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# Anomolous multi-origin marine notch sites: Three case studies in the central Mediterranean Sea

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ABSTRACT

We present and discuss the genesis, age and evolution of indented landforms carved at sea level in correspondence of carbonatic headlands in three sites of the central Mediterranean coasts, between Marseille (France) and Balzi Rossi (Italy), the island of Tavolara (Sardinia, Italy) and the promontory of Tindari (Sicily, Italy). The shape of these anomalous notches landforms can be referred to is very similar to tidal notches, despite their genesis and morphometric parameters are different from those suggested by other Authors for the central Mediterranean area. Two of these sites are located in tectonically stable areas, while the third falls is located in an uplifting area. Those The notches we investigated along the coast of southern France, are submerged notch-type landforms located in the vicinities of current modern tidal notches. At Tavolara island, these anomalous notches are placed at about 25 m b.s.l. these landforms and have the shape of “mushroom-like notches”. Finally, those investigated along the metamorphic-carbonatic promontory of Tindari, are marine and abrasional notches, that have been uplifted, likely during the Holocene.

## 1. Introduction

The coasts of the Mediterranean basin are shaped by geological processes since millions of years (Anzidei et al., 2014). In this study, we will focus on the geological history corresponding to the time interval following the Last Interglacial during which tidal notches formed along most part of the rocky coasts of this basin. Particularly, we will focus on three areas of the central Mediterranean that are shaped by peculiar geological and climate-related processes that represent a significant factor in the basin evolution and provide new insights on past sea levels and the Present. Marine tidal notches are indentations or undercuttings of size ranging between a few centimetres to several meters of depth, cut in steep carbonatic cliffs at near sea level. Tidal notches have been used as sea level indicators for more than 150 years, and previous authors on this subject have concluded that the causative processes are complex and multiple (Spratt, 1865, Carobene, 1972; Higgins, 1980; Pirazzoli, 1986; Kershaw and Antonioli, 2004; Kelletat, 2005; Furlani et al., 2011a,b; Trenhaile, 2014; Trenhaile, 2015). Antonioli et al. (2015) surveyed 73 coastal sites in central Mediterranean sea, measuring notch widths and depths, the characteristics of the biological rim at their base and correlated these parameters with wave energy, tidal range and rock lithology. These Authors concluded that “tidal notches in the Mediterranean are, rather than the effect of a single process, the result of several processes that co-occur with different rates to the lowering of the cliff”.

In our study we cite previous articles that also indicate multiple causes for notches formation. These previous attempts to understand, at least partially, the origin of tidal notches do justify the present work, and the present intense focus on detail at the new sites showed in ours paper. The microtidal conditions of the Mediterranean sea support this kind of research.

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In general, these forms have been cited in literature as “marine notches” (Pirazzoli, 1986; Boulton and Stewart, 2015; Kelletat, 2005; Trenhaile, 2014). To distinguish them from the “lake” or “inland notches” (Shtober-Zisu et al., 2015; Biolchi et al., 2016), they have been recently renamed “tidal notches” because their shape (particularly the notch width) is affected by the regional local tidal range. For example, tidal notches in Barbados show a width of 140 cm while at Zanzibar 400 cm in agreement with local tidal range. In the Mediterranean sea, the notch width range spans between 95 and 13 cm. Antonioli et al. (2015) defined the tidal notch as the undercutting found at or near tidal level on carbonatic cliffs shaped with characteristic morphology. In particular cases, when the notch lacks a floor, the same Authors defined it as “roof notch”. Nearly half of the Mediterranean rocky coasts are made of carbonatic rocks (Furlani et al., 2014a). Sedimentary carbonate coasts are characterized by a typical set of landforms (Taborosi and Kázmér, 2013), which are related to a combination of mechanical (Trenhaile, 2002), chemical (Higgins, 1980), and biological processes (Torunski, 1979), although recently Trenhaile (2014) has argued that notches form also as a consequence of wetting and drying cycles. While bioerosion plays a role in the consummation of rocks in the intertidal zone, some hard bottom communities can protect the bedrock from erosion (Laborel and Laborel-Deguen, 1996; Naylor and Viles, 2002). A notch near the sand or the sea floor pebbles, is defined “abrasional notch”, has no correlation with sea level, showing depth and width different from a tidal notches (no correlation with local tide).

In this study we will discuss new data from three coastal sites characterized by different geological, lithological, morphological and tectonic features.

The present set of observations extends the range and variety of documented notches, particularly, the investigated areas show marine notches whose shape, size, elevation and genesis, appear to be different from the observations recently reported for the present-day tidal notches in central Mediterranean coasts. The studied sites are located at i) along the Cote d’Azur between Marseille (France) and Balzi Rossi (Italy Fig. 1a). ii) at Tavolara Island (Sardinia, Italy, Fig. 1b), iii) the foot of the promontory of Tindari (Italy, North Sicily, Fig. 1c).

### 1.1. The southern coast of France

The 250 km of coast on southern France facing the Mediterranean sea (Figs. 1 and 2d, Table 1) shows different lithology, including: i) massive Mesozoic limestones at Marseille and the Calanques coastal area, ii) metamorphic rocks at Antibes and Cannes, iii) stratified limestone in the eastern part of the gulf of Cannes, iv) conglomerates at La Ciotat, v) flisch formation at Cap d'Ail and finally vi) Mesozoic limestone in the Balzi Rossi area, at the border with Italy. From a tectonic point of view this region is considered stable after last interglacial (Lambeck and Bard, 2000; Bennett and Hreinsdottir, 2007), with weak vertical land movements that reach maximum altitude of 20 meters in the area between Nice and Menton (Dubar et al., 2008). Both the position of the sea level during the MIS 5.5 and the tidal notches of the same age are still poorly known in this area, likely due to the non-conservative features of local lithology and for the lack of aeolian sediments that could have buried and preserved the tidal notches, as in the case for of other areas of the Mediterranean (e.g. at Orosei Gulf, Antonioli and Ferranti, 1992). Regarding the relative sea level (r.s.l.) dataset published for the late Holocene, Laborel et al. (1994) provided a biological estimates based on fossil calcareous algae sampled on the cliffs at La Ciotat placed up to −1.3 m and formed during the last 5 ka. For the last 2 ka BP, geoarchaeological data of the Roman age, like the port of Marseille and the fish tanks at Frejus (Morhange et al., 2001; Morhange et al., 2013), show a mean altitude of about −0.5 m, in agreement with predicted sea levels curves (Lambeck and Purcell, 2005).

### 1.2. Tavolara Island (Sardinia, Italy)

The coasts of Tavolara island (Figs. 1b and 2b, Table 1) are made of Mesozoic limestone (South-East side) and granite (North-West side). A fossil tidal notch is present occurs between 6.5 and 7.6 m a.s.l.of elevation (Fig. 3e), which is also associated with a fossil beach placed at about 5 m of elevation, containing Senegalese fauna related to MIS 5.5. (Porqueddu et al., 2011 and references therein), suggesting a detachment of Tavolara island from Sardinia between 7 and 8 ka cal. BP, the older prehistoric studied remains are traces of human settlements and graffiti from the Copper Age at 4.4 ka cal BP, Mancini, 2012; D'Arragon, 1997; D'Arragon, 1999; Pani et al., 2013. While the level of the sea during the Roman age has been estimated (at −1.0 m) on the basis of the position of Roman age ship wrecks of the V century A.D., sunk in the port of Olbia (Porqueddu et al., 2011).

