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Abstract: Recent works state that the modern tidal notch is disappearing worldwide due to sea level rise in the last century. In order to assess this view, we measured the largest possible number of sites where the modern tidal notch is present around sea level. We carried out our work in the Mediterranean sea, which has narrow tidal ranges and low-intensity sea storms if compared to other seas, and where the study of tidal notches has been extensively reported in literature. We surveyed 73 coastal sites in Italy, France, Croatia, Montenegro, Greece, Malta and Spain, and we report observations made on tidal notches worldwide. At each site, we measured notch width and depth, the characteristics of the biological rim at the base of the notch, and we correlated these parameters with wave energy, tide gauge data and rock lithology. The results of observations and measurements shed a new light on: i) the accurate elevation of mean sea level with respect of the notch position; ii) the correlation between morphometric features and meteomarine processes; iii) the mechanisms that influence the genesis and evolution of tidal notches, including those derived from: chemical (mixing-corrosion), biological (erosion by intertidal organisms), mechanical (meteomarine), vertical tectonics, and climatic processes. Our data show that in tectonically stable areas the current tidal notch is always present, apart from rare exceptions (2/73 sites) related to local limiting factors. Our results suggest that notches are not disappearing worldwide, but modern notches are the result of complex interactions between a series of factors affecting their formation. This leads to new interpretations on the genesis and evolution of tidal notches and restates their importance as sea level indicators.

ENEA
Agenzia nazionale per le nuove tecnologie, l'energia
e lo sviluppo economico sostenibile

Roma 23.10.2014

Prof Colin Murray Wallace,

Editor in chief

Dear Editor,
please find attached the manuscript entitled 'Tidal notches in the Mediterranean Sea: a comprehensive analysis', signed by myself and other 15 authors. Such a large number of authors has allowed us to collect data in 73 sites in the Mediterranean and 5 out of the Mediterranean for comparison. Our manuscript is accompanied by 12 figures, 4 tables , and, as supplementary material, 1 Table, 1 excel file, 1 kml file and 1 short movie (ftp://utmea.enea.it/fabrizio.antonioli/notches.mpg). .

Our manuscript, as described in the introduction, has been motivated by recent works that state that the tidal notch is disappearing worldwide due to the modern sea level rise. We tried to assess this view measuring the largest possible number of sites in the Mediterranean, which has narrow tidal ranges and low intensity storms if compared to other seas. We believe that our results open to new interpretations on the genesis and evolution of tidal-notches and their use as sea level indicators.

I attach a list of opposed Reviewers:
Paolo Pirazzoli, retired CNRS
contrasting opinion on present marine nothes existence

Niki Evelpiou PHD
Earth Science, Athene university Greece
contrasting opinion on marinetidal notch existence

Christophe Morhange Researcher
CNRS CEREGE

We look forward to hear from you in due course

Best regards,

FABRIZIO ANTONIOLI

Ps as requested we attached a link with a short video that we wish to submit with article.

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Highlights (for review)

- Our manuscript, has been motivated by recent works that state that the tidal notch is disappearing worldwide due to the modern sea level rise.

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Tidal notches in Mediterranean sea: a comprehensive analysis.

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Keywords: *tidal notches, Mediterranean sea, relative sea level rise, Holocene.*

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Abstract

Recent works state that the modern tidal notch is disappearing worldwide due to sea level rise in the last century. In order to assess this view, we measured the largest possible number of sites where the modern tidal notch is present around sea level. We carried out our work in the Mediterranean sea, which has narrow tidal ranges and low-intensity sea storms if compared to other seas, and where the study of tidal notches has been extensively reported in literature.

We surveyed 73 coastal sites in Italy, France, Croatia, Montenegro, Greece, Malta and Spain, and we report observations made on tidal notches worldwide. At each site, we measured notch width and depth, the characteristics of the biological rim at the base of the notch, and we correlated these parameters with wave energy, tide gauge data and rock lithology. The results of observations and measurements shed a new light on: *i*) the accurate elevation of mean sea level with respect of the notch position; *ii*) the correlation between morphometric features and meteomarine processes; *iii*) the mechanisms that influence the genesis and evolution of tidal notches, including those derived from: chemical (mixing-corrosion), biological (erosion by intertidal organisms), mechanical (meteomarine), vertical tectonics, and climatic processes.

Our data show that in tectonically stable areas the current tidal notch is always present, apart from rare exceptions (2/73 sites) related to local limiting factors. Our results suggest that notches are not disappearing worldwide, but modern notches are the result of complex interactions between a series of factors affecting their formation. This leads to new interpretations on the genesis and evolution of tidal notches and restates their importance as sea level indicators.

1. Introduction

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

'*The most recent continuous sea level rise has resulted to the absence of a present-day notch*' (Evelpidu et al., 2012): this sentence contrasts with the observation of the presence, along the world's stable carbonatic coasts, of a well evident present-day tidal notch, and stimulated the collaboration of the group of researchers authoring this paper. In less than one year we visited and measured 73 sites in central Mediterranean sea (Fig.1a; S1 supplementary material, hereafter s.m.) and 5 outside Mediterranean, with the aim to understand why tidal notches are indeed present along most calcareous coasts.

Although the measurement of tidal notches in the field is trivial and can be done using simple instruments such as a stick meter, two aspects in the study of notches remain challenging. The first is understanding the mechanisms of their formation, which can be ascribed to chemical dissolution in the intertidal zone, 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 case, on dating of organisms forming the biological rim covering part of the notch or, in the worst case, on relative age estimates that compare notch (bio)erosion rates and the dimensions of the notch.

Mainly due to these problems in establishing the age of notches cut at different level in coastal cliffs, there is an ongoing debate regarding the origin of MTNs. The classical view is that, if a MTN forms around mean sea level, each time that a MTN is found out of the tidal range, or each time the form of the notch deviates from the typical half-ellipsoidal shape (Carobene 1972, Pirazzoli 1986), this means that there has been a land movement, either rapid (coseismic) or gradual (tectonic). To this view, recently some authors (Cooper et al., 2007; Evelpidou et al., 2012) countered a view where notches can form only during period of relative climatic and sea level stability, when bioerosion can ‘keep up’ with the pace of sea level rise. Building on this hypothesis, Pirazzoli and Evelpidou, 2013, based on fieldwork from Greece, 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. For this reason they argue that ‘present-day tidal notches are worth being re-measured and re-interpreted’, arguing that they may correspond to fresh-water visors or surf notches.

Boulton and Stewart, 2014 addressed this discussion analysing a database of Holocene tidal notches dated using radiocarbon on fossil incrustation on the notch, and 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 true. In this paper, we tackle this discussion from a slightly different angle: as suggested in the recent paper by Pirazzoli and Evelpidou, 2013, we performed a reassessment of notches that are located near present sea level at 73 sites distributed along many coasts of the Mediterranean basin (Fig. 1a; S1 s.m.), for which tectonic stability or quasi-stability has been postulated on the basis of independent markers (e.g. the MIS 5e shoreline).

We collected in-situ observations and measurements of the morphology of MTNs along carbonatic stable or quasi-stable coasts of Croatia, France, Grece, Italy, Malta, Montenegro and Spain. At each site we measured the different elements of the MTNs and the presence and characteristics of the thickness 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 investigate the causes of notch formation.

Our results show that considering active bioerosion, at any time in the Holocene or Last Interglacial, as the only driver for MTNs formation and development (Evelpidou et al., 2012) is a simplification that can lead to misleading results. Important roles can be played by wave action, rate of karst dissolution, salt weathering and wetting and drying cycles (Trenhaile, 2014), and notch formation can be augmented by facilitative bioerosion (i.e the effect of the biota on the properties of rock material, Naylor et al., 2012). Our dataset shows that notches are carved by an ensemble of processes rather than by a single one, 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 question the hypothesis that sea level rise has drowned modern notches. In conditions of tectonic stability, this will happen only if the rates of rock consumption by the processes responsible for notch formation as a whole will be surpassed by rates of eustatic sea level rise.

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 driven 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 (Serpelloni et al., 2007, Jolivet and Faccenna, 2000, Channell and Horvath, 1976, 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 pertaining to Holocene and the Last Interglacial. From these data it is evident that many sectors of the Mediterranean sea exhibit vertical tectonics movements for late Holocene and MIS 5.5 (Ferranti et al., 2006, 2010) (Fig. 1c), while others can be considered stable or affected by low tectonic motions; these last are the areas studied in this work. In general, the western Mediterranean coasts can be considered tectonically stable in the last 125 ka, while Italy, Greece and Turkey are characterized by rapid transitions between subsiding, uplifting or stable coasts during the same span of time. Stability or low-tectonic motion characterizes in general the coasts of North Africa (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., 2014).

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). The maximum measured significant wave height reaches 10m, but model estimates for some non-documented storms suggest larger values. Even in the Adriatic Sea, that has a relatively small fetch, Cavaleri (2000) reports that an oceanographic tower located 15 km offshore and anchored on16 m water depth, suffered heavy damage up to 9m above sea level.

The Mediterranean winter climate is dominated by the westward movement of storms originating over the Atlantic and impinging upon the western European coasts (Giorgi & Lionello 2008). Furthermore, Mediterranean storms can be produced within the region in cyclogenetic areas such as the lee of the Alps, the Gulf of Lyon and Genoa; moreover, recently the number of exceptional storms linked to Like Tropical Cyclones generated in Southern Mediterranean region is increasing (Lionello et al. 2006).

Differently, high pressure and descending motions dominate over the Mediterranean region during the summer, leading to dry conditions particularly over its southern part. 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.

Genetically connected to the presence of extended carbonatic coastal areas, karst groundwater springs the Mediterranean Sea is largely interested by karst groundwaters springs that emerge both above or below the mean sea level along these ones; they have been inferred to influence the development of marine notches (Higgins, 1980; Furlani et al., 2014a). Karst drainage systems can produce high discharges because they represent the output point from an extensive network of groundwater conduits. Flows from springs can be perennial, seasonal or intermittent, anyway, in the Mediterranean, it follows the seasonal pattern of the rainfall regime. During strong rainfall events, or flash flood due to Cyclonic perturbations, a large number of new springs can be activated (Bonacci et al., 2006). A map of the coastal and submarine springs with outflow larger than 1000 liters per second is shown in Fig.1a (Civita, 2008).

Tides vary from place to place along the coasts of the Mediterranean, depending on more parameters, such as coastal geometry and bathymetry. Tides in this region have low amplitudes with respect to those of the Oceans. They have an average amplitude of about 40 cm, with the exception in the Gulf of Gabes and, in some cases, in the North Adriatic sea, where may reach amplitudes up to 1.80 m.

In other areas, such as in Greece or Sicily, tides are very small, especially near the amphidromic points where the tidal range has about zero value. In the vicinity of the Strait of Gibraltar, the Atlantic ocean affects the tides in the Mediterranean, but its influence declines further east rapidly. However, atmospheric conditions may affect the rhythmic tidal rise and fall in sea level, causing larger oscillations or even hide them at all.

2.3 Formation of notches

Nearly half of the Mediterranean rock coasts (Fig. 1a) are built of carbonatic rocks (Furlani et al., 2014b) that date back from Mesozoic to the Quaternary. Carbonatic coasts are characterized by a typical set of landforms, which are related to a combination of physical, chemical, and biological processes. Their relative importance are dependent to the geographical setting and the local conditions. Chemical solution and biological weathering are the driving factors in carbonatic coasts development in the Mediterranean coasts (De Waele and Furlani, 2013).

As a result of the lithological composition of the coast, the coastlines of the Mediterranean offer the possibility to observe a wide variety of coastal karren, bioerosional, depositional and bioconstructed features (Taborosi and Kazmer, 2013), such as, for example, notches, tide pools, solution pans, potholes and shore grykes. Carbonatic coastal landforms are affected by a wide set of interrelated processes that are locally contingent, and cannot be described by a global scheme (De Waele and Furlani, 2013). In this study we focus on two of such coastal landforms. We define Marine Tidal Notches (MTNs) the undercuttings found at or near tidal level on carbonatic cliffs with characteristic shaped morphology (Fig. 2a,b,e). MTNs are characterized by both roof and a floor, which is often covered by biological incrustations. In the particular case where the notch lacks a floor, we defined it as Roof Notch (RN, Fig.2c). We highlight that these two definitions are entirely based on morphology, and not on the processes forming the MTNs and RNs. Also, hereafter we refer to ‘notches’ to indicate univocally both MTNs and RNs.

