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Submerged notches, coastal changes and tectonics in the Rijeka area, NW Croatia

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ABSTRACT

Submerged coastal notches characterize the coast of the wider Rijeka area, NW Croatian coast, Adriatic Sea. These notches originate from a notch formed approximately 2,000 years ago, their depth ranges between 0.50 and 1.15 m and their subsidence history is a matter of debate. A detailed study of all the available data in relation to the tectonics of the area was made using signal analysis techniques. Our analysis revealed that the notch depth reflects the superimposition of two different effects, a quasi-regional relative sea-level rise of about 55 cm, and of a subsequent, local, tectonic subsidence with amplitude gradually increasing to 60 cm in the vicinity of the major thrust in the Bakar Bakar–Vinodol area. Elastic dislocation modeling permitted to explain this last local subsidence in terms of loading of the footwall of this thrust and provide evidence for an unrecorded earthquake of minimum magnitude M_w 6.8, which occurred most probably in the last few centuries. This result indicates that the convergence between the Southern Alps and the Adria is at least partly accommodated by earthquakes, and puts some constraints in the estimations of the seismic risk in the wider region.

1. Introduction

Coastal notches represent erosion marks in carbonate coasts, formed in response to biological and mechanical erosion. The notch vertex is adjusted to the mean sea level, and for this reason, fluctuations of the sea level are printed on the notch profile and elevation and their study permits to put some constraints on the sea-level change history (Fig. 1; Pirazzoli, 1982, 1986; Laborel and Laborel-Deguen, 1994). Submerged coastal notches, evidence of a fossil sea-level approximately 0.5 m lower than the present one, have since long been identified along the Croatian coast, in the Adriatic Sea, along a distance of more than 150 km, between Zadar and Rijeka (Fig. 2 Pirazzoli, 1980; Fouache et al., 2000).

The submerged notches in the wider Rijeka area, in the innermost part of the Adriatic, covering an area 30×40 km wide, have been recently studied in details by Benac et al. (2004, 2008) who showed that their depth ranges between 0.50 and 1.15 m below present mean sea level.

The variable depth of this notch in the Bakar area has been assigned to tectonic events and earthquakes by Benac et al. (2004), but in absence of major earthquakes in coastal Croatia in the last centuries (Del Ben et al., 1991; Camassi and Stucchi, 1996; Herak et al., 1996; Slejko et al., 1999; Albini, 2004; Guidoboni et al., 2007; Stucchi et al., 2007), the processes responsible for their subsidence became a matter of debate and these notches have been even regarded as an "enigma" (Antonioli et al., 2004; Pirazzoli, 2005).

The aim of this article is to shed some light on the relationship between earthquakes, tectonic movements and coastal changes, and hopefully provide a solution to this enigma.

2. Geomorphological and Seismotectonic background

The study area is at the innermost part of the Adriatic Sea, and is underlain by a Mesozoic carbonate platform marked by sub-parallel, usually oblique-slip north-dipping thrusts or reverse faults. These faults belong to a main fault zone, shown for simplicity as a line in Fig. 2 and which accommodates crustal shortening at the border of the Adria-Eurasia plates at a rate of approximately 2 mm/year (Anderson and Jackson, 1987; Carulli et al., 1990; Del Ben et al., 1991; Caporali et al., 2003; Serpelloni et al., 2005; Pondrelli et al., 2006; Meletti et al., 2008). Tectonic activity controls to some degree the relief; for instance, the Bakar Bay–Vinodol Valley represents a topographic depression between two fault-controlled folds (Fig. 3). However, there is no clear evidence of major (M_w>6) earthquakes, nor of seismic faulting during the Holocene in the study area (Del Ben et al., 1991; Camassi and Stucchi, 1996; Herak et al., 1996; Slejko et al., 1999; Albini, 2004; Guidoboni et al., 2007; Stucchi et al., 2007).

From the geomorphological point of view the study area can be classified as an area of marine transgression, as is the case with the adjacent Dalmatian coasts, which are characterized by ria-type shorelines, i.e. a relief produced by aerial or sub-aerial erosion, subsequently modified by marine transgression. The flat-floor, 50 m-deep Bay of Rijeka and the 30 m-deep nearby Bay of Trieste have since long been recognized as

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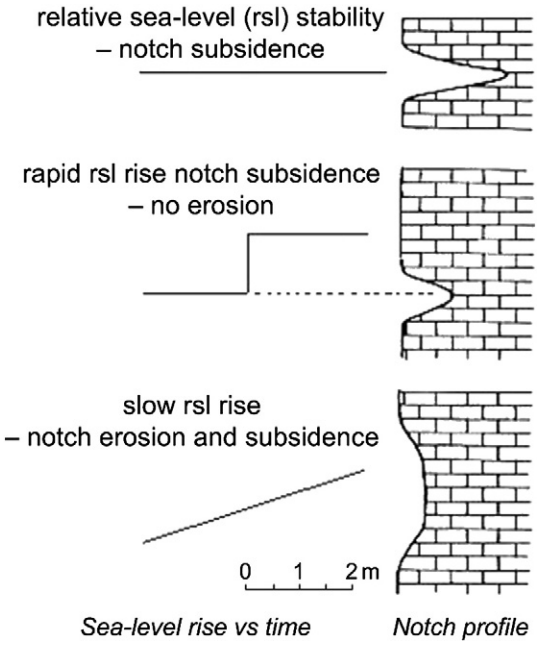

Fig. 1. Scenarios for the formation, modification and fossilization of a coastal notch profile in carbonate rocks as a function of the tidal range and of the relative sea-level changes. The Croatian notches analysed correspond to the upper two diagrams. Modified after Pirazzoli 1986.

examples of submerged, fossil sub-aerial erosion levels (Demek et al., 1984). Sea-level rise has continued in Holocene, as the submerged notches (see above), underwater springs and caves (Benac, 1996; Benac et al., 2003; Surić et al., 2010) and submerged ancient ruins (Fouache et al., 2000) reveal. Recently, based on stratigraphic data, Faivre et al. (2011) identified a rather rapid marine transgression in this area at around 500 BP.

