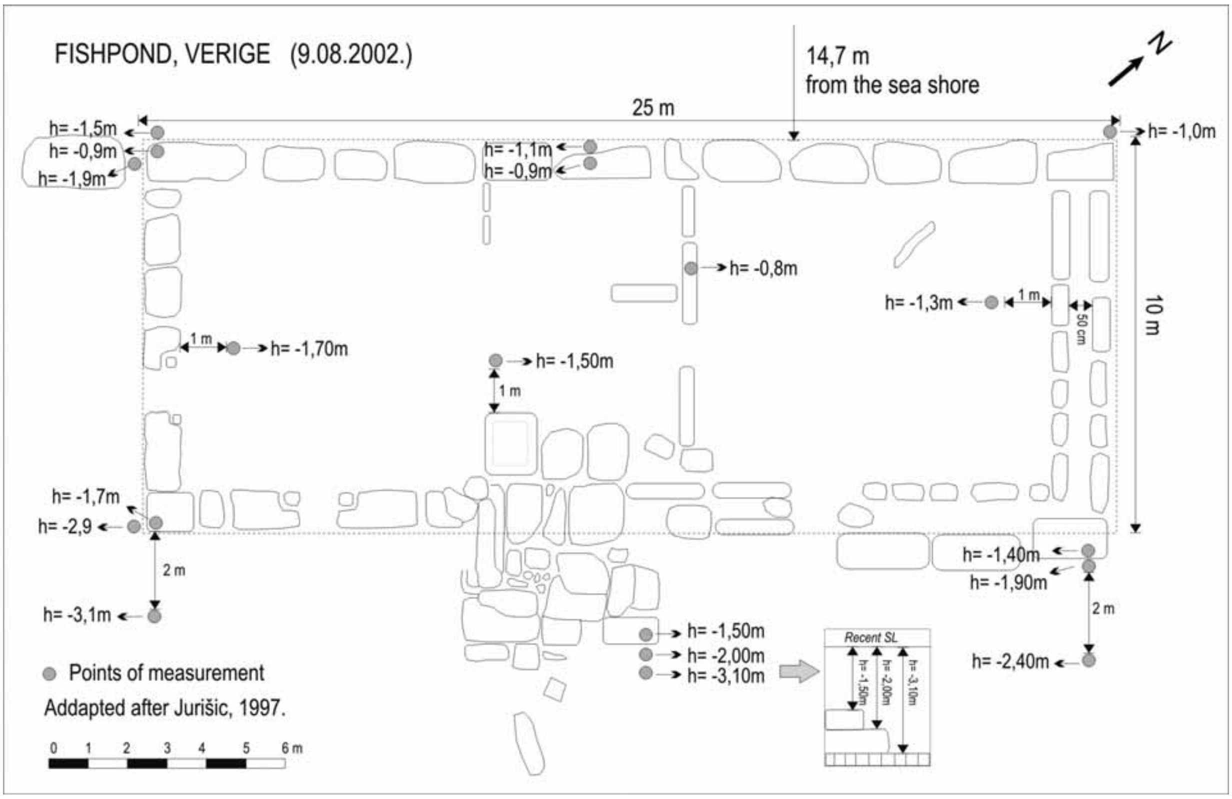


Fig. 7 - Submerged remains of the Roman fish pond in Verige Bay (adapted after Jurišic, 1997).

2000) as well as at the fish pond in Verige Bay on Brijuni Island (Fig. 7). Well preserved remains of a Roman jetty also were discovered in Verige Bay (Fig. 8).

The Zadar-Šibenik region

Down the coast from Zadar the geomorphological context changes: the slopes are gently inclined and the relief is low. In this area no trace of either present or submerged notches were found. In the whole region of northern Dalmatia, the markers of corrosion and biocorrosion which could be used as sea level indicators are absent. However, submerged Roman remains dating from the first and second centuries C.E. are abundant. The positions and depths of these numerous archaeological remnants point to a submersion of at least 1.5 m.