MTNs and RNs are most common on carbonate rocks, although recently Trenhaile (2014) has argued that notches form also as a consequence of wetting and drying cycles in volcanic lahar deposits in Mexico. Focusing on carbonate rocks, four processes are considered responsible for the formation of notches.

Biological agents - Different kinds of organisms can live attached to the rock near sea level and contribute to the evolution of notches. Among them, the most known is *Lithophaga lithophaga* (Bromley et al., 1990; Spencer, 1992), that is an endolithic bivalve living in galleries bored in calcareous rocks by glandular secretions (Morton & Scott, 1980). The removal of rock particles is guaranteed by the movement of the valves. Another important class of bioeroders are grazers (mainly sea urchins), that play a major role along coral reef coastlines (Peyrot-Clausade et al., 2000; Spencer & Viles, 2002). In the Mediterranean, Torunski (1979), quantified bioerosion by urchins in 19 g CaCO3m^{-2} for *Paracentrotus lividus*, and in 295 g CaCO3m^{-2} for *Sphaerechinus granularis*. *P. lividus* and

Arbacia lixula bores in the bedrock depressions that vary from cup-shaped to deep pockets having a narrow entrance opening. The boring of this species is major in the north-western coasts of Europe, whereas in the Mediterranean the species is widespread but generally does not bore. However, Martinell, 1982, observed that in the Western Mediterranean *P. lividus* is commonly found in its cup-shaped borings in extremely shallow rocks of very different lithology (igneous, metamorphic and sedimentary rocks). Schneider & Torunski, 1983, highlighted that drastic changes in the biological zonation (like the mass invasion of the sea urchin *P. lividus* in the Northern Adriatic since 1972) can have a profound effect on the bioerosion rates.

S. granularis erodes large and easily identifiable areas on Corallinaceae thalli. Its erosion rates vary between 16 and 210 g CaCO3 m-2 (Sartoretto & Francour, 1997), the higher values corresponding to areas where *S. granularis* is steadily replaced by Echinus melo, another large echinoid (Laborel et al., 1961). Further bioerosion is caused by endolithic Cyanobacteria (Le Campion-Alsumard, 1979) in the supralittoral zone, together with limpets (*Patella* spp.) and Chitons in the midlittoral zone (Laborel & Laborel-Deguen, 1996).

On the other hand, some hard bottom communities can protect the bedrock from erosion (Laborel & Laborel-Deguen, 1996; Naylor & Viles, 2002; Spencer & Viles, 2002). In the Mediterranean, constructional (and therefore protective) elements are the rim-building coralline rhodophyte *Lithophyllum lichenoides*, brown algae (*Cystoseira* and *Sargassum*), fixed Vermetid Gastropod Molluscs (*Dendropoma* spp., *Petaloconchus* spp.), Cirrhipeds (*Balanus* sp. and *Tetraclita* spp), as well as *Mytilus* sp. and *Ostrea* sp.

Wetting and drying cycles and salt weathering - The importance of these processes in notch formation has been recently highlighted by Trenhaile (2014). In the spray zone, called supralittoral in biological zonation (Laborel & Laborel-Denguen, 1996), haloclastic processes trigger cliff erosion through the penetration of saline water into structural discontinuities of the bedrock and its evaporation, with the subsequent deposition of salt crystals, which can grow from solution, expand due to heating or change their volume due to hydratation. These processes lead to modification in the volume of the crystals, which causes an increase of pressure on the walls, triggering the fragmentation of the rock. Another important weathering process along rocky coastlines is associated to wetting and drying cycles (Stephenson & Kirk, 2000; Kanyaya & Trenhaile, 2005; Trenhaile & Porter, 2007). In cold climates, weathering due to frost action plays also a significant role in the upper part of the cliff (Trenhaile & Mercan, 1984).

Hyperkarst - The debate upon the possibility that carbonates can be dissolved in seawater lasts since the early 30's (MacFadyen, 1930). Solution of a calcareous rock depends on the saturation of the seawater with respect to calcium carbonate. If the seawater is under saturated in this component with respect to the lithology, then dissolution can occur. This happens in proximity of springs of groundwater (Higgins, 1980) or due to water mixing (Kaye, 1957; Verstappen, 1960) or by surface film effects due to gaseous exchanges with the air (Emery, 1962). Kelletat (2005) argues that seawater is always oversaturated (in tropical and subtropical latitudes several times supersaturated) by dissolved carbonates and is not able to destroy carbonates by solution. To falsify this hypothesis, Furlani and Cucchi (2013) collected micro erosion meter data on a vertical limestone slab in the Adriatic Sea and suggested that the shape of the tidal notch is consistent with the distribution of erosion rates along the slab. Downwearing rates range from about 0 mm/yr to 0.260 mm/yr, according to the elevation of the measured point with respect to sea level. Furlani et al. (2014a) argue that, in the northeastern Adriatic Sea, the carbonate dissolution seems to be strictly linked to the presence of spring water as hypothesized by Higgins (1980).

Mechanical erosion - While wave abrasion *sensu stricto* (i.e. wave abrasion due to sand or pebbles used as abrasion tools against the rock) plays no part in notch development, mechanical erosion can still happen in the intertidal to slightly supratidal zone for two main reasons.

Firstly, the resistance of the rock to wave attack is function of its lithology and of the structural discontinuities characterizing it (Kleypas et al., 1999). These can be cracks, cleavages, joints, faults, and bedding planes, some being inherent in lithology and others being of tectonic origin. Under wave action, the air contained inside the interstices is suddenly compressed, resulting in a pressure increase exerting a stress on the walls of the opening, widening and deepening it until the removal of part of the rock. This process acts in the zone where air and water alternate, i.e. above and below the fluctuating waterline (Trenhaile, 2002). Secondly, along limestone coastlines, chemical and biochemical dissolution processes happening near tidal level may favour mechanical erosion by influencing the material properties of rock and weakening or creating joint or boundaries (Table 4 of Naylor et al., 2012).

2.4 Rates of erosion in the intertidal zone

Recently, studies on the dynamics of intertidal erosion have been conducted (De Waele and Furlani, 2013). These studies focused mainly on processes and rates of bioerosion and karst corrosion. Torunski (1979) proposed the bioerosion as the main factor for erosion processes in the intertidal zone, whereas Higgins (1980) and Furlani et al. (2014a) suggested that freshwater is the driven factor for the genesis and development of the tidal notch. Naylor & Viles (2002) suggested that algal covering significantly reduces biological and chemical weathering.

Field measurements have been conducted in different areas since the end of the seventies mainly using the micro erosion meters traversing micro erosion meter (MEM and TMEM) to measure erosion rates offshore platforms and sloping limestone surfaces (Furlani and Cucchi, 2013). Torunski (1979) reported erosion rates in the range of 0.07-1.114 mm/yr from a carbonate intertidal zone of the northeastern Adriatic, which is mainly composed by slightly inclined plunging cliffs. Furlani et al. (2009) indicated lower values for the supratidal zone, at 0.09-0.194 mm/yr and suggested that erosion rates in the supratidal and subtidal zone are one order of magnitude lower than the intertidal zone for the same type of coast. Moreover, it has been pointed out that seasonal variations are possible in carbonate lowering rates, with higher rates in summer (Torunski, 1979) and in autumn (Furlani et al., 2009).

Swantesson et al. (2006) and Fornós et al. (2006) measured shore platforms lowering rates using MEM, TMEM and laser scanners on limestone rocky coasts along the Balearic islands. They estimated erosional rates in the range of 0.021-0.323 mm/yr, while Gómez-Pujol et al. (2006) measured values ranging between 0.003 and 2.1 mm/yr and they attributed the large span to ecological constraints and rock lithology. Gómez-Pujol et al. (2006) compiled erosion rates of cliffs and shore platforms and concluded that they are not in equilibrium with contemporary processes. Primary control is mainly exerted by geological constrain and inheritance, such as the sea level change. In any case, bioerosion, granular disintegration, are slowly modifying the main cliff-platform morphology.

In some cases, such as in the Gulf of Trieste, the lacking of the present-day notch and the occurrence of an underwater notch (Fig. 2d) has been related either to the tectonic subsidence of the area (Antonioli et al., 2004, 2007) or to temperature variations, such as the Medieval Warm Period where enhanced dissolution was possible. In the Gulf of Trieste, Furlani et al. (2010) estimated erosion rates of limestone surfaces located in the intertidal zone, and on the contribution of seawater and the bioerosion effects to notch development (Furlani and Cucchi, 2013), through a micro erosion meter. Furlani and Cucchi (2013) measured maximum rates up to about 0.3 mm/yr occurring in the mid-intertidal zone. Even if bioerosion and bioconstruction are thought to be the most effective processes involved in the notch development, Higgins (1980), De Waele and Furlani, (2013) suggested that fresh groundwater from coastal and submarine springs can significantly increase the dissolution of carbonates. Furlani et al. (2014a), from the processing of morphological and hydrogeological data collected along 250 km of the southern and western Istrian coast, suggests that the location of the submarine notches are matching the distribution of the main submarine springs that pour freshwater into the sea.

The brief review of lowearing rates reported above show that measurements indicate that lowering rates (that include all the notch formation processes described in the previous paragraph) range from 0.02 to 2.1 mm/yr, a range which contains the rates of bioerosion reported by Evelpidou et al., 2012 of 0.2 to 1.28 mm/yr. This reinforces the idea that, although bioerosion is one of the mechanisms intervening in notch formation, it is not the only one.

3. Methods

3.1 Field data

In this study, we measured the modern notch in 71 out of 73 visited sites along carbonate coastlines in the Mediterranean, as illustrated in Fig. 3, S2 (s.m.). We took the following measures: Average notch width (A); Notch depth (B); Bottom (reef when present) depth (C); presence, thickness and main species constituting the biological rim at the base of the notch (D); Depth of cliff toe (E).

All measurements were taken with calm sea and were referred to mean sea level using the tide gauge data from the nearest tidal stations (www.idromare.it; http://www.ioc-sealevelmonitoring.org/map.php), including corrections for atmospheric pressure at the time of measurement. Repeating our measures several time at the same site, we estimated an error of 5% in the recorded values.

We measured the dimensions of the notches by an invar rod, while the geographic positioning by a GPS Garmin Montana 650T and plotted on Google Earth maps (S1 s.m.). All coordinates are expressed as Lat/Long in WGS84 reference system. Accuracy of the investigated sites is within 10 meters.

At each site, we used official nautical cartographies and data from oceanographic buoys to evaluate the exposure of the site to wave action. According to this, we classified the investigated sites in very exposed, exposed or sheltered.

At each site, we documented the notch by photographs and videos. Part of this documentation is attached as supplementary material to this publication. At each site we also reported bedrock lithology and age. We also report the elevation above sea level and width of the Last Interglacial notch (if present).

3.2 Tidal ranges

As the availability of tidal records does not cover adequately our measurement sites, we adopted a twofold strategy to include for each observation an estimate of the tidal range.

We first analyzed the sea level records at 17 stations in the Mediterranean sea. All the datasets are characterized by 1h sampling rate. Some data span an interval of ~16 yr (Bari, Cagliari, Civitavecchia, Imperia, Marseille, Napoli, Otranto, Palermo, Taranto), ~15 yr (Carloforte, Catania, Lampedusa, Porto Torres, Salerno), ~3,5 yr (Gaeta), ~3 yr (Ponza and Elba islands). Data from Italian stations have been provided by the Italian tidal network managed by ISPRA (www.mareografico.it); the Marseille records have been retrieved from the Réseaux de réféence des observations marégraphiques (REFMAR, http://refmar.shom.fr/home). To characterize the sea level variability at each station we show the histogram representing the number of hours per year for which a given sea level occurs (Fig. 4). These plots have been built by calculating the residual sea level (LR) obtained by subtracting the temporal mean <L> from the original sea level time series L:

$$LR = L - \langle L \rangle \ .$$

Then, the interval over which the residual sea level ranges [Lmin, Lmax] is divided into N bins of 5 cm length; the number N depending on the station. N, Lmin , Lmax values for each station are shown in Table1. Finally, the number of data points falling into each bin is counted and converted into hours per year.

As the tide gauge stations often are located far from our study sites, we extracted tidal range for all our 73 locations the Mediterranean regional version of the Tidal Prediction Software developed at the Oregon State University (OTIS, Egbert and Erofeeva, 2002). The model can be considered as a state-of-art tidal model that assimilates most of the available satellite altimetric data (Topex Poseidon, Topex Tandem, ERS) and in situ observations (i.e. tide gauges, ship born ADCP). The Mediterranean model has a resolution of 1/30° (about 3.7 Km) and makes use of the GEBCO 1' database as bathymetry. The model considers the main eight tidal components (m2, s2, n2, k2, k1, o1, p1, q1) that account for more than 99% of the total tidal elevation. In Table 1 we report the values calculated using the model described above at our tide gauges against the values calculated from the tide stations. We obtain differences in the range of ~4cm (Table1). We highlight that this number should be taken at face value, as it is possible that some of the data in the tide gauges have been used to develop the tidal model, therefore elements of circularity might be present in our calculations. Nevertheless, we argue that the model produces values of tidal range that are consistent with the tide gauge data available.

3.3 Wave energy

Wave action has an intrinsic energy, that at least in deeper waters is function of wave height and period. This energy is transferred from the offshore seas to the nearshore coastal region, where diffraction and refraction processes come into play and energy offshore traduces into energy on the coast. In this paper we estimated the yearly climatological wave energy flux (in kW/m) associated to our sites (excluding those with roof notches and those repaired in bays or gulfs) using the daily data produced by Liberti et al. (2013) for the period 2001-2010. The computed yearly values are shown in Fig.5a,b,c.

4.0 Results

We measured MTNs and RNs at 68 and 5 localities, respectively, and only at two sites, Circeo and Capri, the notch is absent. The results of measurements are shown in Table 2, S3 (s.m.) and Fig.6, while photographs representing some of the notches are shown in Fig.2 (supplementary information and coordinates of our sites are shown in the S3, attached to this publication). We also studied and measured 5 notches outside Mediterranean (see chapter 5.5).

In general, the lithology and age where notches are carved are varied. As Table 3, S4 (s.m.) points out, the geological units range from the Early Cambrian (Gonnesa Formation) in Sardinia to the Middle Trias (Dolomites of San Pietro dei Monti) in Marseille; from Lower Jurassic- Lias (Inici Formation) at Scopello in Sicily, to Upper Jurassic- Malm (Monte Bardia Formation) at Orosei Gulf and Cefalù Formation in Sicily; from the Cretaceous limestone in Apulia to with the Oligocene (Brecciole Nummulitiche) at Talamone and in Apulia (Castro Limestone); from the Miocene (Capraia Formation) at the Tremiti Islands to the Miocene-Pleistocene calcarenite at Favignana island and Jonian Apulia.

As a consequence of the great variability in age and lithology, the fabric and the physic-mechanical characteristics of these rocks are quite different. A first classification is possible between massive and hard rocks and calcarenite that can be defined as “weak rocks”.

It is necessary to point out that intact rocks materials and samples coming from quarries seem different from the open air masses where the measured notches are present, due to the exposition to weathering and wave actions along with the presence of tidal reef that have deleted at least to the naked eyes, the original fabric and the petro-physical properties. Therefore the following classification takes into account the intact rock without considering other parameters such as if the rock mass is stratified or contains joints or discontinuities. The physic-mechanical parameters of the different groups of rock types described in Table 3 are merely indicative. Abstracting and analysing the geological formations in Table 3 it is possible a first classification on the basis of the content of calcite and/or dolomite, fabric and petrophysical characteristics in *Limestones facies and Calcarenitic Facies* (S4, s.m.).

At all sites, some kind of biological coverage of the notch bottom was found. We refer to this as a ‘biological rim’, derived from the term ‘algal rim’ that has been largely used in Mediterranean marine ecology to indicate the rim formed around sea level by corallinaceous algae (Laborel and Laborel-Deguen, 1996) The most conspicuous coverage is constituted by corallinaceous algae, especially *Lithophyllum* spp., and Vermetids, but in many cases the biological community inhabiting the notch was composed by Mytilus, Patellae, Chtamalidae and Balanidae. The biological coverage reaches thicknesses of up to 25 cm.

At twelve sites we also measured the elevation above mean sea level and the width of the notch pertaining to the Last Interglacial (Ferranti et al., 2006, Fig.2g). These notches have been preserved in most cases thanks to the presence of younger sediments covering them (Fig.2f).

5. Discussion

5.1 Is there a relationship between notch size and tidal and wave conditions?

Comparison of the width of notches located near the tide gauge stations with the tidal data (Fig.7) highlights that the width of the notch is always higher than the mean tidal range, but smaller than the maximum and minimum tidal ranges. In order to investigate how width and depth of notches vary between exposed and sheltered sites, we plotted these values against the tidal range calculated using the OSU tidal model described above (Fig.8a,b,c,d). In average, all the tidal notches we measured are 45-70 cm wide and 40-100 cm deep, although more extreme values are possible.

In sheltered areas, the notch width is ~0.3 to 3.2 times the tidal range (Fig.8c, Fig.7), a ratio that seems maintained in exposed sites (Fig.8d,e,f), although with larger variability. In exposed sites, the depth of the notch seems to increase with respect to sheltered sites (Fig.8a,b). This is also evident by comparing notch width and depth. These results suggest that increased wave action results in an increased notch depth rather than an increased notch width, which seems more constant and related, to some extent, to the tidal range and maximum and minimum tidal values (Fig.7). We also note that, grouping our data according to the lithology (Fig.8g), stratified limestone seem to have a width/depth ratio lower than sandstones and limestone, reinforcing the hypothesis that, in weaker lithologies, wave action affects notch depth rather than notch width.

5.2 Thickness of the biological rim and wave energy

It is difficult to quantify the role exerted by the wave action on the genesis of MTNs because waves have both a direct (mechanical abrasion) and an indirect (reef growth) action on notch development. Because the former process can be hardly quantified, here we focus on the indirect contribute to notch growth, by analyzing at each site the relation between reef thickness measured at the notch base, and wave energy (kw/m) at the coast. We excluded from computation the sites located in sheltered settings (S3 s.m.). It is evident from Figure 5d the tight relation between high wave energy and reef thickness.

In some sites (Badisco, Biddiriscottai, Cala Fuili, Fig. 6), also from outside the Mediterranean area (Fig.9b, Barbados) one or more steps (10-12 cm in size) in the *Lithophyllum* reef has been observed, whose origin is still to be understood.

5.3 Notches in the past

According to the conceptual model shown in Fig.9a the formation of the MTN starts at the first sharp decrease of the sea-level rise at 6.8 ka cal BP (Lambeck et al., 2011). This flex in the relative sea-level (RSL) curve has been widely recognized in the Mediterranean Sea independently from the relative role of contributing processes (and namely the glacio-isostatic component). We extracted from Lambeck et al. (2011) the RSL curve for Trieste, which has a minor glacio-isostatic contribution when compared to other coastal sites from the Mediterranean Sea (blue line in Fig.10a), and the RSL curve for Cagliari (SE Sardinia, purple line in Fig.10a), which, conversely, has a larger glacio-isostatic contribution. A sharp decrease in RSL rise is evident in both curves (5.6 and 7.36 mm/yr, respectively, between 8.0-6.8 ka cal BP; 0.6 and 1.42 mm/yr between 6-2 ka cal BP, 0.27 and 0.78 mm/yr cal BP between 2 ka and the past century, when the RSL rise increases to 1.25 mm/yr).

These observations, when integrated with the maximum age of uplifted notches in the Mediterranean Sea (Fig. 2h), are in agreement with the database published by Boulton e Stewart (2014) (Fig. 10b), where the oldest notches are always younger than 6.5 ka. Fig. 10a shows that at coastal sites with relatively minor glacio-isostatic contribution, MTNs are presently located at shallower depths (-4 m b.s.l. at Trieste compared to – 10 m at Cagliari). Isostatic processes therefore play an important role on conditions leading to notch formation: tide gauges at Cagliari, Trieste and Genova record slightly different ranges. The rate increase observed during the last century in the RSL rise, and the past and present notch evolution, suggest that MTNs will continue to form when the RSL rise will be >1.42 mm/yr and until it will not exceed 5.6 mm/yr (Fig. 10a).

During development, the MTN evolves between ~6.8 ka cal. BP (coinciding with the decrease in RSL rise) and the present-day (Fig. 10a, 10c). Within geologically stable areas, older notches are not preserved above -10 m b.s.l. because the continued sea-level rise and the accompanying abrasion led to destructive retreat of the sea-cliff. The rapid dissolution and destruction of the rocky coast is testified by the characteristic “nose” (Fig. 10c, Fig. 6). Where the organic reef (mainly coralline algae and Vermetid reef) covers the bedrock and shelter it from dissolution and abrasion, the cliff retreat is halted, as documented by the morphology of fossil notches aged above 5 ka BP.

As showed in Fig 10c, the tidal notches evolution allow a retreat of the cliff of at least 3 meters or more for the last 6.8 ka cal. BP.

The Last Interglacial notch, well preserved only when sheltered by younger deposits, observed today at 4-7 m a.s.l., shows on average a higher (10-15 cm) width than the modern notch. This difference is attributed to the existence of an active reef which conceals the floor of present notches and partly alter its size (Fig. 2g, f).

5.4 Notch: yes or not?

In rare occasions the MTN does not form. Apart from the obvious lack of the notch at coasts made of non-carbonate rocks, it also does not occur where carbonate beds have vertical dips (Fig.11a), it is discontinuos when carved in light limestone (Fig.11c,d, where it attains a 4-5 m depth and then collapses, e. g. Barbados). Besides, we did not observe the notch at the Circeo promontory (Fig.11b) and at Capri island (Table 2).

At Circeo, where the Last Interglacial notch is also absent, the coast is crowded of colonies of Mytilus and large Balanids. We make the hypothesis that the biological tapestry acts against notch development. In addition, large fresh-water springs do not exist at this coast (Civita, 2008). At Capri, instead, the Last Interglacial notch is well and continuosly developed (Ferranti and Antonioli, 2007), but the present notch does not exist (only a wide *Lithophyllum* rim is observed at few sites), because fresh water spring with a ≥1000 m^3/sec flow are absent. Of course, the remarkable development of the Last Interglacial notch requires that important springs existed during the MIS 5.

5.5 Outside the Mediterranean

Comparison between tidal changes (both predicted and observed) and notch morphometric data at each studied site documents that: 1) the notch concavity is always some dm wider than the tidal range (Table 2, S3 s.m.) the mean tide never exceeds the maximum notch curvature (Fig. 7). Based on this, we argue that the salt water sprayed from waves is responsible for consumption of the upper part of the notch either through dissolution and through the enhanced upward growth of consuming organisms. Analysis of extra-Mediterranean notches such as those found at Barbados, Zanzibar (Tanzania), Bonaire (Netherland Antille), Phi Phi island, (Thailand) and Blue Bay and Port Luis (Mauritius) (Fig.9, Table 4) shows that the present notch is invariably wider than the maximum local tide (recorded by tide forecast http://www.tide-forecast.com)

5. Conclusions

We may summarize the conclusion of our investigations by the following key points:

- The tidal notch in the Mediterranean is, rather than the effect of a single process, the result of several processes that concur with different rates to the lowering of the cliff. These processes act iteratively. Considering only one process (Evelpidou et al., 2013) may lead to wrong conclusions with respect to lowering rates.
- As an example, we showed that in exposed sites the depth of the notch increases with respect to sheltered ones, while the width of the notch seems correlated to the tidal range, suggesting that exposure and tidal range play an important role in notch genesis and evolution.

- While bioerosion is surely an important factor, we also show that bioprotection by encrusting organisms should not be discarded, and it seems to work more effectively in areas where the wave energy is higher, and therefore constitutes a negative feedback on notch formation. In some cases, these forming processes are not enough to initiate notch formation.

- During its evolution over the last 6.8 ka, the tidal notch has undergone a continuous change in shape tracking the sea level rise and isostatic (negative) movements causing the cliff retreat. This is the reason why submerged tidal notches are not detected in stable sites, and, conversely, they are found in uplifting (Fig. 2h) or subsiding (Fig. 2d) coasts.
- The local tide amplitude is always less than the tidal notch width, and the maximum notch concavity does not correspond to maximum tide (Fig.12).
- The width of the Last Interglacial and the modern notches is similar, suggesting that marine tides have not changed during the last 125 ka.
- One of the main factors leading to notch development is the existence of submarine fresh-water springs which enhance rock dissolution.
- Notwithstanding the current sea-level rise at 1.24 mm/yr in the Mediterranean Sea, the presence of the modern notch is explained with a process involving continuous modeling of the notch during cliff retreat (Fig. 10c)
- Morphometric analysis of 73 coastal sites documents that notches have average concavity slightly larger on rocky headlands and pillars, than on extended cliffs. This happens because on the former, exposed settings, dissolution and abrasion occur with enhanced energy.

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Captions FIGURES and Table

Fig.1**: a)** Main carbonate outcrops in Mediterranean coasts (orange areas); location of studied tidal notch (red dots with number, Table 2; S1 s.m.); location of tide gauges (green dots); coastal and submarine springs larger than 1000 liters for second (blu arrows from Civita, 2008). **b)**Tectonic setting of western and central Mediterranean region (modified after Oldow et al. 2002): 1) Water depth >1000,

2) Water depth 0 to 1000 m, 3) Contractional fault system, 4) Transcurrent fault systems, 5) Extensional fault system. **c)** Holocene and MIS 5.5 vertical tectonic movements along the Mediterranean coasts. Data calculated from: Antonioli et al., 2009; Faivre et al, 2010, 2011, Ferranti et al 2006, Ferranti et al., 2010, Galili et al., 2011; Pavlopulos et al., 2012, Radic Rossi and Antonioli 2008, Rodriguez-Vidal et al., 2007; Poulos et al., 2009; Stanley & Toscano 2009; Stewart & Morhange 2009; Tsimplis et al., 2011; Yaltirak et al., 2002; Vött 2007, in supplementary material.

Fig.2: Notches along the central Mediterranean carbonatic coast: a) a tidal notch (Zinzulusa, Apulia). b) an impressive tidal notch on an isolated limestone rock (Cala Fuili, Sardinia). c) a roof notch (Malta) d) a submerged notch (Limski canal, Croatia). e) a well developed tidal notch carved on the rocky headlands of Favignana. f) Eolianite deposit covering the Last Interglacial notche (Biddiriscottai, Sardinia), g) Present and MIS 5.5 tidal notches (Masua, Sardinia), h) uplifted tidal notch (Taormina, Sicily), i) one meter high corallinae algae in a cul de sac with high pressure splash (Malta) l) outsized notch in a cul de Sac (Buggerru, Sardinia).

Fig.3: Morphometric measures: A) Average notch width, B) Notch depth, C) Bottom depth (reef when present), D) reef and step (if present) thikness, E) Depth of cliff toe at mean sea level.

Fig.4: Statistical diagrams of tide gauges data: a) height tide trend (hours/year) of the analyzed tide gauges: Bari, Naples, Ponza, Catania, Marseille, Elba; Civitavecchia, Gaeta, Carloforte, Cagliari, Imperia, Otranto, Lampedusa, Palermo, Porto Torres, Taranto;b) Gaeta tide gauge: tide trend from 2010 to 2014;c) Gaeta tide gauge: trend of tide (hours/year, blu line); mean value of significant height tide (vertical axis) and significant hours/year at the same height tide, horizontal axis.

Fig.5: Mediterranean mean waves Energy Flux (kW/m) http://utmea.enea.it/energiadalmare/ (a). A zoom on Sardinia and Sicily (b and c). Correlation between the reef thikness and mean waves energy flux (d).

Fig.6: Representative sections of most significant tidal notches studied. a) limestone, b) sandstone and very erosive limestone, c) stratified limestone, d) stratified sandstone and very erosive limestone, e) reef, f) supposed limit between rock and reef. Fetch and kind of sea energy: g) very exposed, h) exposed, i) sheltered. l) geographical exposure. (see Table 1)

Fig.7: Relationship between notch width (a), mean tide values (b) and extreme (max-min) tide values (c) in locations where notches have been measured near a tide station.

Fig. 8: Statistical diagrams. Relationship between tidal range and average depth of sheltered (a) and exposed (b) notches; relationship between tidal range and width of sheltered (c) and exposed (d) notches; relationship between average width and depth of sheltered (e) and exposed (f) notches; g) relationship between tidal notch and their lithology.

Fig.9: Extra Mediterranean tidal notchs: a) Barbados, notch width: 140 cm, b) Barbados, presence of reef steps, c) Zandibar, notch width: more than 400 cm, d) Bonaire, Netherland Antille, notch width: 100 cm, e) Thailand: a smoothed mid Holocene (Sheffer et al., 2012, +2.6 m 5.5 ka cal BP) notch 310 cm width and the Present day MTN, 210 cm width, f) Mauritius; notch width 150 cm, g) world wide ditribution of ours observations, redrowned from: Church et al., 2013 IPCC report.

Fig.10: a) Sea level rise rates from 8 ka cal BP to the Present using the predicted sea level rise curves (Lambeck model, 2011) with maximum (Cagliari, purple line) and minimum (Trieste, blue line) isostatic subsidence values. The inflection at 6.8 ka marks the change of rise. b) Frequency of notches formation from 8 ka to 0 ka, (modified from Boulton and Stewart, 2014). c) Model of tidal notches formation from 6,8 ka to the present.

Fig.11: Absence of tidal notchs: a) Sardegna: the nearly vertical strata slope does not allow the tidal notch formation, b) Circeo, Italy, molluscs (*mytilus*) create a very dense concretion. Evolution of tidal notchs: c) Barbados, excetionally developed tidal notchs, d) collapse of the upper part of tidal notches.

Fig.12: Tidal range measured on the Polignano San Vito notch (site 68 Table 1 and S1. Measured on 09/28/2014 at 10.00 am, (a,b), and 16,30 pm (c,d). Observations are in agreement with the instrumental data collected at the nearest tide gauge located at Bari (about 40 km North of Polignano). Plots show the daily tide during the observations (e) while in f) are the tides for one month cycle of September. The red arrow indicate the time of the notch measures (a,b,c,d).

Table1: Data obtained from tide gauges (Fig. 4 for example) and the OSU tidal prediction model, regional solution for the Mediterranean. 1 Station names. 2 lower Lmin and upper Lmax values of the residual sea level calculated for about 10 hours/year. 3 Sum of values on column 2: maximum tide level. 4 Number of hours for year at the histogram maximum (Fig 4), tide level values at half maximum of the histogram (sixth and seventh columns). 5-6 Lower and upper limit at half maximum (cm) of the histogram. 7 Sum of columns 5 and 6. 8 Average notch width cm (see Table 1).We show that overall, the root mean square error between the tidal gauge data and the model data is ~4cm.

Table 2: Tidal notch data in Mediterranena sea

1) Site number; 2) Site name; 3) Type of notch; 4) Average notch with; 5) Average notch depth; 6) Bottom depth of biological rim; 7) Thikness of biological rim; 8) Tidal range as predicted by OSU model; 9) Width of MIS 5.5 notch (if present); 10) Exposure.

Table3: Geomechanical properties of the rock masses carved by tidal notches

Table4: Extra Mediterranenan Present day notches width, depth and tide prediction. For the tide prediction on the sites 1, 2, 3, 4, 5 we used : http://www.tide-forecast.com/, for sites 6 an 7 we used the original local tide gauge data.

References and Caption Supplemetary material in a separate file.

Table1

1	2		3	4	5	6		7	8
Tide gaudge station[1]	L_{min} (cm)[2]	L_{max} (cm)	*Maximum tidal level*	*Maximum value of hours/year*	*Significant hours*	*Lower and upper value at significant hours (cm)*		*Mean tide value at half maximum tide level (cm)*	*Values obtained from OSU tidal model (cm)*
Bari	-44,9	55,1	99	1223.38	586,75	-19.9	15,1	35	37.7
Cagliari	-41,2	38,8	80	1510.32	711,05	-16.2	13.8	30	27.9
Palermo	-52,8	42,2	95	1410.15	543,8	-17.8	17.2	35	34.5
Civitavecchia	-41,9	43,1	85	1343.29	549,25	-21.8	13.2	35	-
Carloforte	-38,7	51,3	90	1494.60	588,1	-18.7	11.3	30	28.4
Catania	-40,0	35,0	75	1616.03	617,45	-15.1	14.9	30	23.8
Elba	-40,9	44,1	85	1566.48	647,15	-15.9	14.1	30	32.4
Imperia	-42,1	37,9	80	1481.72	629,8	-17.1	12.9	30	31.2
Lampedusa	-42,2	37,8	80	1442.68	614.15	-17.2	12.8	30	25.6
Marseille	-39,3	55,7	95	1527.65	647,6	-19.3	10.7	30	27.8
Napoli	-43,9	41,1	85	1275.24	563,2	-18.9	16.1	30	38.2
Otranto	-40,0	40,0	80	1547.23	455,6	-20.0	15.0	35	25.8
Ponza	-44,3	35,7	80	1317.40	533,75	-19.2	15.7	35	37.9
Porto Torres	-43,2	36,8	80	1475.44	480,7	-18.2	16.8	35	27.9
Salerno	-49,5	45,5	95	1207,8	439,75	-19.5	20.5	40	38.2
Taranto	-42,2	42,8	85	1461.16	643,35	-17.2	12.8	30	22.1
Gaeta	-40,8	44,2	85	1532.25	485,9	-20.8	14.2	35	37.9
								RMSE	**4.08**

Table2

Site N	Site name	Type of notch	Average notch width with uncertainty (cm)	Average notch depth with uncertainty (cm)	Thickness of biological rim with uncertainty (cm)	Tidal range as predicted by OSU model (cm)	MIS 5.5 notch width (cm)	Exposure
1	Colonia de S.Jordie Palma (Spain)	MTN	55 ± 2.8	90 ± 4.5	2.5 ± 0.1	18.66		Exp.
2	Marseilles (France)	RN	30 ± 1.5	50 ± 2.5	2.5 ± 0.1	27.8		Exp.
3	Balzi Rossi	MTN	44 ± 2.2	60 ± 10.4	10 ± 0.5	30.54		Exp.
4	Noli	MTN	100 ± 5	75 ± 25.3	1 ± 0.1	31.2		Exp.
5	Capo Caccia	MTN	70 ± 3.5	143 ± 63.4	45 ± 2.3	27.9	0.75	Exp.
6	Porto Conte	MTN	48 ± 2.4	30 ± 1.5	5 ± 0.3	25.8	0.7	Shelt.
7	Porto Conte	MTN	60 ± 3	60 ± 3	10 ± 0.5	23.6	0.7	Shelt.
8	Biddiriscottai	MTN	56 ± 4.9	70 ± 3.5	10 ± 0.5	34.1	0.8	Shelt.
9	Cala Fuili	MTN	66.5 ± 4.8	240 ± 160.4	10 ± 0.5	32.6	0.75	Exp.
10	Sella del Diavolo	MTN	55 ± 2.8	100 ± 5	15 ± 0.8	25		Exp.
11	Cala Mosca	MTN	50 ± 2.5	190 ± 41.1	15 ± 0.8	27.9		Exp.
12	Cala Mosca	MTN	55 ± 2.8	175 ± 26.5	15 ± 0.8	27.3		Exp.
13	Masua	MTN	50 ± 2.5	75 ± 6.3	10 ± 0.5	24.5	0.75	Exp.
14	Masua	MTN	56.5 ± 4.5	140 ± 7	20 ± 1	27.2		Exp.
15	Masua	MTN	48 ± 2.4	50 ± 2.5	20 ± 1	28.4		Exp.
16	Pan di zucchero	RN	30 ± 1.5	30 ± 1.5	20 ± 1	28.3		Exp.
17	Pan di zucchero	MTN	66 ± 3.3	120 ± 20.9	15 ± 0.8	26.7		Exp.
18	Pan di zucchero	MTN	50 ± 2.5	60 ± 3	20 ± 1	24.2		Exp.
19	Cala Domestica	MTN	48 ± 2.4	50 ± 2.5	5 ± 0.3	28.1		Exp.
20	Cala Domestica	MTN	78 ± 3.9	60 ± 3	10 ± 0.5	26.3		Exp.
21	Buggerru	MTN	68 ± 3.4	60 ± 3	10 ± 0.5	22.9		Exp.
22	Buggerru	MTN	73 ± 3.7	80 ± 4	30 ± 1.5	25.3	0.8	Shelt.
23	Tharros	MTN	72 ± 3.6	60 ± 3	3 ± 0.2	28.9		Exp.
24	Talamone	MTN	42 ± 2.1	40 ± 2	2 ± 0.1	32.4		Exp.
25	Circeo	No Notch			15 ± 0.8	36.9	0.26	Exp.
26	Gaeta	MTN	35 ± 1.8	40 ± 2	35 ± 1.8	37.9	0.5	Exp.
27	Capri	No Notch			15 ± 0.8	38.2	0.7	Exp.
28	Marettimo Harbour	MTN	55 ± 2.8	100 ± 5	5 ± 0.3	26.4		Shelt.
29	Marettimo Castello	MTN	60 ± 3	70 ± 3.5	10 ± 0.5	26.8	0.75	Exp.
30	Favignana. Cala rossa	MTN	60 ± 3	145 ± 75.3	20 ± 1	27.2		Exp.
31	Levanzo	MTN	60 ± 3	40 ± 2	15 ± 0.8	32		Exp.
32	Levanzo Harbour	MTN	60 ± 3	100 ± 5	15 ± 0.8	29.59		Exp.
33	San Vito Castelluzzo	MTN	52 ± 2.6	40 ± 2	5 ± 0.3	35.9		Exp.
34	Macari	MTN	55 ± 2.8	45 ± 2.3	5 ± 0.3	35.9		Shelt.
35	Zingaro	MTN	50 ± 2.5	200 ± 10	5 ± 0.3	34.7		Exp.
36	Scopello	MTN	50 ± 2.5	60 ± 3	5 ± 0.3	32.3		Shelt.
37	Palermo Mondello	MTN	60 ± 3	90 ± 4.5	5 ± 0.3	36.4		Exp.
38	Palermo harbour	MTN	51.5 ± 4.3	125 ± 55.4	5 ± 0.3	34.5		Exp.
39	Mongerbino	MTN	70 ± 3.5	85 ± 15.6	5 ± 0.3	37.4	0.8	Exp.
40	Cefalù	MTN	70 ± 3.5	125 ± 25.8	5 ± 0.3	37.7		Exp.
41	Cefalù	MTN	60 ± 3	80 ± 4	5 ± 0.3	37.7		Exp.
42	Siracusa	MTN	60 ± 3	60 ± 3	20 ± 1	23.8		Exp.
43	Siracusa	MTN	45 ± 2.3	60 ± 3	20 ± 1	23.8		Exp.
44	Siracusa	MTN	60 ± 3	80 ± 4	20 ± 1	23.8		Exp.
45	Siracusa	MTN	30 ± 1.5	70 ± 3.5	20 ± 1	23.8		Exp.
46	Siracusa	MTN	62 ± 3.1	150 ± 7.5	20 ± 1	23.8		Exp.
47	Marzamemi	MTN	55 ± 2.8	80 ± 4	20 ± 1	24.4		Exp.
48	Calamosche	MTN	60 ± 3	80 ± 4	20 ± 1	23.88		Exp.
49	Gozo (Malta)	MTN	95 ± 4.8	80 ± 4	5 ± 0.3	21.4		Exp.
50	Gozo Eroded mushroom	MTN	70 ± 3.5	90 ± 4.5	5 ± 0.3	21		Exp.
51	Comino	MTN	60 ± 3	75 ± 3.8	10 ± 0.5	22.4		Exp.
52	Malta	MTN	38 ± 1.9	10 ± 0.5	0 ± 0	25.1		Exp.
53	Lampedusa. Cala Calandra	MTN	35 ± 1.8	50 ± 2.5	0 ± 0	25.6		Exp.
54	Lampedusa	MTN	44 ± 2.2	60 ± 3	3 ± 0.2	24.1		Exp.
55	Lampedusa	MTN	36 ± 1.8	40 ± 2	3 ± 0.2	25.2		Shelt.
56	Marina di Pulsano	MTN	70 ± 3.5	55 ± 2.8	3 ± 0.2	22.1		Shelt.
57	Torre Colimena	MTN	60 ± 3	50 ± 2.5	3 ± 0.2	23.2		Exp.
58	Serra Cicora	MTN	45 ± 2.3	130 ± 6.5	10 ± 0.5	22.57		Exp.

59	Serra Cicora	MTN	45 ± 2.3	174 ± 8.7	10 ± 0.5	23.25		Exp.
60	Santa Maria di Leuca	MTN	60 ± 3	150 ± 7.5	20 ± 1	22.43		Exp.
61	Santa Maria di Leuca	MTN	80 ± 4	90 ± 4.5	20 ± 1	21.55		Exp.
62	Ciolo	MTN	60 ± 3	90 ± 4.5	20 ± 1	24.87		Exp.
63	Zinzulusa	MTN	70 ± 3.5	90 ± 4.5	25 ± 1.3	25		Exp.
64	Badisco	RN	13 ± 0.7	49.5 ± 8.9	0 ± 0	25.8		Shelt.
65	Badisco	MTN	50 ± 2.5	30 ± 1.5	5 ± 0.3	25.8		Exp.
66	Badisco	MTN	65 ± 3.3	110 ± 5.5	20 ± 1	25		Exp.
67	Polignano Modugno	MTN	60 ± 3	30 ± 1.5	40 ± 2	33.3		Exp.
68	Polignano San Vito	MTN	70 ± 3.5	90 ± 4.5	2 ± 0.1	36.7		Shelt.
69	Giovinazzo	MTN	45 ± 2.3	50 ± 2.5	5 ± 0.3	37.7		Exp.
70	Tremiti	MTN	40 ± 2	40 ± 2	0 ± 0	32.1		Exp.
71	Dubrovnik	RN	10 ± 0.5	50 ± 2.5	0 ± 0	39.8		Shelt.
72	Montenegro	RN	10 ± 0.5	50 ± 2.5	0 ± 0	35.8		Exp.
73	Gavathas (Lesvos. Greece)	MTN	52 ± 2.6	45 ± 10.3	3 ± 0.2	22.58		Shelt.

Table3

	Massive limestones	Organogenic limestones	Calcitic dolostones	Dolostones	Calcerenites (sandstones)
Specific Gravity (Gs)	2.65 ÷ 2.73	2.65 ÷ 2.73	2.65 ÷ 2.73	2.65 ÷ 2.73	2.68 ÷ 2.73
Porosity (n%)	4 ÷10	10÷20	10÷20	4 ÷11	44.00 ÷ 50.00
Dry density γd (KN/m3)					12.4 ÷ 15.20
Water absorption (wa %)	2.00	10.00	10.00	4.00	28.40 ÷ 36.20
Uniaxial Compressive Strenght (MPa)	227.51	135.33	131.40	117.67	2.22 ÷ 5.08
Flexural Strenght (MPa)	20.10	16.67	14.51	11.76	1.09 ÷ 8.10

Table4

N.	Site	Coordinates	Notch width (cm)	Notch depth (cm)	Predicted tide (cm)
1	Barbados	13° 20' 03" N 59° 36' 47''W	140	210	115
2	Zanzibar Tanzania	06° 22' 38" S 39° 17' 03'' E	400	200	410
3	Zanzibar Tanzania	06° 21' 14" S 39° 18' 16'' E	400	400	410
4	Bonaire, Netherland Antille	12° 13' 01" N 68 20' 48" N	100	120	55
5	Phi Phi Island Thailand	07° 41' 07"N 98° 46' 14"E	210	120	205
6	Port Louis (Mauritius)	20° 23' 43"S 57° 46' 36"E	110	210	45
7	Blue Bay (Mauritius)	20° 24' 51"S 57° 20' 14"E	150	320	33

Figure1

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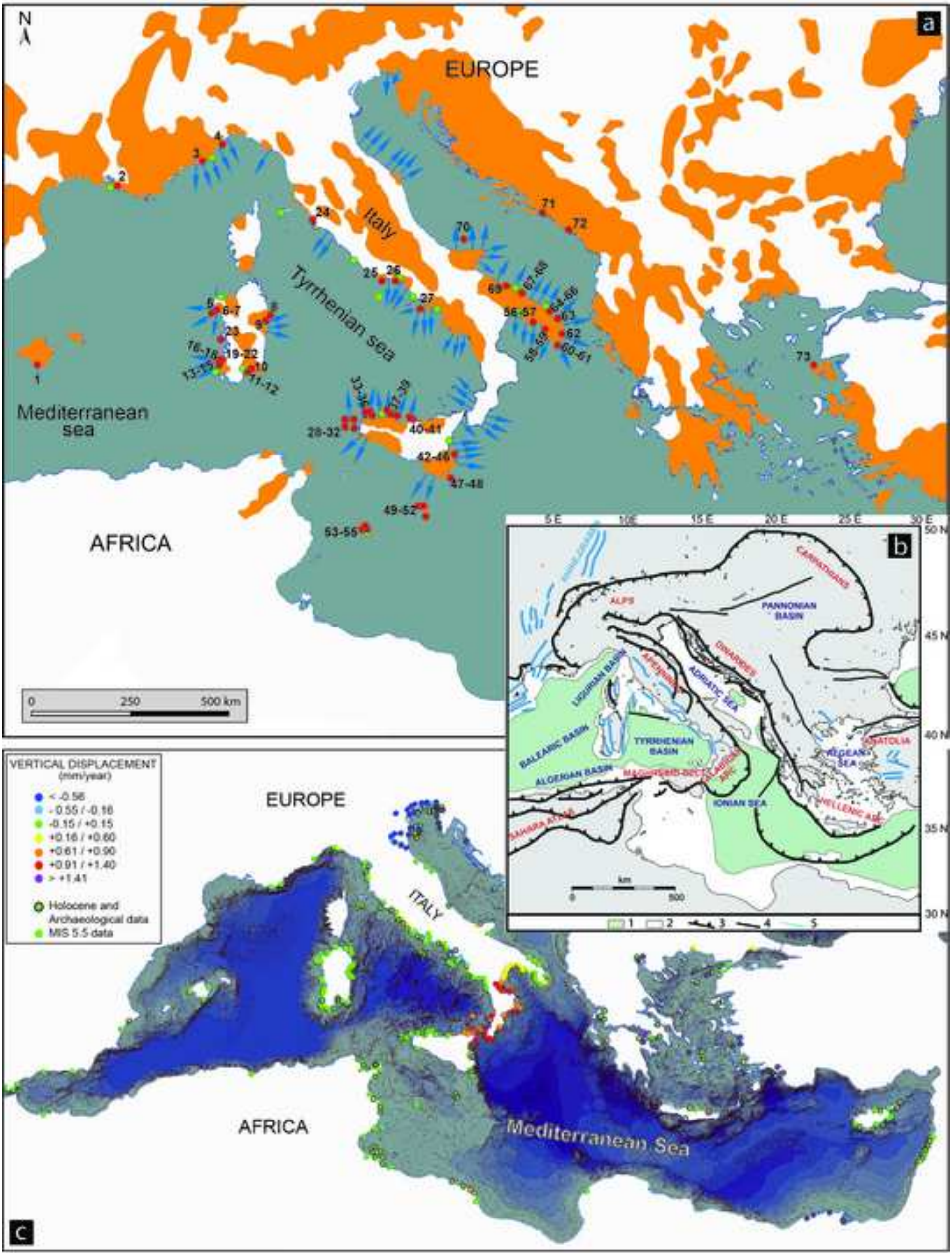

Figure2

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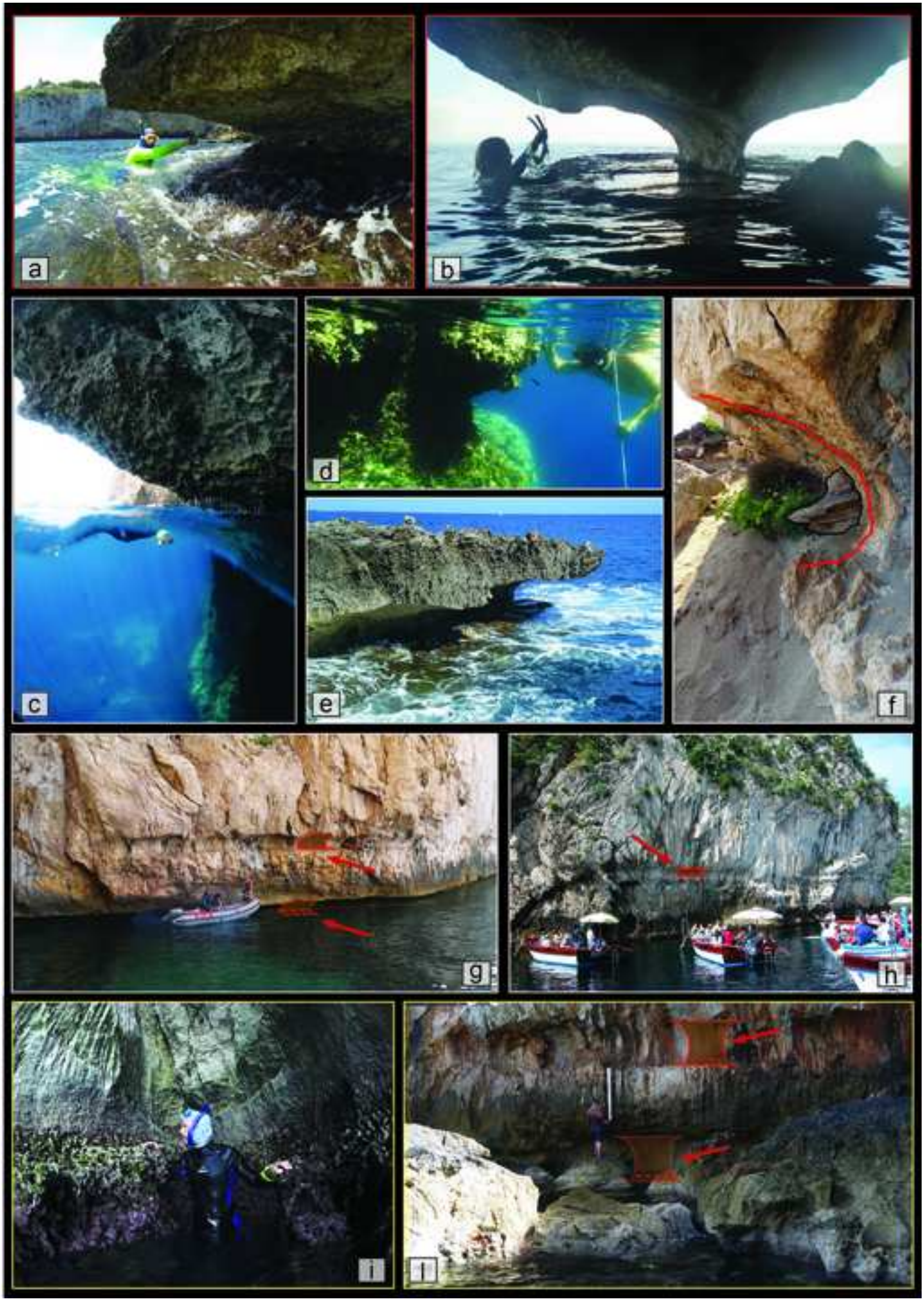

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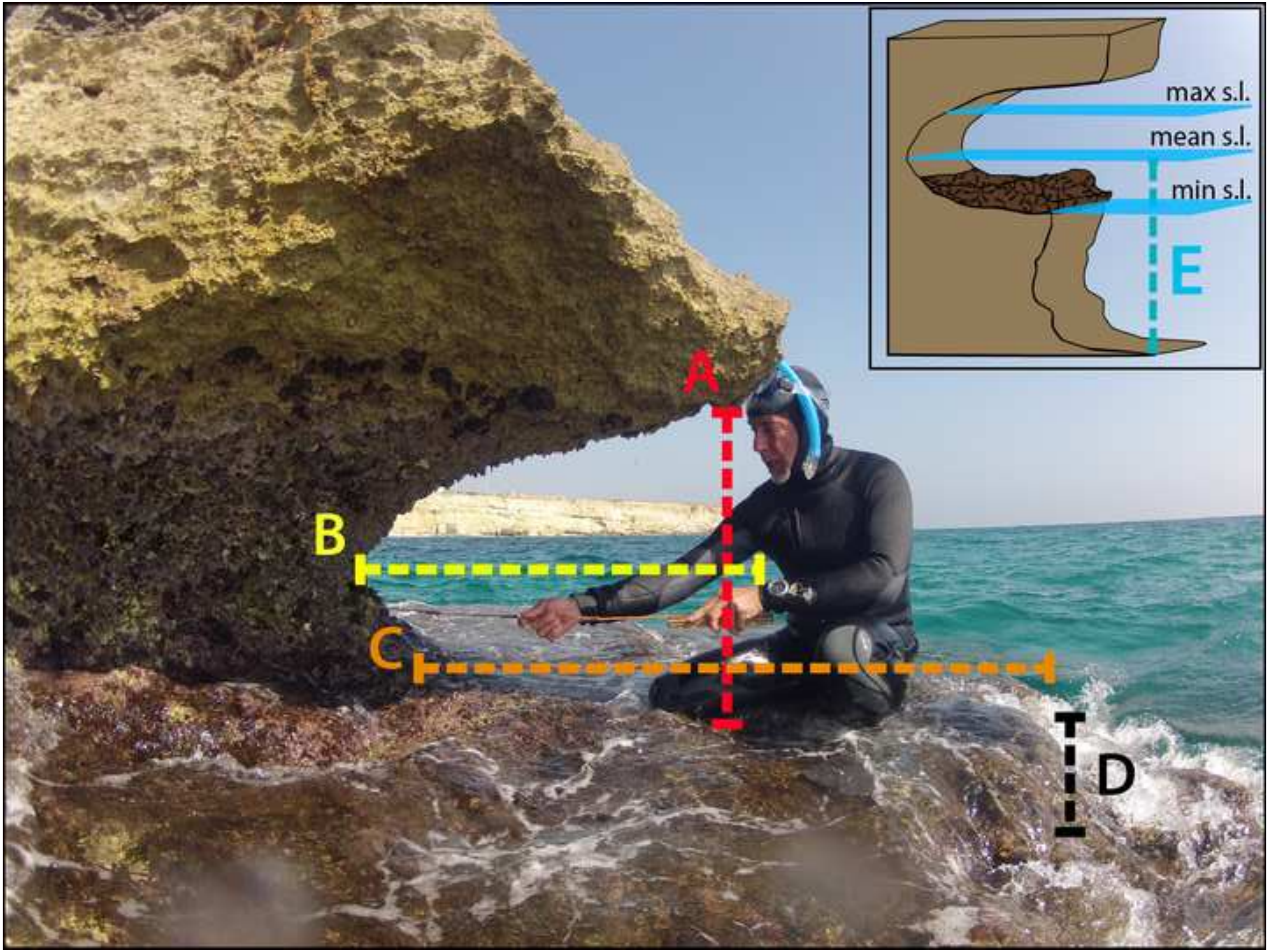

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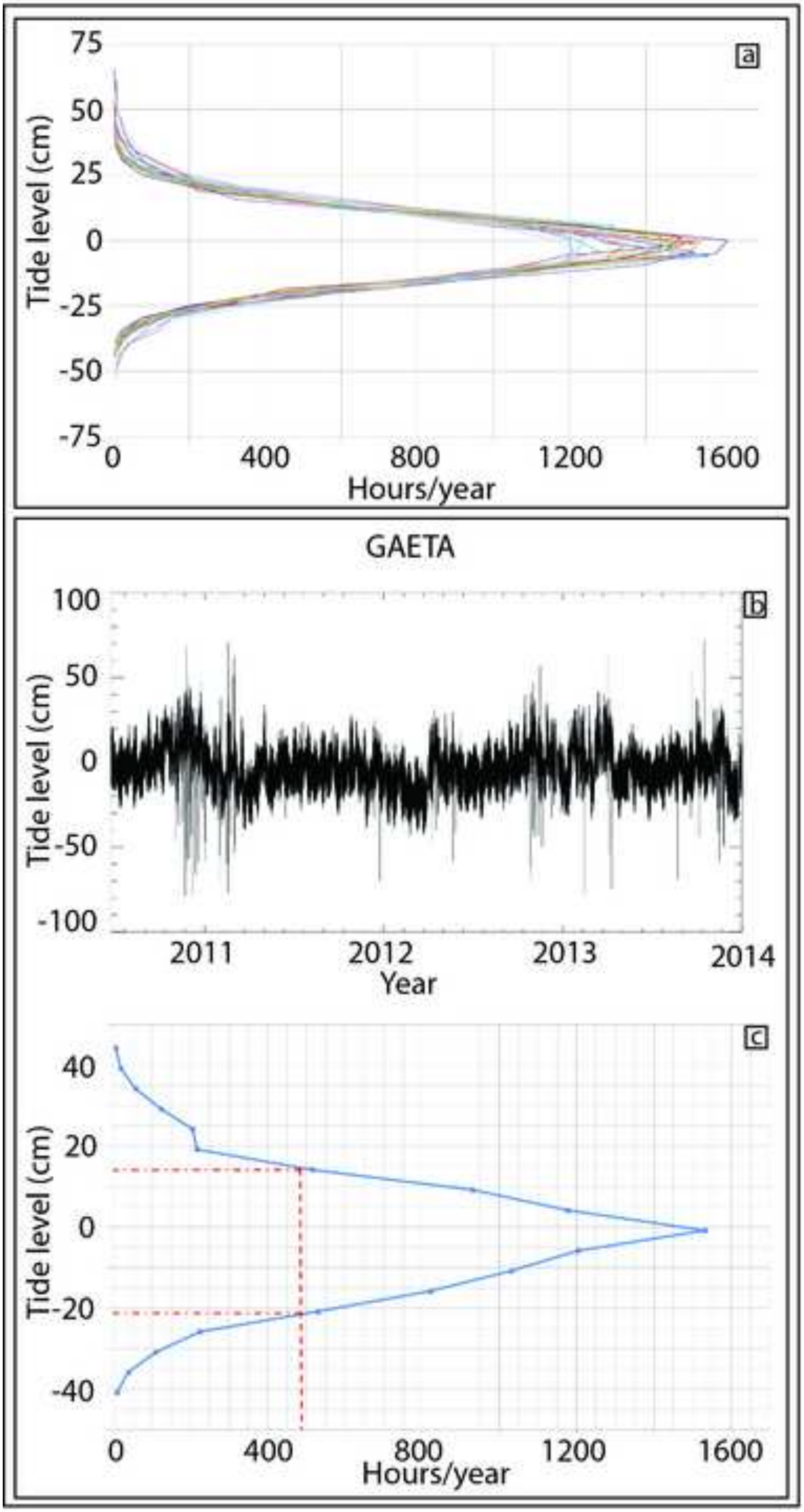

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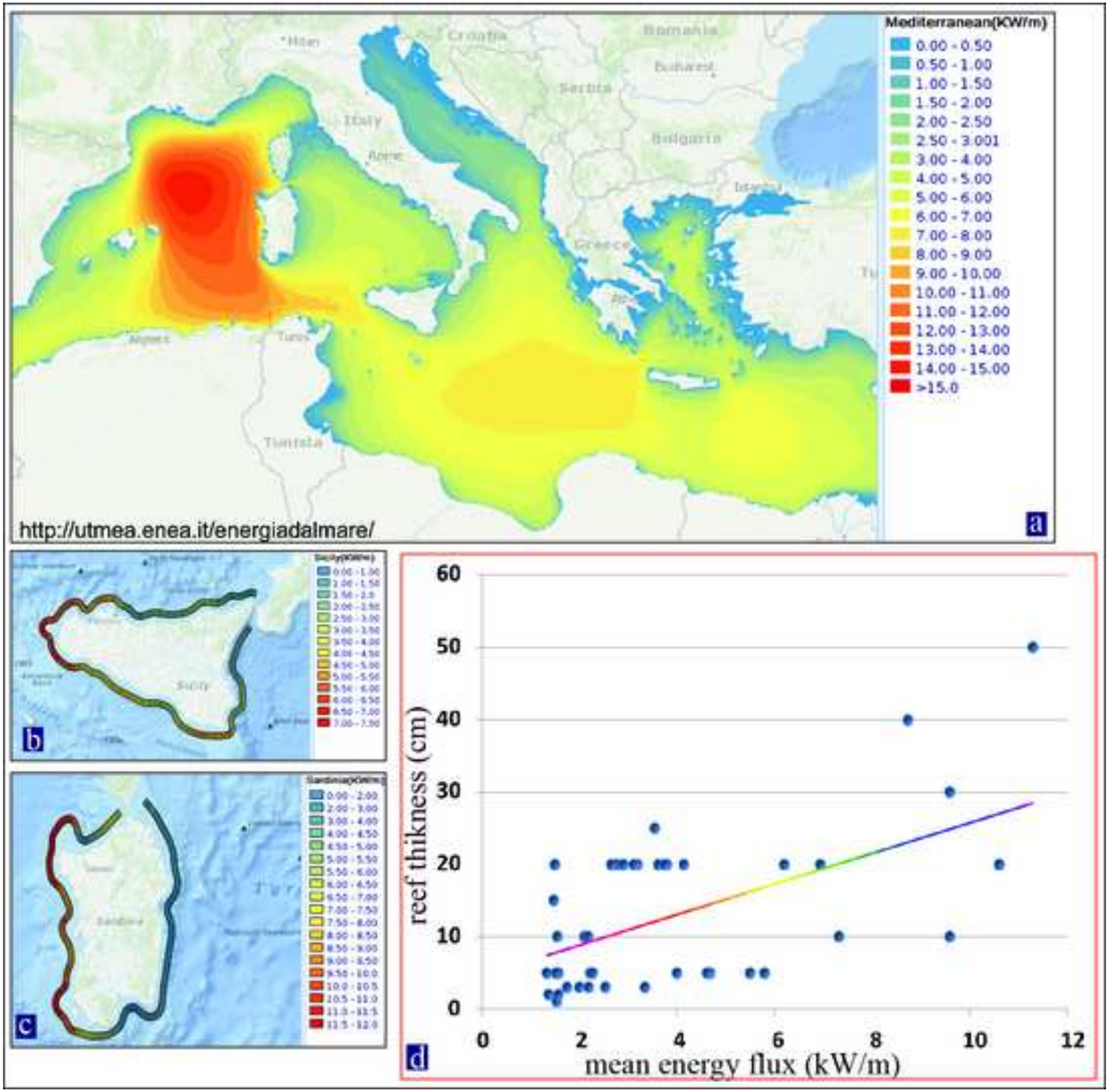