### 1.3. Tindari (Sicily, Italy)

The Tindari Promontory is belonging to the Tyrrhenian margin of the Peloritani Belt on the northern coast of Sicily (Fig. 1c). It is formed by a set of south verging tectonic units piled up since Oligocene and consists in middle to high metamorphic grade crystalline rocks, with prevailing felsic-Ca-silicatic marbles. The overlapping tectonic nappes consist of terrains of the Hercynian basement underlying by Meso-Cenozoic sedimentary deposits (Atzori and Vezzani, 1974; Lentini and Vezzani, 1975). The Holocene sediments deposited in marine and continental environments consist in colluvium of variable thickness. These are placed at the base of scarps and slopes, valley floors, beaches and, in particular, in the Marinello lagoons located at the base of Tindari Cape (Fig. 2d). The structural evolution of this area is mainly controlled by the Tindari Fault System (TFS). This is a regional zone of brittle deformation located at the transition between the ongoing contractional and extensional crustal compartments and lying above the western edge of a narrow subducting slab. This zone of deformation consists of a NNW striking set of faults previously documented in the northeastern Sicily between Mt. Etna and the Aeolian Islands (Atzori and Vezzani, 1974; Ghisetti, 1979; Ghisetti and Vezzani, 1981).

During the Middle and Late Pleistocene, several marine terraces originated in response to the interaction between the Pleistocene glacio-eustatic change of the sea level and the long-term tectonic uplift affecting North-Eastern Sicily and Messina Straits area. In Fig. 6, the MIS 5.5 and Holocene sea-level high-stand positions in North-Eastern Sicily and Messina Straits area, are summarized.

In this area, coastal swim-surveys performed between Cape Tindari and Mongiove (Fig. 1c) evidenced high cliffs and pocket beaches. The outcropping lithology is represented by pre Mesozoic metamorphic medium-high grade, intensely altered with prevailing pallets of marble, belonging to the Aspromonte Unit (Atzori and Vezzani, 1974; Lentini et al., 1995, 2000). Although the crystalline bedrock is not the best geological environment for the development and preservation of past sea level indicators, a marine notch was found along Cape Tindari, where limestones are prevailing (Bonfiglio et al., 2003). The fault activity in this area is as young as middle-upper Pleistocene, as inferred from extensional fractures affecting the beach rocks of the Marinello beach formation, which are dated at 120–130 years BP. These are located eastward of Cape Tindari on the hanging wall of a segment of the TFS (Barbagallo, 2003; Ghisetti, 1979; Catalano and Cinque, 1995; Catalano and Di

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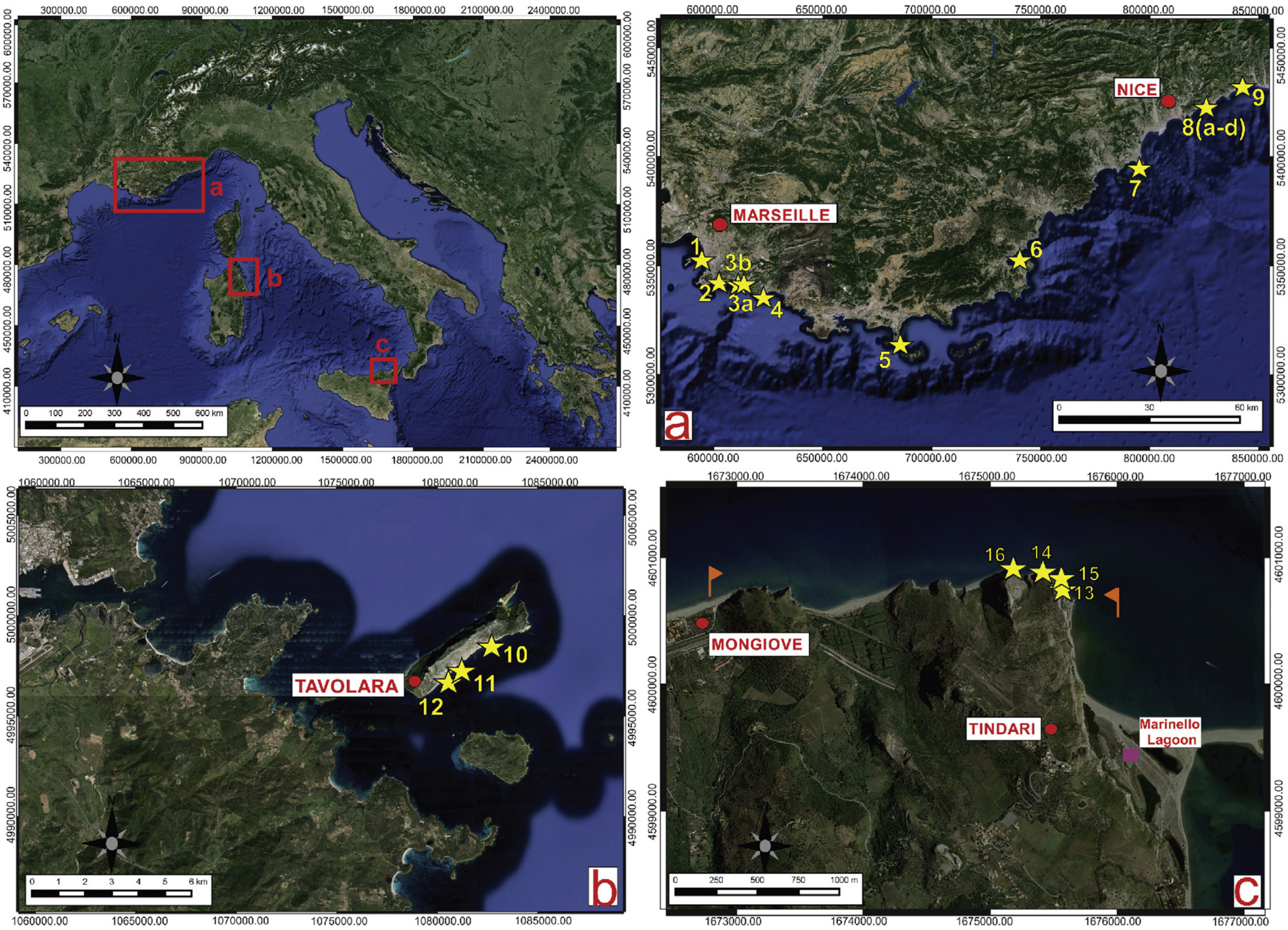

**Fig. 1.** Map showing the studied sites in central Mediterranean sea: a) the coast of southern France, b) the Tavolara (Sardinia, Italy), c) Tindari Promontory (Sicily, Italy).

Stefano, 1997; Billi et al., 2006). At the foot of the Cape Tindari cliff, raised marine cemented gravels up to 2–4 m above the present sea level have been mentioned by Atzori et al. (1978) and Fabbri et al. (1980). Northward, cliffs are incised by a well-defined marine notch at 4–6 m a.s.l., not yet dated (Bonfiglio et al., 2003). Earthquake distribution, neotectonic and GPS data provided the evidence that the Tindari Fault System is still active with right lateral and extensional displacements in the central and northern sectors, with earthquakes characterized by both extensional and strike-slip fault plane solutions (Neri et al., 1996; Serpelloni et al., 2010; Ghisetti, 1979; Lentini et al., 2000; Billi et al., 2006).

According to Gliozzi and Malatesta (1984) and Bonfiglio et al. (2010) on the walls delimiting the Donnavilla Cave, the lithophaga holes are densely distributed, not abraded and confined between 73 m and 85 m of elevation a.s.l. The lithophaga holes were correlated by Gliozzi and Malatesta (1984) with the MIS 5.5 raised beach of Cape Milazzo, which extends between 85 and 50 m a.s.l. The elevation of the inner margin of raised Pleistocene marine terraces in North Eastern Sicily has been used to evaluate the uplift rate of this region and to infer neotectonic events (Catalano and Di Stefano, 1997; Monaco and Tortorici, 2000; Catalano and de Guidi, 2003; Catalano et al., 2003; Antonioli et al., 2006; Ferranti et al., 2006). The elevation of the last interglacial (MIS 5.5) indicates, for Cape Tindari, a long-term uplift rate of 0.63 mm/a.

## 2. Method

The studied coastlines have been investigated through field observations and dives performed very close to the coast, as described in Furlani et al. (2014b). The occurrences of tidal or roof notches were located and mapped and notch morphometry was measured by fixed or extensional rods, following Antonioli et al. (2015). For the deepest sites, i.e. the tidal notches at Tavolara island placed at −25 m, four dives have been carried out (Figs. 3 and 5). The depths of these notches have been measured by depth gauges (Aladin pro, accuracy ±10 cm). Data reported in Table 1 have been corrected for tides using the methodology described in Lo Presti et al., 2014), using tidal data from the nearest tide gauge stations (www.mareografico.it;ioc-sealevelmonitoring.org/), while positions have been estimated at the surface by GPS handheld receivers.

## 3. Field results

We will discuss here the field results for the three investigated areas of the Central Mediterranean: the southern coast of France, between Marseille and Monaco, Tavolara island and Cape Tindari located in Sardinia and Sicily (Italy), respectively.

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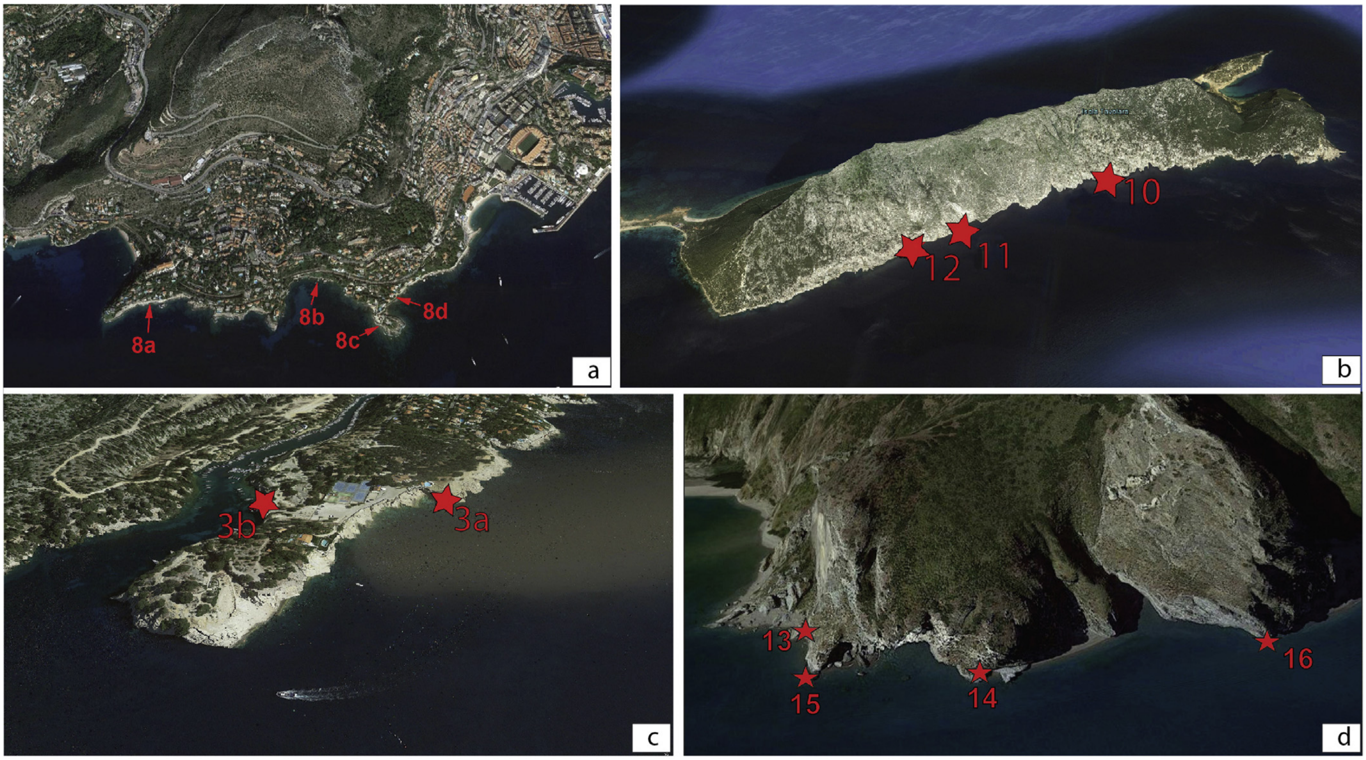

**Fig. 2.** Particular of the studied sites. 2a, Southern coast of France. 2b, the Tavolara island (Italy) with studied sites numbers. 2c the Cassis rias, southern coast of France. 2d the Tindari promontory (Italy) with studied sites numbers, (see also Table 1).

### 3.1. *The southern coast of France*

The coastal area between Marseille and Monaco (France), shows a wide variety of lithology including metamorphic formations, massive and stratified limestones and conglomerates. Between Marseille and Monaco have seven sites have been surveyed showing tidal notches, as described in the following sub-chapters (Table 1 Fig. 1).

#### 3.1.1. *Marseille*

In Marseille, was observed and measured a roof notch with considerable morphological continuity, extending with same features for about 4 kilometers South of Marseille (Table 1; Fig. S1 and Fig. 4a). It is a roof notch formed in Mesozoic limestones (sometimes dolomitic limestones) that at the time of surveys showed a strip of about 60 cm wide of red algae grown above the Cystoseira canopy. The seabed in this section does not exceed 2 meters of depth. We underline that this site is located about 200 meters from the tide gauge station of Marseille (which we used for tidal corrections).

#### 3.1.2. *Sormiou*

By the end of Sormiou canyon, carved on the limestones of the Barremian facies (Urgonian level), a marine tidal notch with a morphological continuity for at least 200 meters, was observed (Table 1; Fig. S1; Fig. 4d). At the time of surveys, it was located at some decimeters below the sea level. It shows a concavity of about 0.3m, while width and morphology remain the same, although the depth of the sea-bottom progressively changes from 1 to 4 m.

#### 3.1.3. *Cassis*

At Cassis it has been identified a marine tidal notch with identical morphological and lithological characteristics morphometric features we found in Sormiu (Table 1). Its width is 0.28 m and it was completely submerged at the time of surveys (Fig. S2; Fig. 4b,c). It is worth noting the presence of a layer of fresh water on the sea surface, with a thickness of some cm. The notch displayed an homogeneous and continuous morphology while, about 400 m offshore the canyon (Fig. S2; Fig. 4c) we found a tidal notch having morphometric shapes and sizes in agreement with those described by Antonioli et al., 2015 for the central Mediterranean. Here, the mean sea level is marked by a trottoir of coralline algae placed at the base of the notch (Fig. S1).

#### 3.1.4. *La Ciotat*

The lithology of this coast displays well-cemented conglomerates that do not allow the formation and preservation of notches. At the mean sea level it is present a concentration of cthamalid barnacles and encrusting corallinales (Fig. 4e, Fig. S3a-b).

#### 3.1.5. *Hyeres and Saint Tropez*

In these two areas, characterized by metamorphic rock (shales), notches were not found at any elevation. On the tip of the promontories, only rare cthamalid barnacles and limpets were found at sea level (Fig. S2 c).

#### 3.1.6. *Cannes*

On the carbonate cape to the East of the Bay of Cannes, a bedrock of intensely stratified limestone does not show marine notches. At sea level were found only cthamalid barnacles and limpets (Fig. S2d).

#### 3.1.7. *Cap d'Ail*

This coast is characterized by different lithologies on which some sea level indicators developed. In the most western side, between points 8a and 8b of Fig. 2a, a well-cemented continental

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**Table 1**
1) Site number and name of the investigated sites. 2) Sites coordinates (WGS84). 3) Type of notches. 4) Date and time (GMT) of surveys. 5) Altitude from sea level (base of the notch). 6) notch width (cm). 7) notch depth (cm). 8) Bottom (reef) depth (cm). 9) depth of cliff toe (m). 10) Bedrock. 11) Tide (cm). 12 Corrected altitude of the base notch (cm). 13) altitude of MIS 5.5 (m). Reference elevations (cm) for the tidal correction at the tide gauge stations of Marseille: Z0 = 57.8, Cagliari: Z0 = 18.3 and Palermo: Z0 = 11.7.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 Marseilles | 43 16 718<br>5 21 232 | roof | 03.05.15 12.45 | +45 cm | – | – | – | 1.5 | Mesozoic limestone | +14 | +0.6 | – |
| 2 Sormiou | 43 12 38 57<br>5 25 15 81 | submerged | 03.05.15 10.20 | −42 cm | 28 | 21 | 15 | 2 | Triassic limestone | +13.8 | −0.28 | – |
| 3 Cassis a | 43 12 17 92<br>5 31 08 55 | tidal | 02.05.15 14.30 | 0 | 42 | 35 | 35 | 2 | Triassic limestone | +9.6 | – | – |
| 3 Cassis b | 43 12 19 86<br>5 30 58 24 | submerged | 02.05.15 15.45 | −43 cm | 29 | 20 | 13 | 4 | Triassic limestone | +9.9 | −0.33 | – |
| 4 La Ciotat | 43 09 58 18<br>05 35 49 82 | no | – | – | – | – | – | 3 | Conglo-merate | – | – | – |
| 5 Hyeres | 43 01 41 61<br>06 09 23 34 | no | – | – | – | – | – | 1 | Metamo-rphic | – | – | – |
| 6 Sain Tropez | 43 16 26 52<br>06 38 26 33 | no | – | – | – | – | – | 1 | Metamo-rphic | – | – | – |
| 7 Gulf of Cannes | 43 32 40 30<br>07 07 54 59 | no | – | – | – | – | – | 1 | Stratified limestone | – | – | 10.2 |
| 8 Cap d'Ail a | 43 43 12 27<br>07 23 31 19 | no | – | – | – | – |  | 2 | Quat. breccia |  | – | 18–10 |
| 8 Cap d'Ail b | 43 43 15 53<br>07 24 03 12 | tidal | 30.04.2015<br>13.00 | 0 | 80 | 35 | 30 | 2 | Mesozoic limestone | +16.8 | – | 18–10 |
| 9 Balzi Rossi | 43 46 978<br>07 32 206 | tidal | 10.10.14<br>13.30 | 0 | 44 | 50 | 75 | 1.2 | Triassic limestone | +4 | – | 12 |
| 10 Tavolara Scoglietto | 40.904576<br>09.719851 | mushroom | 22.09.215<br>11:05 | −24.7 m | 115 | 250 | 250 |  | Giurassic limestone | −5.7 | −24.1 | 8.5 |
| 11 Tavolara Occhio di Dio | 40.896533<br>09.707200 | mushroom | 22.09.215<br>11:15 | −25.5 m | 115 | 280 | 280 |  | Giurassic limestone | −8.7 | −24.6 | 8.5 |
| 12 Tavolara Cala Cicale | 40.895333 09.705600 | mushroom | 2209215 12:45 | −25.2 m | 110 | 340 | 340 |  | Giurassic limestone | −10.7 | −24.1 | 8.5 |
| 13 Tindari | 38 93 28<br>15 2 46 89 | roof | 13.09.2015<br>10.10 | +5.6 m | 220 | 100 | 200 |  | Metamo-rphic | +2.7 | – | 85 |
| 14 Tindari | 38° 9′6.86″<br>15°2′42.01″ | roof | 13.09.2015<br>10.50 | +5.3 | 190 | 80 | 260 |  | Metamo-rphic | +5.7 | – | 85 |
| 15 Tindari | 38° 9′5.62″<br>15°2′46.52″ | abrasional | 13.09.2015<br>10.40 | −1.90 | 80 | 60 | 260 |  | Metamo-rphic | +5.7 | – | 85 |
| 16 Tindari | 38° 9′7.56″<br>15°2′34.69″ | abrasional | 13.09.2015<br>12.10 | −1.15 | 90 | 60 | 210 |  | Metamo-rphic | +12.7 | – | 85 |

Quaternary breccia is outcropping, on which millstones have been cut (see also Antonioli et al. 2015, 2006, this volume, Fig. 6i).

The shoreline is deeply eroded and presents collapsed boulders at sea level. Also eroded and collapsed medieval millstones witness a fast coastal evolution that did not allow the formation and preservation of tidal notches. The coastal zone between points b and c is marked by limestone and discontinuous tidal notches, which show geomorphological features in agreement with those reported by Antonioli et al. (2015) (Fig. 4 i,l,m,n; Fig. S1, Table 1). The section between points c and d are characterized by well-cemented conglomerates, extended platforms (even up to 25 m width) with cthamalid barnacles and limpets, and the absence of notches (Fig. 4 m). At 10 to 11 m of elevation, an abrasion terrace and some conglomerate pebbles with holes of lithofaga, placed on the Last Interglacial terrace, were found.

### 3.1.8. *Balzi Rossi (Italy)*

A present-day tidal notch is well carved on the dolomitic limestone immediately below the MIS 5.5 deposits (Table 1).

## 3.2. *Tavolara island (north-eastern coast of Sardinia, Italy)*

On the South-East side of the carbonate cliffs of Tavolara island, a tidal notch of 0.6 m width, is present at mean sea level. While a fossil tidal notch aged MIS 5.5 level (Porqueddu et al., 2011) is carved on the limestoneswith morphological continuity at the average elevation of 7.5 meters a.s.l. (Figs. 1b, 2b and 3e). It displays the same dimensions of the present day tidal notch (about constant over the entire carbonate cliff), thus suggesting the absence of any differential vertical land movements along the investigated coast and the overall tectonic stability of the island along the vertical. However, our surveys mainly focused on the submerged sector, which is the most interesting for this study. Here, we found tidal notches 2.5 m deep and 1.2 m wide, that formed “mushroom-like” morphologies (Furlani et al., 2011a) either set up on stand-alone rocks or diffuse along the submerged cliff, at the same elevation. These formations are placed extended along 2.6 km of the submerged carbonate platform (we surveyed as example 3 exemplary mushroom-like formations at sites 10, 11 and 12 on Fig. 2b), which is placed at the mean depth of −25 meters (Figs. 3 and 5 Table 1). We underline that the “mushroom-like notches” formed on a carbonate platform due to the combination of different forces of mechanical abrasion and chemical dissolution with respect to tidal notches, on vertical cliffs characterized by deep seafloor at the foot. They represent small residual stacks, or pinnacles, shaped by waves crossing the platform and flowing around them, forming the notch. The mechanical abrasion from small particles transported by waves and current, contribute to give them the observed shape. This is a hydrodynamic process quite distinct from reflected waves, which are totally reflected when they approach vertical cliffs the total reflection of a wave interacting with a vertical cliff. Figs. 3d and 5, illustrate the

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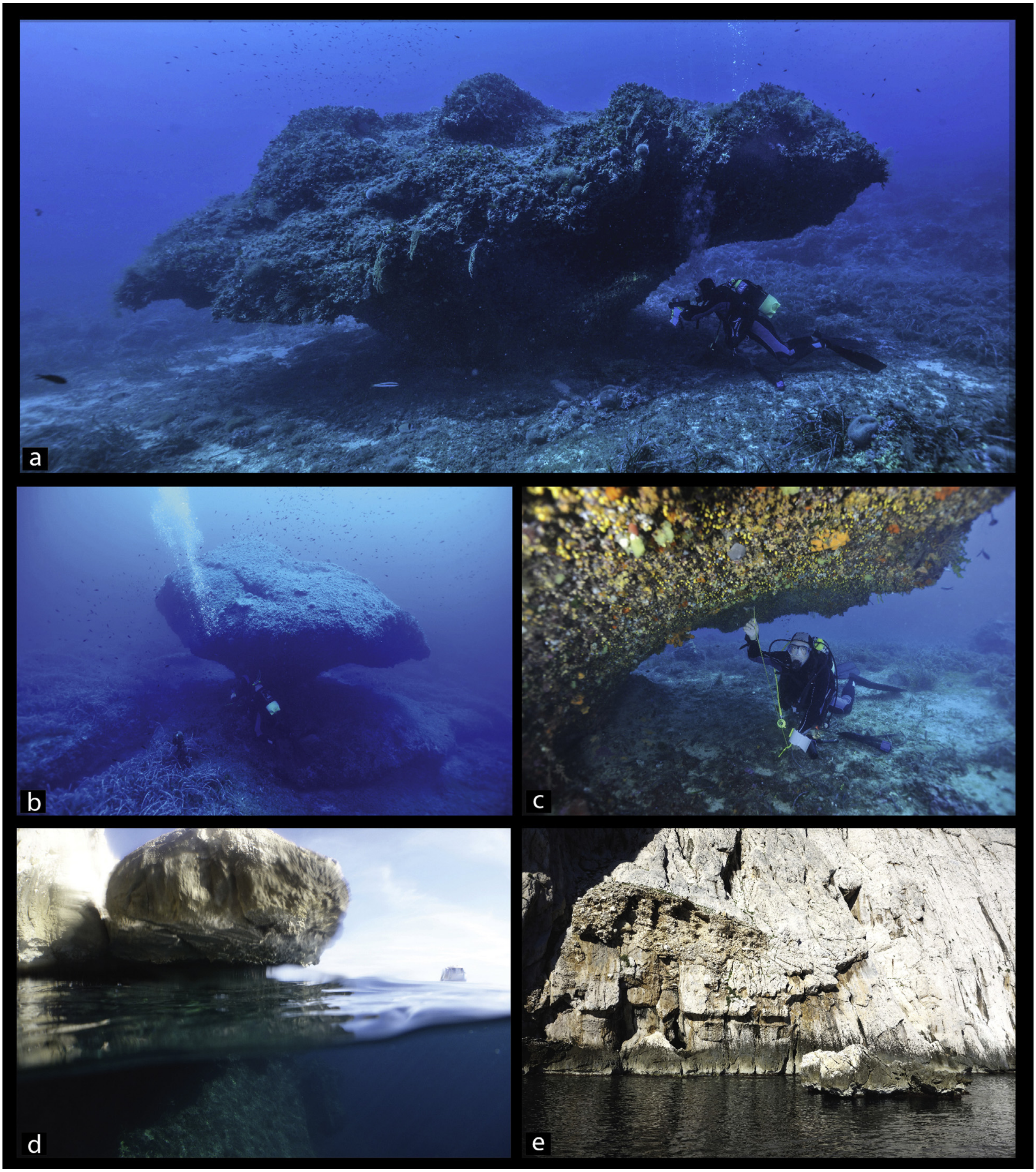

**Fig. 3.** Tavolara island photo tables: a) the submerged mushroom-like notch 1 (see Fig. 2b, site, 12 for location); b) the submerged mushroom notch 2 (see Fig. 2b, site 11, for location); c) measuring width of the submerged mushroom-like notch 1; d) Tavolara island, a present day mushroom notch; e) Tavolara island: fossil (MIS 5.5) and present-day tidal notches.

evolution of their formation process. Details are provided in Supplementary material S5).

### 3.3. *Tindari*

Our investigations were performed along a route running east-west along the cliff of Cape Tindari. Here, a wide and well preserved roof notch extending for about 15 m along the eastern side of Cape Tindari, was observed (Figs. 2d and 8). The notch is 2.2 m wide and 1 m deep, with the maximum concavity filled with a well cemented deposit, placed at an elevation of 6.8 m a.s.l. (Fig. 8a and b).

The remains of a fossil band of Litophaga holes, is present up to a mean altitude of about 0.4 m above the maximum concavity width of the notch. A fossil of Litophaga shell was collected and dated from the upper portion of the band providing an age at 28.553 ± 232 years cal BP (Lab. CIRCE, Caserta Italy, Code DSH1220).

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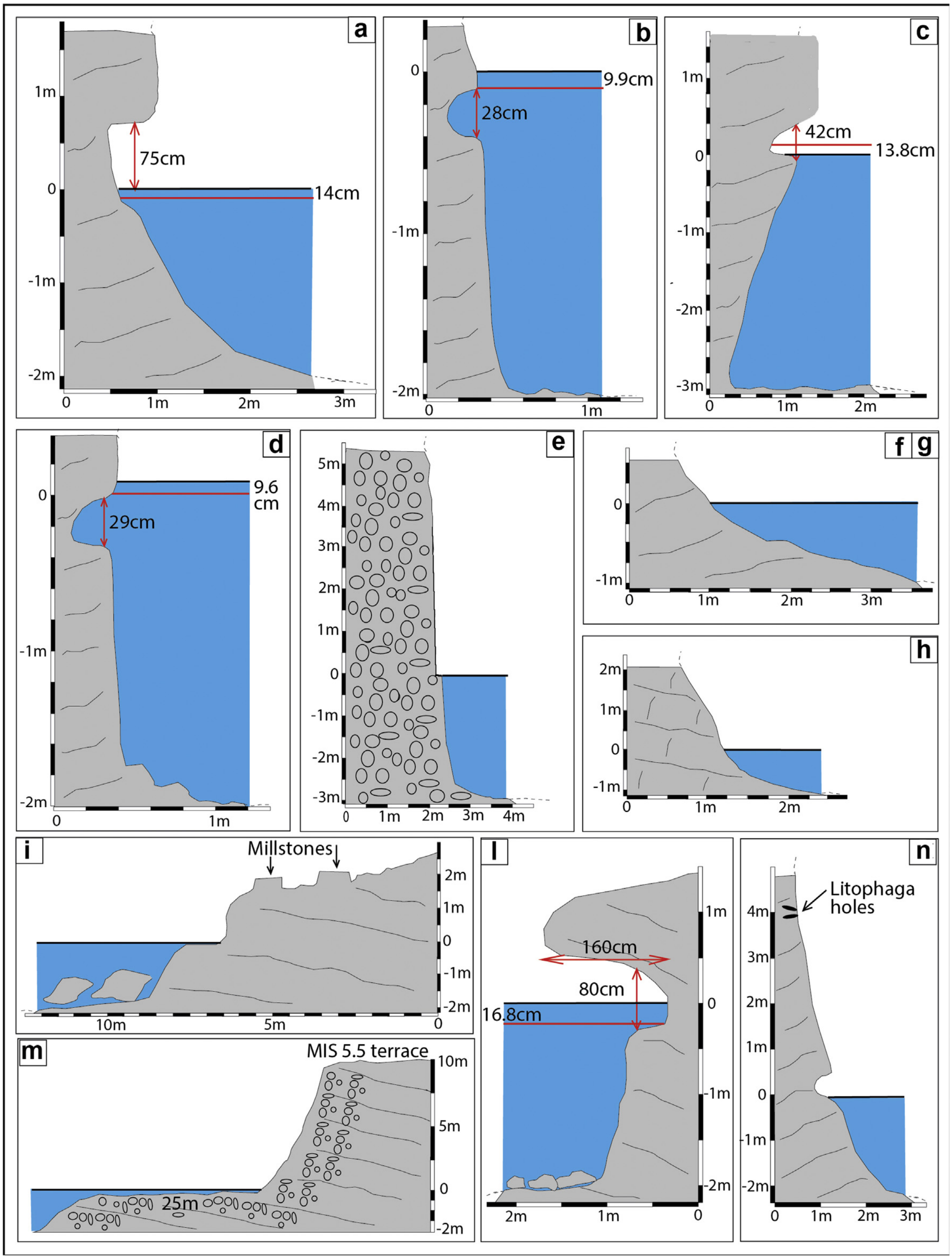

**Fig. 4.** Schematic cross sections of the studied sites in southern France: a) Marsiglia; b) Cassis (in the ria); c) Cassis (outside the ria); d) Sormiou; e) La Ciotat; f) Hyeres; g) Saint Tropez; h) Cannes gulf; i) Cap d'Ail millstone area; l) the tidal notch at Cap d'Ail; m) the terrace at Cap d'Ail; n) the present-day tidal notch and fossil lithophaga holes at Cap d'Ail.