Particular significance has been assigned to fish

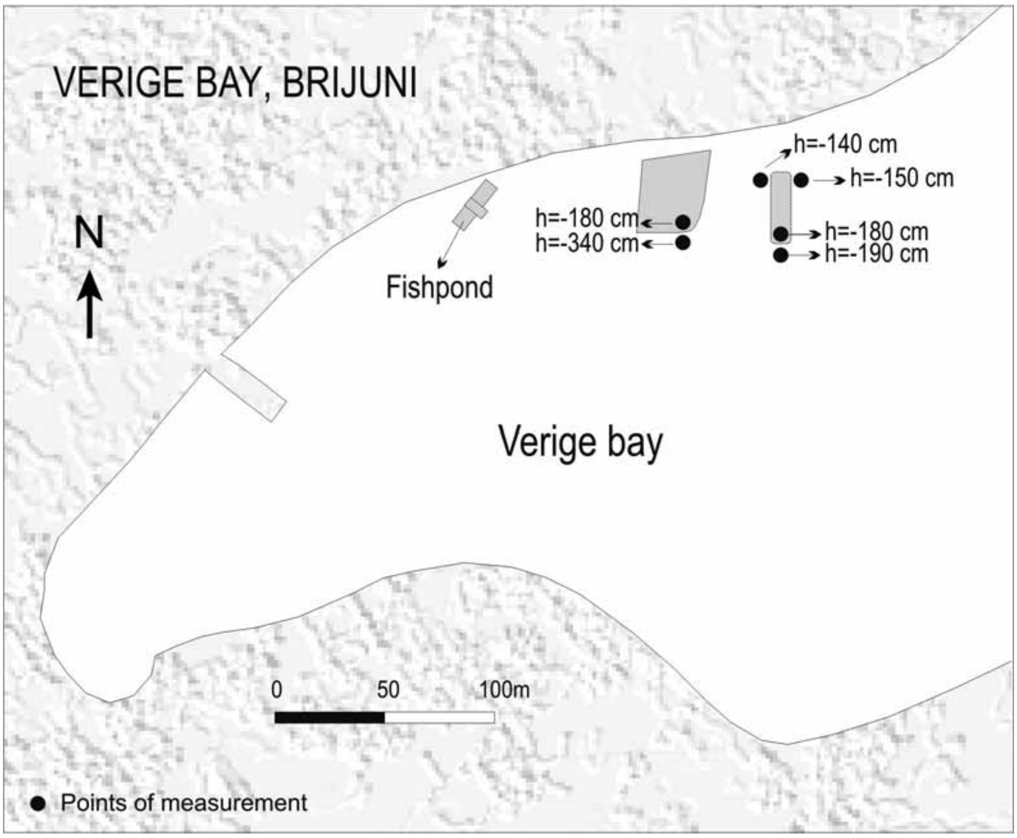


Fig. 8 - Submerged remains of the Roman fishpond and jetties in Verige Bay on Brijuni Island.

ponds. Unfortunately, no marker was derived from one located at the foot of the Roman villa of Mala Proversa because it was almost entirely destroyed during the digging of the navigation channel. The second one on Svršata Island is relatively well preserved (Fig. 9). The archaeological topographical measurement of its outline shows that the depth at which the breakwater structures (which protected the fish pond) join the shore are today between -1.3 and -1.4 m beneath sea level (Fig. 10). This indicates submersion of at least 1.5 m.

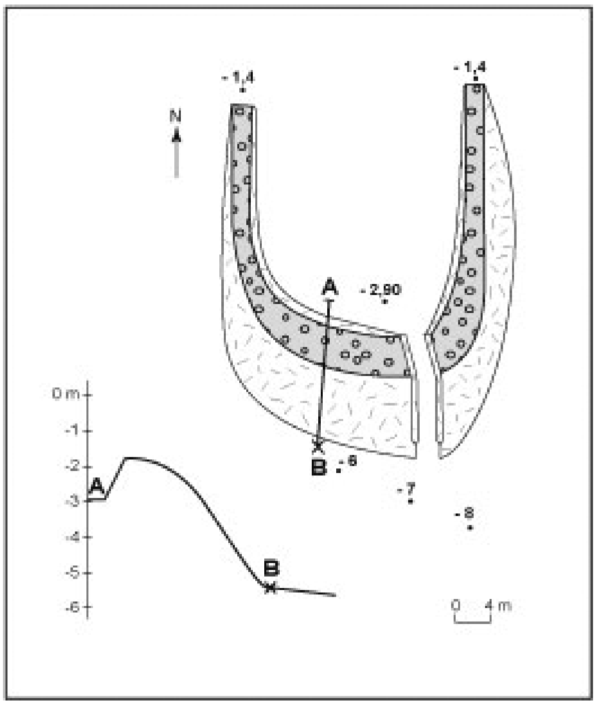
The port jetties at the Kumenat and Polacine sites east of the island of Pašman, provided similar indications. The jetty structures begin to appear at a depth of -1.4 m in the Kumenat area and at -1.6 m in the Polacine area. The latter is particularly interesting because of a long wall built on land which presently is -1.2 m under the sea (Fouache *et al.,* 2005).

The Šibenik-Prevlaka region

South of Šibenik there is a complete lack of appropriate archaeological markers useful for the reconstruction of past sea-levels. Therefore, geomorphological markers were sought. Seventeen sites in the region from Split to the Prevlaka Peninsula were explored and two interesting locations were found. The most intriguing was on the island of Korcula, where the coasts primarily are formed in Cretaceous limestone beds that have a steep inclination, often in excess of thirty degrees. We investigated seven sites: two on the north shore of the island and five on the south shore. In the northern sites no notches were identified, but in the southern ones a submerged notch was found at -0.4 m ± 0.1 m below present mean sea level (Fig. 11).

Further to the south, from Dubrovnik to the Prevlaka Peninsula, a few dives have been carried

Fig. 9 - Photo of the submerged Roman fishpond on Svršata Island.



out, but no submerged notches were located. However, a recent notch was found near Dubrovnik, which makes it the only area along the entire eastern Adriatic coast where a well developed recent notch has been discovered (Fig. 12). It is 0.44 m high and indented about 0.2 m, fitting precisely the data of the average tide. If the rates of marine corrosion of limestone in the intertidal zone proposed by Torunski (1979) – 0.7 to 1.0 mm per year – are taken into account, the approximate age of this notch can be calculated and an estimate of two hundred to three hundred years of sea level stability can be surmised. The recent notch was also observed and measured in few points at the nearby Lokrum Island.

Fig. 10 - Submerged Roman fish pond on Svršata Island (modified after Vrsalovic, 1979).

Discussion

The development of the significant submerged notch shows that the Istria-Kvarner region has undergone a rather long phase of sea level stabilization. A very slow sea level rise could also be envisaged, as indicated by Benac *et al.* (2004, 2008). Taking into account the rate of biocorrosion in the limestone rock (Torunski, 1979), this stabilization or very slow sea-level rise lasted at least five hundred years. It was followed by a quick subsidence; otherwise the notches would be destroyed or deformed. At present, the variation among measured points of depths of the notch is 0.2 m. The only important exception is in Bakar Bay where the notch reaches a depth of -1.1 m. Taking into account this depth, the variation is 0.6 m. This is probably due to the position of Bakar Bay on the active regional fault. The abundant archaeological remnants in the Istria region show different values for the depth of the structure points closest to the land. Consequently, it is difficult to establish a general conclusion for the whole area. According to the evidence at Sveti Ivan Bay, Valeta Bay, and the Kupanja fish pond, the mean value of those connections is -0.56 m. Because these structures must have been above sea-level at the time of construction, sea-level at that time could not have much exceeded -1.0 m. In Busuja Bay and at the Verige jetty, those connection points are deeper. So the variations are present among the archaeological remains as well.

The Zadar-Šibenik region displays relatively homogeneous properties. Here no notches were found, but there are abundant archaeological remains. Comparing the depth of the closest points of jetties to the land it is apparent that Frmic Island is at -1.3 m, Kumenat is at -1.4 m, Polacine is at -1.6 m, and Svršata fish pond is at -1.4 m – an average depth of -1.4 m. These results indicate that sea-level change over the past two thousand years in the Zadar-Šibenik region was greater than 1.5 m. The absence of fossil and recent notches may point that there has been no sea-level stabilization for the last two millennia.

In the Šibenik-Prevlaka region there are no appropriate archaeological markers which can be used for reconstruction of past sea-levels. The geomorphological markers in the area show varying and sporadic properties. The notch in the Korcula area is situated along a fault and is only locally present. The well developed recent notch in the Dubrovnik-Lokrum area points to the recent stabilization of relative sea level, which is in accordance with the tide gauge data. Calculating sea-level trends using the second degree polynomial for the four tide gauge stations at Rovinj, Bakar, Split, and Dubrovnik, Orlic and Pasaric (1997, 2000) concluded that over the last forty years, the values (correcting for local meteorological conditions) show 1.0 mm per year of sea level rise for the northern part of the Adriatic Sea, while in the southern part it is nearly stable.

Fig. 11 - Submerged notch on Korcula Island.

Comparing the results here with global positioning system (GPS) measurements obtained between the years 1994 and 1996 at fifteen points in Croatia (Altiner, 1999), some general agreement may be noted. For the computation of the station absolute coordinates and the velocity field, four International GNSS Service stations (Wettzel, Matera, Graz, and Zimmerwald) were involved in the processing, fixing their coordinates and velocities. This model indicates uplift for the majority of points in Croatia, but subsidence on

Fig. 12 - Recent notch in the Dubrovnik area.

the western side of the Istrian Peninsula (Kopar, Rovinj, and Pula), in the Zadar area, and at the islands of Vis, Hvar and Lastovo. In the relative model, station velocities were determined relative to the fixed coordinates and velocities of the station of Graz, Austria. In this case, all measured points show an increase of elevation. Because the variance between the two models is rather large, only the relative difference between the measured points can be considered.

Conclusion

Taking into consideration all of the results obtained along the Croatia's portion of the eastern Adriatic Sea, it is necessary to conclude that none of these sites, taken individually, allows the establishment of sea-level in the Roman era with absolute certainty. However, considered as a whole, it is possible to infer that sea level in the first and second centuries C.E. in the Istria-Kvarner region was probably between 1.0 and 1.5 m below present mean sea level and in the Zadar-Šibenik region at least 1.5 m below present mean sea level. In order to explain the difference between the regions, we suggest a possible phase of five hundred years of stabilization of the land-sea relationship – the time needed for the notch to be curved in the Istria-Kvarner region. This stabilization was not observed in the Zadar-Šibenik region over the same time period. The Šibenik-Prevlaka region shows local lowering in the Korcula area, and local stability is discernable in the Dubrovnik-Lokrum area.

Comparing our results with those of Orlic and Pasaric (1997, 2000) concerning crustal uplift and the GPS measurements (Altiner, 1999) taking into account only the values of relative movement, it is clear that the results fit into a general trend. It is hoped that further research will provide more precise indicators.

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