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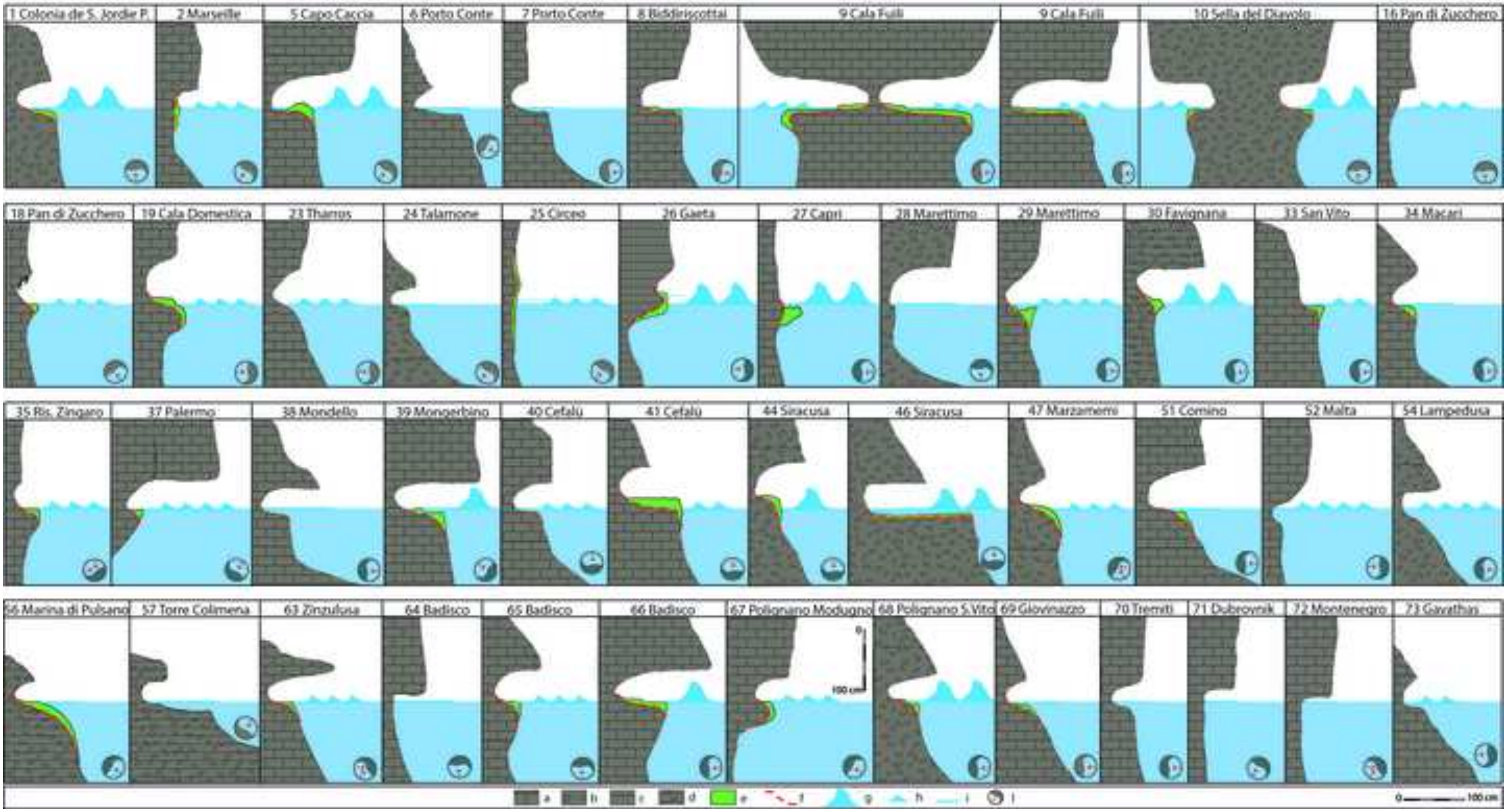

Figure7

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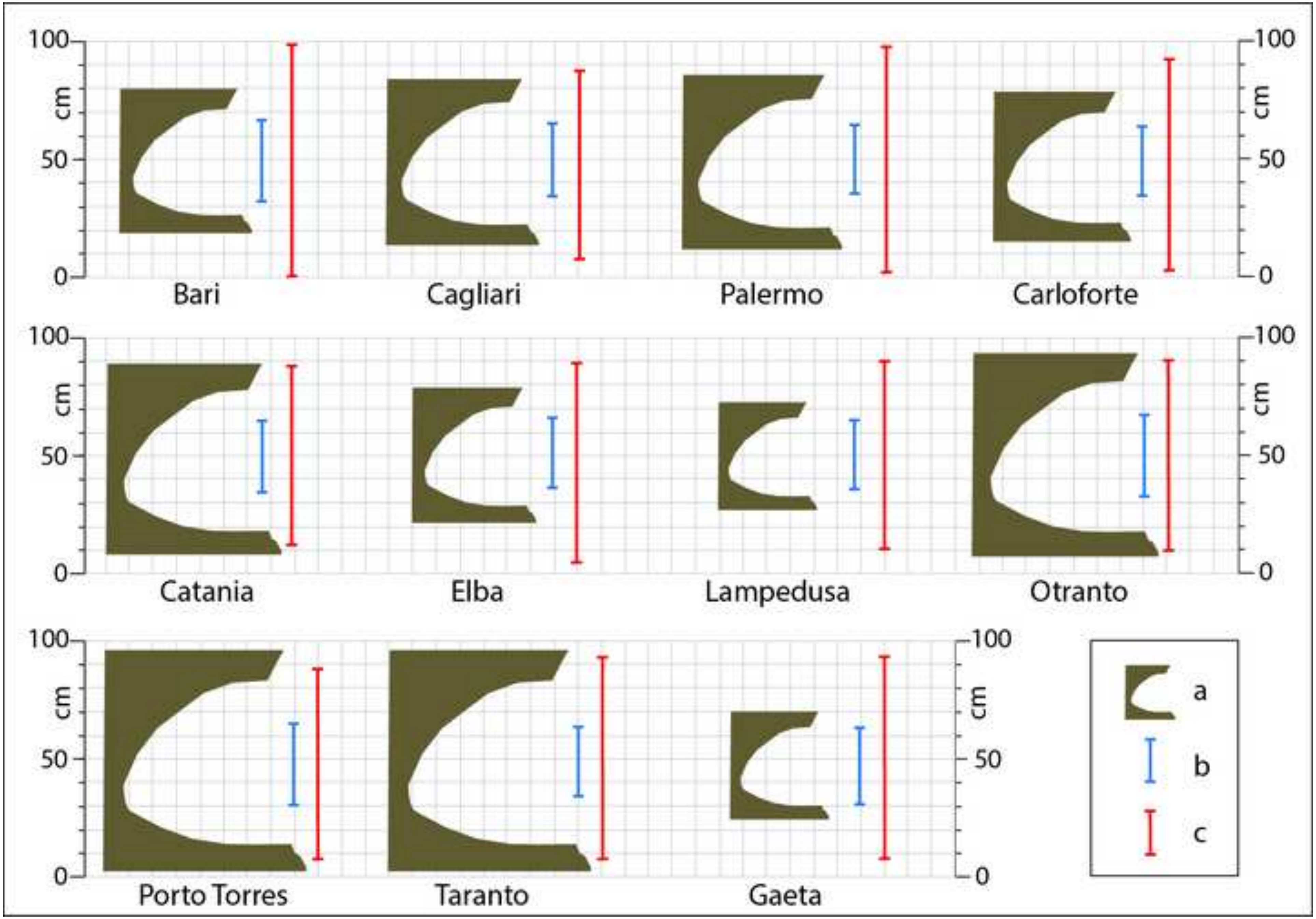

Figure8

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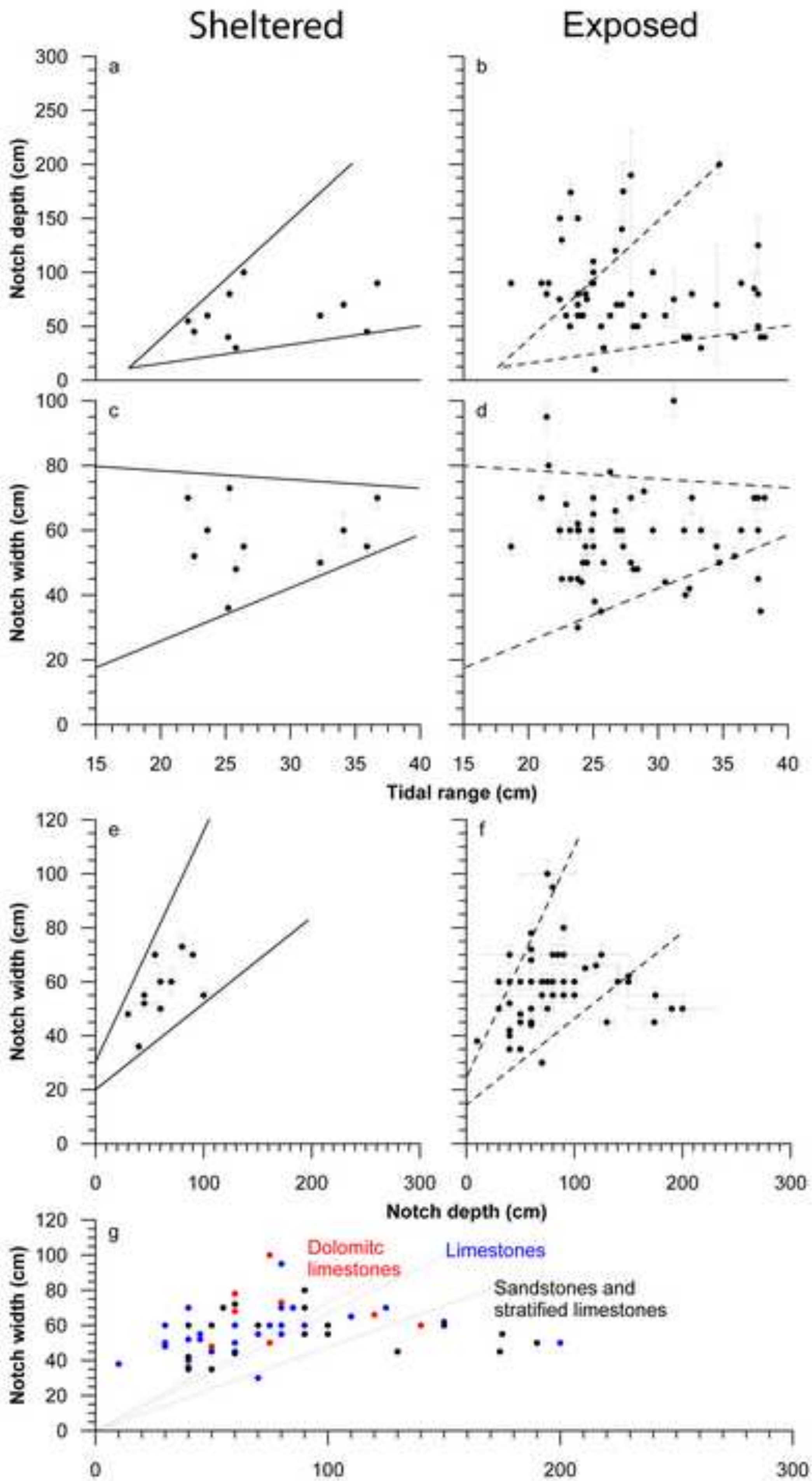