We believe that this age is unreliable likely due to the deposit covering the fossil band that altered the dating during the analysis. Our surveys confirmed that the elevation of the maximum concavity of the notch is constant and equal to 6.8 m a.s.l.

Continuing westward, the uplifted roof notch was observed along the north side of Cape Tindari (Figs. 2d; 6, 8). This is 1.90 m wide and 0.80 m deep and its maximum concavity is placed at the elevation of 5.90 m a.s.l. (Figs. 6 a, b, c, d; 8 a, c, d, e, f). In this site, we also observed cemented deposits filling the notch and the fossil band of Litophaga holes that was found at the base of the notch itself.

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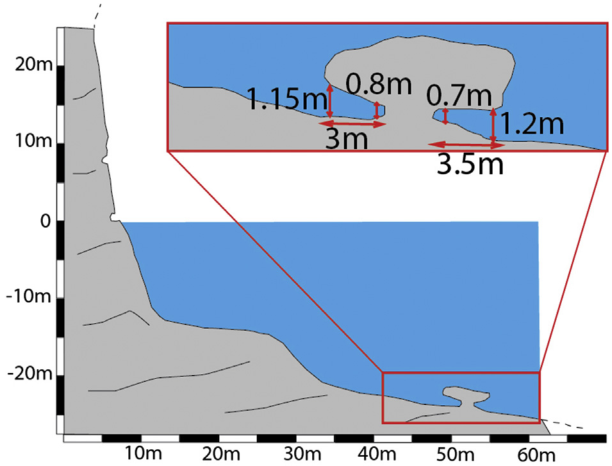

**Fig. 5.** A representative cross section of the submerged mushroom-like notch at Tavolara island (SE portion). Elevation and morphometric size (in m) are shown in the figure.

Near the locality of Mongiove, an outcrop of a fossil band of Lithophaga holes up to a height of 4 m above the present sea level, was found (Fig. 2d).

During the surveys, submerged morphologies related to two well preserved abrasional notches and a beachrock, have been identified. The first notch (Figs. 6a and 8c) has a width of 0.8 m and is 0.6 m deep; its base is placed at −1.9 m b.s.l. The base of the second notch (Fig. 8d), is at −1.15 m b.s.l., and is characterized by a width of 0.9 m and a depth of 0.6 m.

The beach-rock runs discontinuously northwest of Cape Tindari, forming a sedimentary body with thickness up to 0.4 m and dipping gently at about 5° offshore. Its bottom is at −2.50 m of depth while its top is at −1.50 m b.s.l. Clasts included in the deposit (poor in macroscopic shell fragments), are ranging in size from fine sands to conglomerates. The latter occurring in the lowest portion of the body.

Along the present sea level, a discontinuous roof notch with a maximum width of about 0.4 m, was found. A living barnacle band extends on average up to 0.5 m above the present sea level, with peaks up to more than one meter in major splash areas.

## 4. Discussion

### 4.1. The coast of southern France

Regarding the morphometric size and positions below the sea level of the submerged tidal notches at Cassis and Sormiu, it should be noted that their amplitude is similar to the mean annual tidal excursion as obtained from the nearby tide gauge station at Marseille (See also Antonioli et al., 2015 for the analysis of the tidal range in the Mediterranean). Antonioli et al., 2015 showed that in the central Mediterranean and also in the Oceans, the average amplitude of the tidal notches is between 100 and 50% larger than the actual tide amplitudes (80-60 cm against 35 cm of tide). We retain think that these notches are different from others already studied in the Mediterranean and can be considered anomalous for the following reasons: i) for their small concavity width with respect to their exposition to waves, ii) they are placed well below their natural elevation, usually with the maximum tide level corresponding to the base of the notch. In this case they are completely submerged (Table 1). We speculate that the causes of the anomaly can be due to: i) the considerable amount of spring water coming out from the coast that stratifes above marine water, and that may have a key role in the chemical dissolution of limestone, as suggested by Furlani et al (2014b) in the northern Adriatic Sea, ii) the morphology of the coast, similar to a narrow canyon (the distance between the opposite cliffs is 150–200 meters), that retains spring water, thus favoring the rock dissolution. To double check if these two sites preserve anomalous marine tidal notches with respect to other sites of the Mediterranean, we have also investigated part of the coast of the French Riviera, between Marseilles and Nice, where for which exist only a few studies on the geomorphological features of this region and on the elevation of the Tyrrhenian level were produced. The most important notch was found in Cassis (Fig. 4 and Fig. S2), outside the rias. Here, the tidal notch is placed at a normal elevation, not submerged and related to local mean sea level. Always in Cassis, Lithophaga holes were found up to an altitude of 3 meters a.s.l. (Fig. S2h). We attribute this fossil holes to the MIS 5.5 level by their altitude correlation with several sites located in the Central Mediterranean (Ferranti et al., 2010). The studied sites show the presence of marine or tidal notches. Their morphometric size and appearance is similar as that in the central Mediterranean coast, such as in Marseille, where dolomia is prevailing and an almost continuous roof notch formed. We discussed previously the results for Sormiou and Cassis, while at La Ciotat, where coastlines are made of rocky cliffs of conglomerate (where samples of Lithopyllum were used to produce the sea level curve by Laborel et al., 1994), notches did not form, like along the metamorphic coast of Hyeres. On the finely stratified limestone of the Bay of Cannes, notches did not form as well (like in other Mediterranean sites with this same lithology). At Cap d'Ail, a fairly continuous notch is found (0.8 m of width) on the limestones, while it did not form where coastal lithology changes to Flysch (with wide platforms). Lithophaga holes are found on the limestone, up to the elevation of 4.5 m a.s.l., in coincidence with a marine terrace placed at about 11 m a.s.l. (likely of the Tyrrhenian level). Obviously this notch (sites 5 and 6 Table 1, Fig. S3c) did not form on the metamorphic units. Finally, at Balzi Rossi, which is a coastal zone made of Mesozoic limestones, a tidal notch (0.5 m wide) is present. Near, up to about 8 m of elevation, there are deposits of Tirrhenyan age containing fossil fauna with Persistrombus. In summary, we observed normal (sensu Antonioli et al., 2015) tidal notches at Cap D'Ail and Cassis; a roof notch in Marseille and submerged tidal notches in the rias of the Calanques (Cassis and Sormiou). We assume that the particular morphology a cul de sac of the rias and the abundant presence of spring water, can play an important role in the dissolution of carbonates and the final form of a such rare anomalous submerged marine tidal notch.

### 4.2. Tavolara

Many examples of small isolated rocks mushroom shaped and with roof notches carved at present-day mean sea level, can be found along rocky coastal zones all around the world, in the Mediterranean (Antonioli et al., 2015; Furlani et al., 2011a,b) or in the Oceans (Trenhaile, 2015). Their shape is related to the 10 times higher erosion rates occurring in the tidal zone with respect to the supratidal and subtidal zone, up to 0.3 mm/yr (Furlani et al., 2009, 2010; Furlani and Cucchi, 2013). These rates are the sum of marine factors acting between high and low tides (De Waele and Furlani, 2013). Furlani et al. (2014b), concluded that the lowering rates in the Mediterranean area show a significant horizontal variability in erosion rates in response to the variability of local lithological and geomorphological setting. Local conditions can significantly increase the erosion rates also outside the intertidal zone due to local different ecological association or to the local geomorphological setting. Lowering rates can exceed 1 mm/yr in favorable conditions, affecting also the supratidal and subtidal zone and widening the

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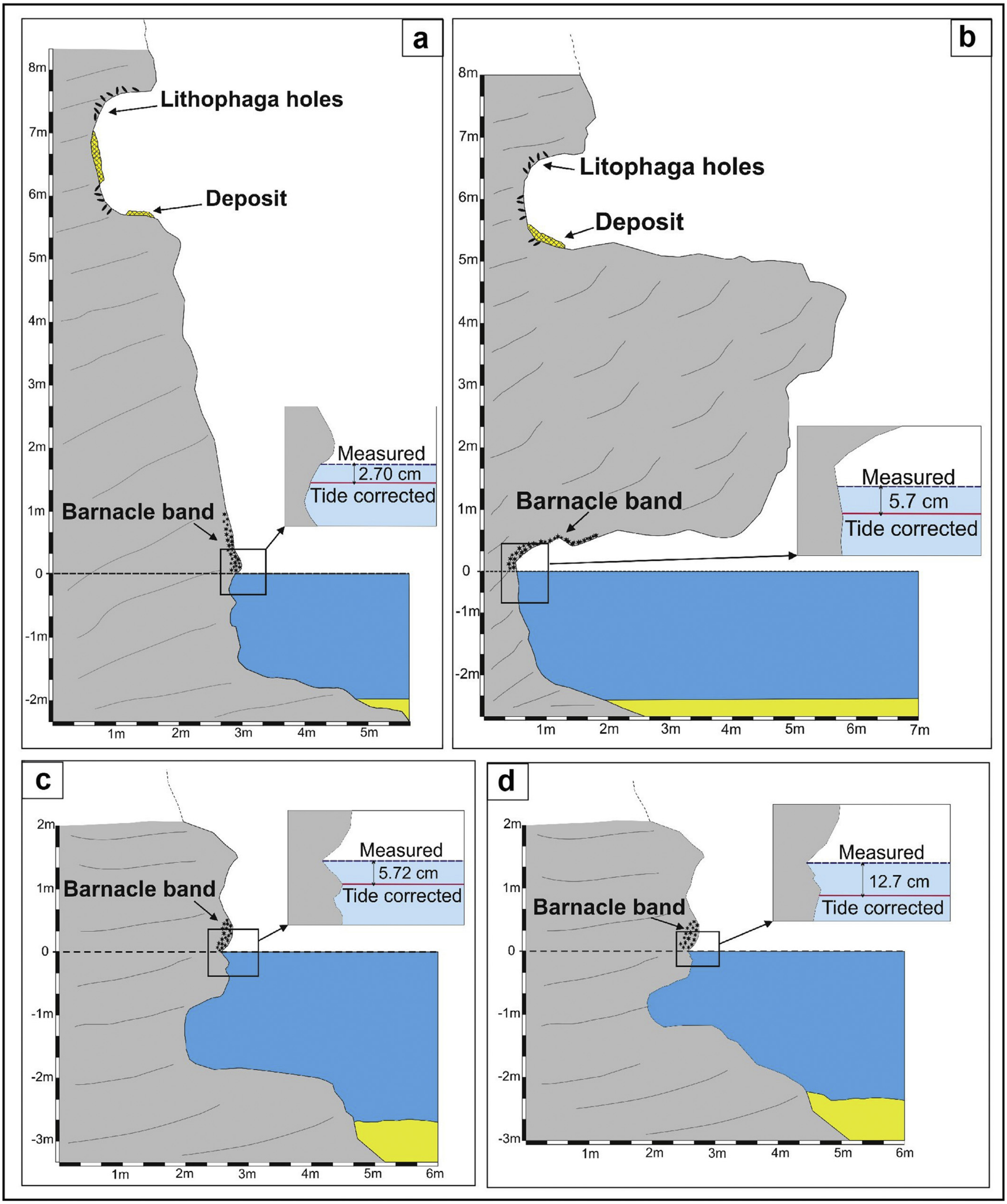

**Fig. 6.** Representative cross sections of the Tindari promontory. The submerged (erosional) notches and the uplifted notches with fossil deposit. See Figs.1 c and 8 for location and Table 1 for data.

amplitude of a standard tidal notch. The shape of the submerged notches of Tavolara can be related to wave diffraction around the base of the notches, which becomes circular in time. The effects of collapsing and surging of broken waves around the notches can increase the removal of weathered materials from the stack, both in front and behind it.

Concerning the chronological attribution of the mushroom-like tidal notches recognized in Tavolara, we wish to emphasize that this morphology repeats (Figs. 3 and 5) with continuity with similar dimensions at the same altitude (−25 m, Table 1) for at least in 4 main sites, besides additional eroded or collapsed structures, along 4 km of coast. Excluding morphologies older than MIS 5, given the freshness of the mushroom type notches and because these are located at 25 m b.s.l., we can hypothesize that these formed during the cold event occurred at 8.2 ka cal BP, when sea level remained constant before rising again up to the present position. Lambeck et al., 2011, predict the same sea level position for this period, when the rapid sea level rise after the LGM was abruptly interrupted (Rohling and Pälike, 2005; Turney and Brown, 2007). Anyway, the related effects on the sea level change in the Mediterranean are still poorly known, even in coincidence with the interruption in the deposition of Sapropel. The latter is an organic-rich sediment that accumulated during the Holocene Climatic Optimum due to reduced deep water ventilation caused by enhanced freshwater discharge linked to the African monsoon (Mannino et al., 2015).

Alternatively, the studied morphologies could be related to the transgression of the MIS 5.1 or 5.3 that was found at about this altitude globally and in the Mediterranean basin. Waelbroeck et al. (2002) and Siddall et al. (2003), on the basis of global sea level curves, indicated the transgression at −21.2 m and −26.7 m, for MIS 5.1. Observational data of MIS 5.1 deposits from coral reefs in the Caribbean Sea seem to be in disagreement with the global sea level curves. In particular, discrepancies are found in a transect on stable areas for the coast of Haiti, Bermuda, Bahamas, South Carolina, and Florida, with altitudes between −20 and + 5 m. These controversial observations, however, are reconciled when the isostatic response of the Earth to the two North American ice sheets melting during the last glacial cycle is considered (Potter and Lambek, 2004). A MIS 5.1 sea level at about +1 m was established using phreatic speleothem sampled in a partially submerged cave at Mallorca (Spain), in the western Mediterranean Sea (Dorale et al., 2010). Recently, Muhs et al., 2015 studied and dated in the island of Mallorca deposits containing fossil of Cladocora at an elevation between +1 and 2 meters a.s.l. All the nine investigated sites have clarified that they are belonging to the MIS 5.5 deposits.

The global sea level curves (Waelbroeck et al., 2002; Siddall et al., 2003) indicate the sea level at −18.7 m and −28 m, respectively for MIS 5.3. Transgressive lagoonal facies from the Po Plain (see core 240-S8 in Amorosi et al., 1999) were assigned to the presence of MIS 5.3 using the ESR method on MIS 5.5 lagoonal deposit (Ferranti et al., 2006). Taking in account the present altitude of this deposit and the subsidence rates calculated using MIS 5.5 (about 1 mm/yr), a relative sea level of −12 m can be established for MIS 5.3. Finally, Gzam et al. (2016) attributed to submerged fossil dune alignments in the Gulf of Gabes, the palaeoshorelines of the MIS 5. In particular, the MIS 5.1 was found at about −8 m, MIS 5.3 at −19 m and MIS 5.5 at +3 m.

Based on the evidences of the morphological continuity of the mushroom-like tidal notches, it is likely that they are formed during a marine transgression. It cannot be excluded the hypothesis of the 8.2 cold event that may have temporarily slowed the rapid ascent of the sea level during the Holocene, thus leading to their formation. In any case, although we leave both the hypothesis open, we prefer to support the MIS 5.3 or 5.1 hypothesis.