On the contrary, to the northern part of the Bakar Bay–Vinodol Valley streams are incised (Benac, 1996; Benac et al., 2005), providing evidence of a local lowering of the stream base level, which, in combination with the marine transgression (base level rise), can only be regarded as evidence of local land uplift (see Weber et al., 1979).

Still, on the basis of eustatic–isostatic modeling Lambeck et al. (2004; Fig. 12) and Antonioli et al. (2007, Fig. 8; 2009, Fig. 1) regarded the study area as a region of predominantly tectonic stability with local areas of subsidence or uplift, and estimated a sea-level rise between 0.4 and 0.75 m for the last 2000 years.

3. Data: submerged notches in the Rijeka Area

Systematic studies of the coastal micro-morphology and biology in carbonate rocks in various parts of the world (Pirazzoli, 1986; Pirazzoli et al., 1988; Laborel and Laborel-Deguen, 1994; Stiros et al., 1994; Stiros and Pirazzoli, 2008) have shown that, under certain conditions, the mechanical and biological erosion along the coasts tend to form notches with their vertex at mean sea level and with their opening (lower-upper level) adapted to the tidal level. In the case of relative sea-level stability in low-tide waters a narrow, deep notch is formed (Fig. 1). Fluctuations of the sea-level are overprinted on the notch profile and permit the identification of the kinematics of relative sea-level change (Fig. 1; Pirazzoli, 1986; Stiros et al., 1994; Laborel and Laborel-Deguen, 1994).

3.1. Main characteristics of the submerged notches

The basic characteristics of the Rijeka notches are the following:

(i) They are observed in an area at least 150 km wide, between Zadar and Rijeka (Fig. 2; Fouache et al., 2000), but they are discontinuous, most probably observed in sites in which lithological and other conditions permitted their formation and preservation. Low salinity water, for instance, near karstic springs, abundant in the area (Benac et al., 2003) is a reason controlling the coastal fauna and hence bio-erosion (Laborel and Laborel-Deguen, 1994) and preventing notch formation (Stiros et al., 2007).

(ii) Their vertex is at the mean depth of 55 cm, with the exception of those in the Bakar area, which range up to 115 cm. The depth of the vertex of these notches is summarized in Benac et al. (2004, 2008) and in Fig. 4 and Table 1.

(iii) The notch surfaces do not show signs of significant erosion, especially their submerged roof, and this indicates that that there was not enough time for significant erosion (Laborel and Laborel-Deguen, 1994), hence their drowning occurred relatively recently,

(iv) As Benac et al. (2004, 2008) have shown, these notches seem to share the same profile and dimensions. Given that the hydrographic conditions in the studied area are characterized by rather uniform tidal conditions and the astronomic tide is small (30 cm; Benac et al., 2004), the observed submerged notches are likely to originate from a single notch which was formed sometimes with its vertex at the mean sea level of that period (Pirazzoli, 1980, 1982, 1986; Benac et al., 2004, 2008).

(v) Archaeological evidence provided by Fouache et al. (2000), in particular a correlation of the notch vertex with the former sea-level deduced from Roman coastal remains, indicate that this notch was formed approximately 2000 years ago, in accordance with previous ideas of Pirazzoli (1980). Despite the recent studies in the Italian coasts (Antonioli et al., 2007; Auriemma and Solinas, 2009; Faivre et al., 2011; Furlani et al., 2011) no finer or alternative estimates of the age of the submerged notches have been proposed. For this reason we adapt the likely hypothesis that these notches were formed during a period of relative sea-level stability in the Roman period (Fouache et al., 2000; Pirazzoli, 2005) and were submerged in a later period, i.e. in less than 2000 years ago.

(vi) Benac et al. (2004) discussed the possibility the subsidence of the Rijeka notches to be associated with certain 4th c. AD earthquakes, but no clear evidence for that was provided.

(vii) West of the study area, in the Italian territory, there is evidence of other notches at larger depths (Bondesan et al., 1995; Fouache et al., 2000; Antonioli et al., 2004, 2007; Faivre et al., 2011; Furlani et al., 2011). These notches, however, have a different pattern, are most probably older than those in the Rijeka area, seem to originate from juxtaposition of different effects and their study is beyond the scope of this paper.

3.2. Dataset analyzed

In our study we used a dataset consisting of coordinates of measuring stations and the notch depth covering an area 40×35 km wide, shown in Fig. 4 and in Table 1. These data come from the merging of the two datasets presented by Benac et al. (2004, 2008). In particular we used the data in the Rijeka Bay and Vinodol Bay by Benac et al. (2004), 32 points in total (first data set), supplemented by a second data set, 42 observations east of the straits between Krk Island and the mainland, i.e. all data in the list of Benac et al. (2008) excluding points 1–9 and 20–26, common in the first data set. In addition, the Cartesian coordinates of the first data set were corrected with zero padding to counteract a missing last digit.

A critical point in micro-morphological data is their accuracy. The depth of the vertex of the submerged notches used in our analysis was measured with much care and with cm resolution using precise underwater techniques in reference to GPS altimeter data. Such elevations are very precise but accurate to ±10 cm at the best for the following reasons: