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Tidal notches in Mediterranean Sea: a comprehensive analysis

Fabrizio Antonioli [a], Valeria Lo Presti [b, a, *], Alessio Rovere [c, d], Luigi Ferranti [e], Marco Anzidei [f], Stefano Furlani [g], Giuseppe Mastronuzzi [h], Paolo E. Orru [i], Giovanni Scicchitano [j], Gianmaria Sannino [a], Cecilia R. Spampinato [k], Rossella Pagliarulo [l], Giacomo Deiana [i], Eleonora de Sabata [m], Paolo Sansò [n], Matteo Vacchi [o], Antonio Vecchio [f]

[a] ENEA, UTMEA, Casaccia, Roma, Italy
[b] Department of Earth Sciences, "Sapienza" University, Rome, Italy
[c] MARUM, University of Bremen & ZMT, Tropical Marine Ecology Center, Bremen, Germany
[d] Lamont-Doherty Earth Observatory, Columbia University, NY, USA
[e] Department of Earth Sciences, Environment and Resources, "Federico II" University, Napoli, Italy
[f] Istituto Nazionale di Geofisisica e Vulcanologia, Roma, Italy
[g] Department of Mathematics and Geosciences, University of Trieste, Italy
[h] Department of Earth and Geoenvironmental Sciences, "Aldo Moro" University, Bari, Italy
[i] Department of Chemical and Geological Sciences, University of Cagliari, Italy
[j] Department of Phisics and Earth Sciences, University of Messina, Italy
[k] Department of Biological, Geological and Environmental Sciences, University of Catania, Italy
[l] CNR, IRPI, Bari, Italy
[m] MedSharks, Roma, Italy
[n] Department of Biological and Environmental Sciences and Technologies, University of Salento, Lecce, Italy
[o] Aix-Marseille Université, CEREGE CNRS-IRD UMR 34, Europole de l'Arbois Aix-en-Provence, France

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A B S T R A C T

Recent works (Evelpidou et al., 2012) suggest that the modern tidal notch is disappearing worldwide due sea level rise over the last century. In order to assess this hypothesis, we measured modern tidal notches in several of sites along the Mediterranean coasts. We report observations on tidal notches cut along carbonate coasts from 73 sites from Italy, France, Croatia, Montenegro, Greece, Malta and Spain, plus additional observations carried outside the Mediterranean. At each site, we measured notch width and depth, and we described the characteristics of the biological rim at the base of the notch. We correlated these parameters with wave energy, tide gauge datasets and rock lithology.

Our results suggest that, considering 'the development of tidal notches the consequence of midlittoral bioerosion' (as done in Evelpidou et al., 2012) is a simplification that can lead to misleading results, such as stating that notches are disappearing. Important roles in notch formation can be also played by wave action, rate of karst dissolution, salt weathering and wetting and drying cycles. Of course notch formation can be augmented and favoured also by bioerosion which can, in particular cases, be the main process of notch formation and development.

Our dataset shows that notches are carved by an ensemble rather than by a single process, both today and in the past, and that it is difficult, if not impossible, to disentangle them and establish which one is prevailing. We therefore show that tidal notches are still forming, challenging the hypothesis that sea level rise has drowned them.

1. Introduction

Marine tidal notches (hereafter MTNs) are indentations or undercuttings, few centimetres to several metres deep, cut in steep calcareous cliffs at or near sea level (Carobene, 1972; Pirazzoli, 1986; Kelletat, 2005). Although the measurement of tidal notches

* Corresponding author. Department of Earth Sciences, Mineralogy-Geology Edifice (no. 5), Sapienza University, 5 Aldo Moro square, 00185, Roma, Italy.
E-mail address: valeria.lopresti@uniroma1.it (V. Lo Presti).

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in the field is trivial and can be done using simple instruments such as a stick metre, two aspects in the study of notches remain challenging. The first is the understanding of the mechanisms of their formation, which can be ascribed to chemical dissolution processes in the intertidal zone, wetting and drying cycles, biological erosion or wave action or, most likely, a combination of these factors. The second is that notches cannot be dated directly, and the estimate of their age relies, in the best cases, on the dating of organisms that form the biological rim covering part of the notch (Pirazzoli et al., 1994; Faivre et al., 2013) or correlating the elevation of a notch with other datable markers. In the worst cases, relative age estimates can be obtained comparing notch (bio)erosion rates and the dimensions of the notch.

Due to the difficulty in establishing the age of MTNs, there is an ongoing debate regarding their origin. The classical view is that MTNs are shaped around mean sea level and each time that a MTN is found out of the tidal range, or each time its shape deviates from the typical half-ellipsoidal shape (Carobene, 1972; Pirazzoli, 1986), there has been either a rapid (coseismic or volcano-tectonic) or a gradual (e.g. due to regional tectonic processes) land movement. To this view, some authors (Cooper et al., 2007; Evelpidou et al., 2012) countered a model where formation of notches can happen only during periods of relative climatic and sea level stability, when bioerosion can 'keep up' with the pace of sea level rise.

Based on areas located in Greece (coasts of the Corinth Gulf, the Euboean Gulf and several Cyclades islands), Evelpidu et al. (2012) stated that: '*The most recent continuous sea level rise has resulted to the absence of a present-day notch*'.