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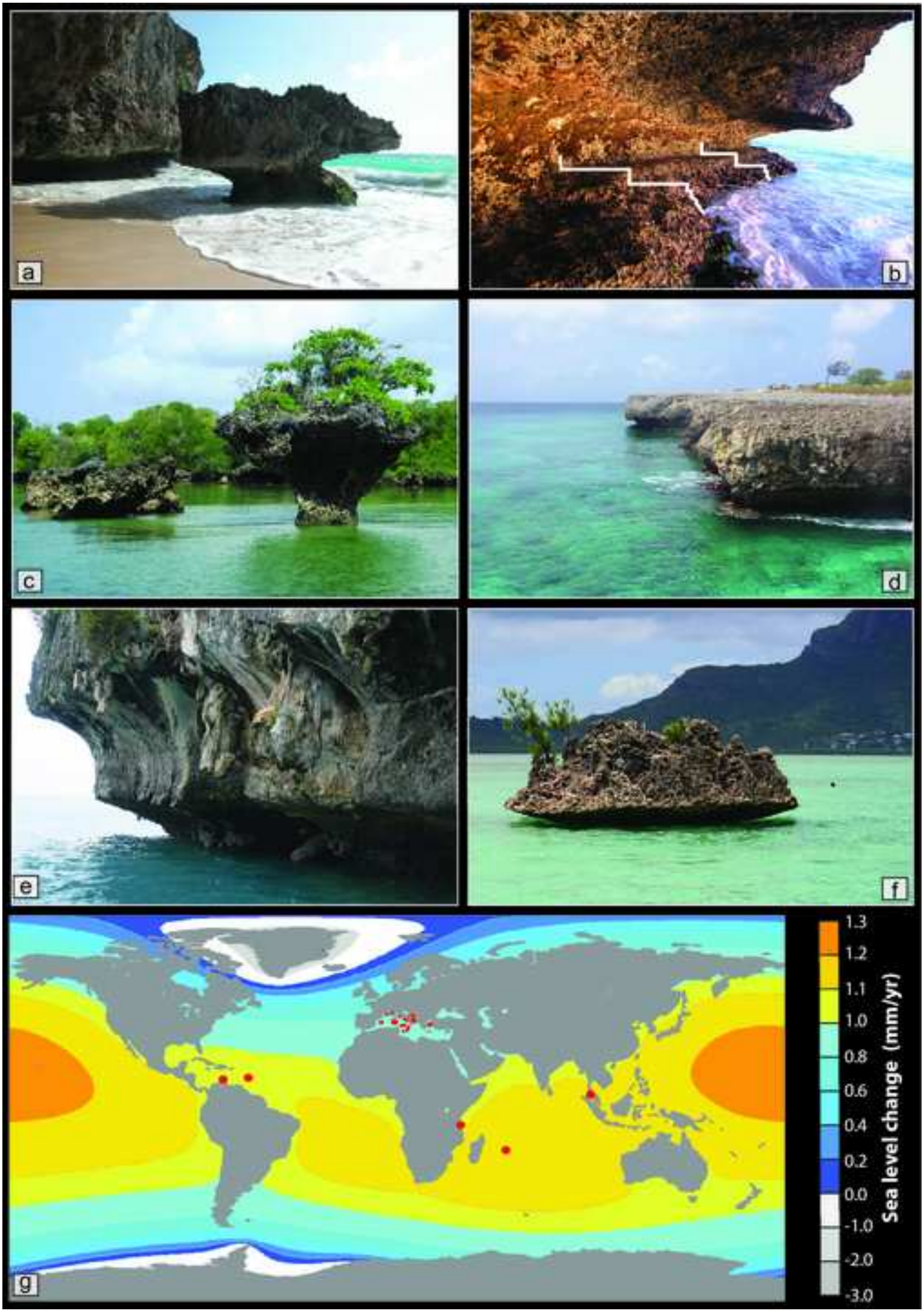

Figure10

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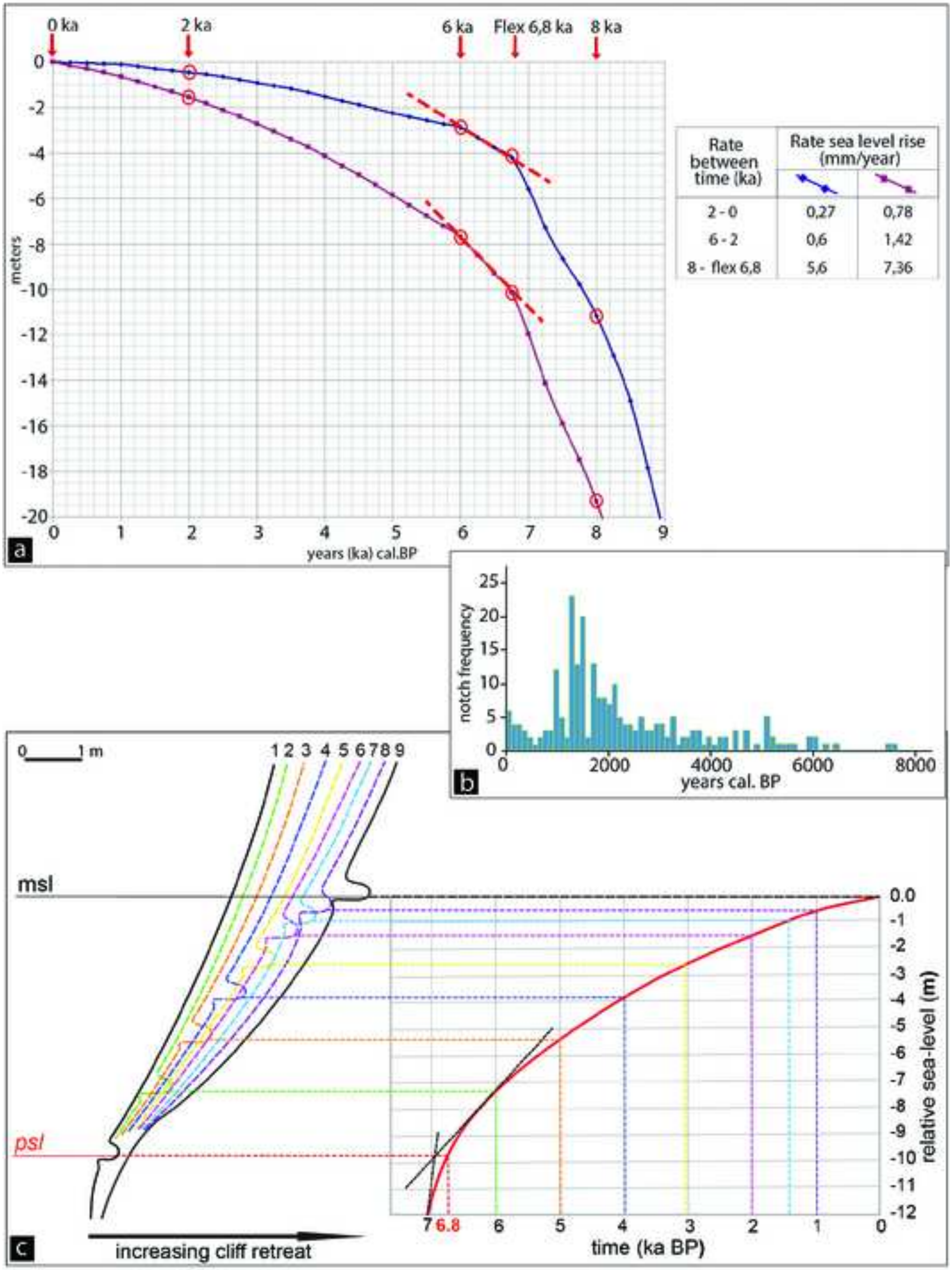

Figure11
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Figure12
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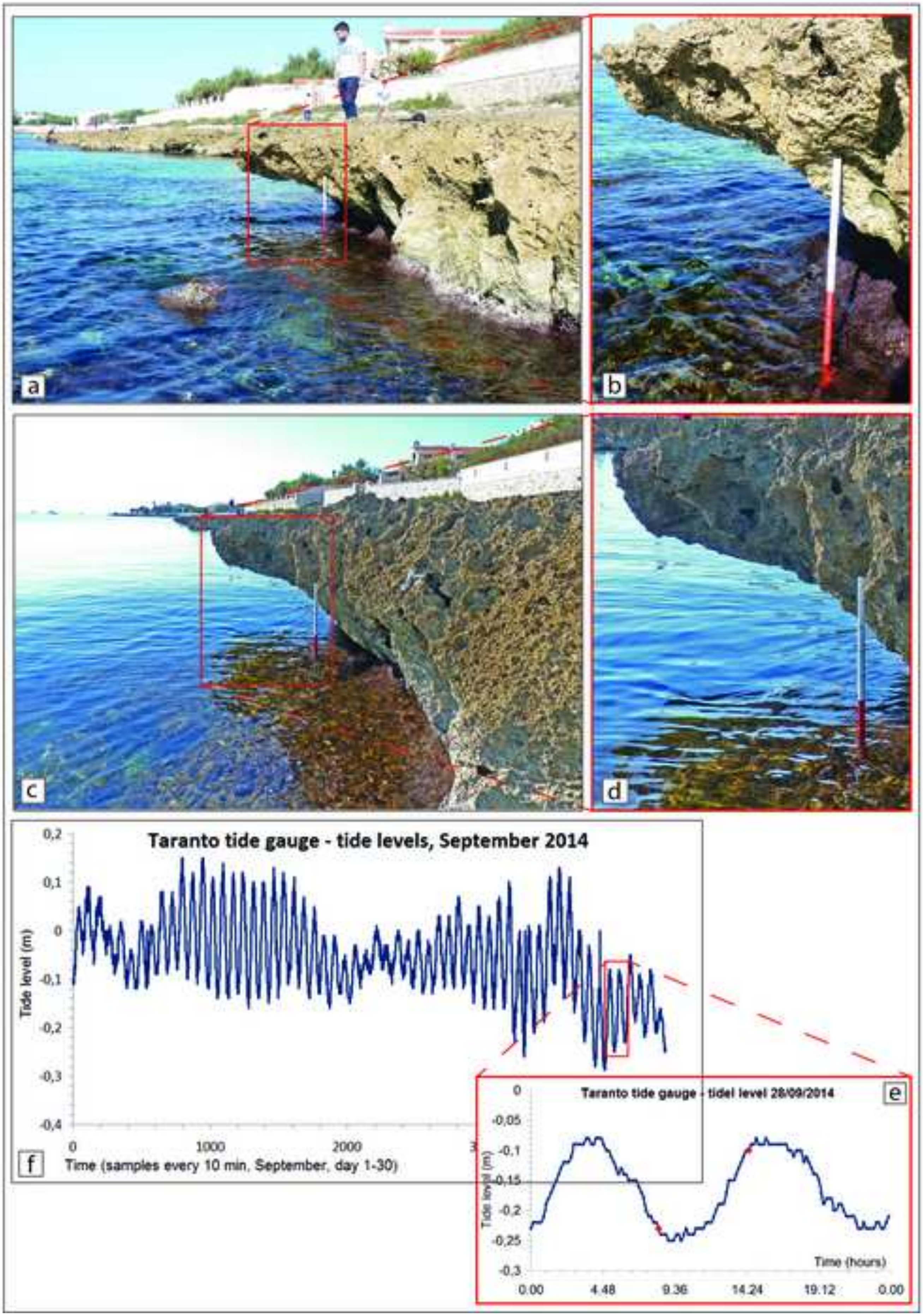

S2_Supplementary Data

S3_supplementary material

Click here to download Supplementary Data: S3.xlsx

S4_Table_supplementary material
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S1_supplementary material

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