Building on this hypothesis, Pirazzoli and Evelpidou (2013) state that present-day tidal notches are not forming anymore near sea level, while a 'fossil' tidal notch (developed before the sea level rise of 19th and 20th century) is often found between −20 and −65 cm below present sea level. They assert that '*present-day tidal notches are worth being re-measured and re-interpreted*'. One consequence of their hypothesis is that, if proved, tidal notches would lose most of their significance as markers of more or less rapid tectonic movements. Boulton and Stewart (2014) addressed this discussion by analysing a database of Holocene tidal notches dated using radiocarbon ages on fossil incrustation on the notch. They showed that the notches are not clustered around any known period of climatic stability as it would be expected if the hypothesis advanced by Cooper et al. (2007) is valid.

This ongoing debate, coupled to the observation of the presence, along the world's stable sedimentary carbonate coasts, of modern tidal notches, stimulated the collaboration of the group of researchers authoring this paper. We performed a reassessment of notches that are located near present sea level at 73 sites distributed along many carbonate coasts of the Mediterranean Sea (Fig. 1a; S1 supplementary material, hereafter SM). These sites were selected because their relative tectonic stability has been postulated on the basis of independent markers, most often the elevation of the Last Interglacial shoreline (MIS 5e, ~125 Ka ago, Ferranti et al., 2006, and references therein). We collected in-situ observations and measurements of the morphology of MTNs along the coasts of Croatia, France, Greece, Italy, Malta, Montenegro and Spain. In addition, we incorporate observations carried at 5 stable sites outside the Mediterranean Sea.

At each site we measured the different elements of MTNs and the presence, thickness and characteristics of the algal rim, as well as the lithological composition of the limestone. We then compare the measured notches and the thickness of the algal rims to wave energy and tidal ranges, to contribute to the understanding of notch formation. In this paper we show the implications of our results in terms of processes contributing to the shaping of tidal notches and relationship between tidal notches and sea level.

2. Notches in the Mediterranean: relevant aspects

2.1. Geologic context of the Mediterranean basin

The Mediterranean area marks the broad convergent boundary between the African and the Eurasian plates. The geodynamic characteristics of this region are dictated by lithospheric blocks showing different structural and kinematic interaction, including collision, subduction, back-arc spreading, and fold-and-thrust belt development. The complexity of the orogen is attributable in large part to the original geometry of the opposing plate margins and the existence of continental blocks within the western Tethys (Channell and Horvath, 1976; Jolivet and Faccenna, 2000; Serpelloni et al., 2007; Royden and Papanikolaou, 2011, Fig. 1b).

The coasts straddling the Mediterranean orogenic belts are characterized by a variable pattern of long-to short-term vertical tectonic motion, as documented by the elevation of ancient strandlines (Ferranti et al., 2006, 2010). An estimate of the stability of Mediterranean coastal areas can be derived from geomorphological indicators of the Holocene and of the Last Interglacial shoreline position. From these data it is evident that many sectors of the Mediterranean Sea exhibit significant vertical tectonic movements at least since MIS 5.5 and up to the recent (Ferranti et al., 2006, 2010) (Fig. 1c). Conversely, others sectors can be considered stable or affected by very low tectonic motions; these last are the areas studied in this work. Stratigraphic, morphological paleontological, archaeological and chronological data (Flemming and Webb, 1986; Pirazzoli, 1991; Antonioli et al., 2009; Ferranti et al., 2010; Vacchi et al., 2012; Sulli et al., 2013; Anzidei et al., 2011; 2014), indicate that, in general, the western Mediterranean coasts can be considered tectonically stable in the last 125 ka, while large sectors of Italy, Greece and Turkey are characterized by rapid transitions between subsiding, uplifting or stable coasts during the same span of time. On the other hand, stability or low tectonics characterize in general the coasts of North Africa for which published paleo shorelines exist.

2.2. Climate, waves, hydrological conditions and tides

Enclosed between the storm belt of northern Europe and the tropical area of northern Africa, the Mediterranean has a relatively mild climate on the average, but substantial storms are possible, usually in the winter months (Cavaleri et al., 1991; Cavaleri, 2000). The Mediterranean winter climate is dominated by the westward movement of storms originating over the Atlantic and impinging upon the western European coasts, he maximum measured significant wave height reaches 10 m, but model estimates for some non-documented storms suggest larger values (Giorgi and Lionello, 2008). Furthermore, Mediterranean storms can be produced within the region in cyclogenetic areas such as the lee of the Alps, the Gulfs of Lyon and Genoa; moreover, the number of exceptional storms linked to Tropical-Cyclones generated in Southern Mediterranean region is recently increasing (Lionello et al., 2006; Rebora et al., 2013). High pressure and descending motions dominate instead during the summer period, leading to dry conditions particularly in the southern Mediterranean.

The summer Mediterranean climate variability has been found to be connected with both the Asian and African monsoons and with strong geopotential blocking anomalies over central Europe (Alpert et al., 2006; Giorgi et al., 2008). The coasts of Mediterranean Sea are genetically connected to the presence of extended catchments shaped on carbonatic rocks. As such, they are largely characterized by karst groundwater springs, that reach the surface both above or below mean sea level. Such springs have been inferred to influence the development of marine notches (Higgins, 1980;