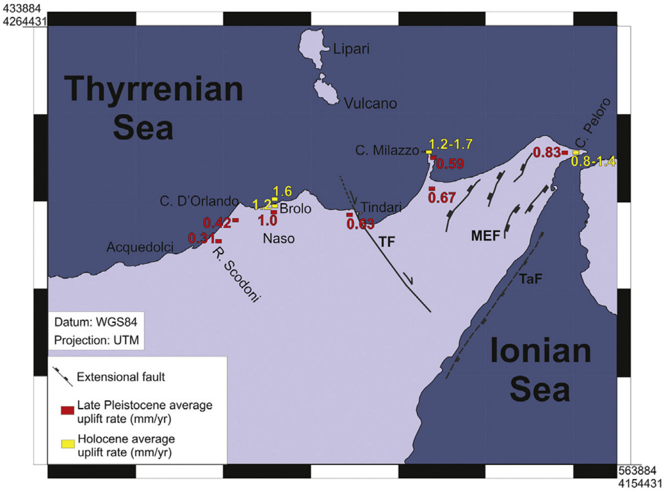

**Fig. 7.** The coast of NE Sicily near the promontory of Tindari. The land uplift rates (in mm/yr) inferred from MIS 5.5 (in red) and Holocene (in yellow) data, are shown in the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 4.3. Tindari

Gliozzi and Malatesta (1984), place the MIS 5.5 stage in the Tindari area at 85 m above present sea level. In this area land uplift has been estimated at 0.63 mm/y (Fig. 7) in the last 125 ka BP and the presence of a roof notch at about 6 m above the present s.l. leads to two questions:

i) what is the age of the roof notch? ii) is the vertical land movement of the area only a regional fact, or is it a combination of the latter with a coseismic contribution?

Unfortunately, we consider far from to be true radiocarbon dating of a Lithophaga shell collected inside the notch gives an age (about 28 ka BP), because the analysis has been altered by cemented deposits covering the fossil shell. Therefore to define the timing of the formation of the roof notch, we attempted a correlation between the sea level curve (Waelbroeck et al., 2002), and the highstand position, considering an uplifting rate at 0.63 mm/y (Fig. S4). The consequence is that, given this rate of uplift, the roof notch at 6 m a.s.l. cannot be correlated to any other eustatic maximum (MIS 5.3, 5.1 and 3). Therefore, we can hypothesize that the roof notch has formed during the Holocene.

Antonioli et al., 2015 suggest for stable areas, that in the Mediterranean the formation of the tidal notch during the Holocene started about 6.8 ka (Lambeck et al., 2011), when the rate of sea level rise had considerably diminished, in agreement with the database by Boulton and Stewart (2015). Because the latter have shown that the oldest uplifted notches are always younger than 6.5 ka BP, as a consequence we suggest an age ≥6.5 ka BP for the investigated uplifted notch.

We feel to remark that it is not easy to estimate the tectonic uplift occurred during the Holocene at Capo Tindari. Lacking an absolute age, we can hypothesize different scenarios corresponding to the different ages of the roof notch (between 6.5 and 0.5 ka BP). As a result, we obtained different and unlikely estimations of the uplifting rate (Table 1): none of the scenarios shows an uplifting rate comparable with the long term rate at 0.63 mm/y. Therefore we speculate that, during the Holocene, the studied area has been affected by vertical land movements caused by the combination of a constant regional component and of episodic coseismic contribution, probably related to the activity of the Tindari fault. The occurrence of fast coseismic movements can explain the current

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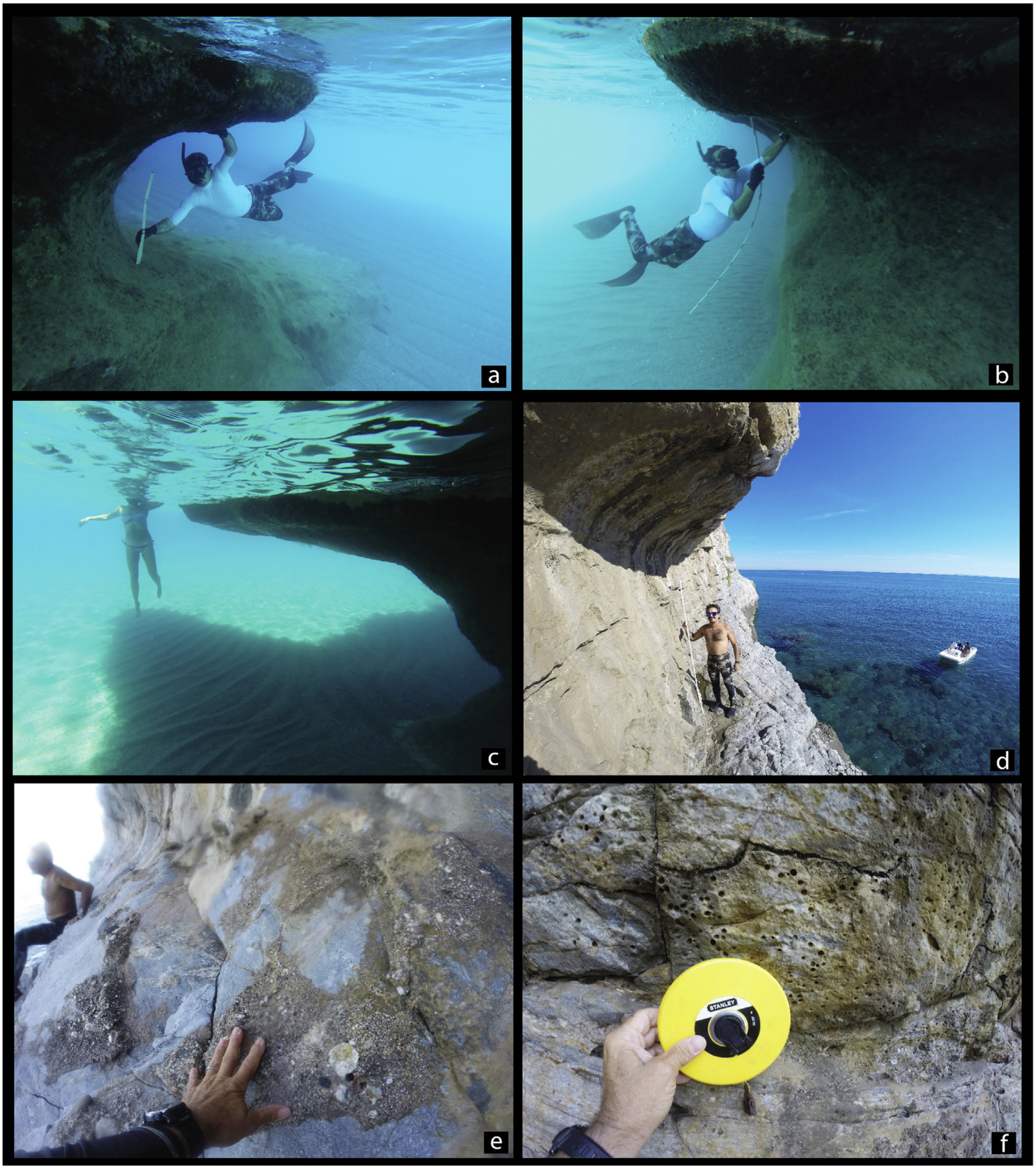

**Fig. 8.** Cape Tindari: a,b,c) the submerged marine notches described in the sketch of Fig. 6 a, b, c, d, the Holocene uplifted roof notch with showing the fossil beach deposit and Lithophaga holes, as also described in Fig. 6.

position and preservation of notches. Their formation are depending on the action of the sea waves, but the possibility of their preservation is higher when a sudden coastal uplift is occurring.

Considering the data reported in Table 1, it is clear that coseismic contribution played an important role in the history of the vertical land movements of the studied area. Unfortunately, the lacking of temporal constraints does not allow us to define the timing of the seismic events, but we can certainly state that episodes of land uplift can be attributed to the sum of repeated seismic events that affected the area, similarly as observed in northwestern Sicily in a period between 4.8 and 5.3 ka BP (De Guidi et al., 2003; Scicchitano et al., 2011; Spampinato et al., 2012).

## 5. Conclusions

The marine tidal notches in the area of the Calanques (Cassis and Sormiou), are submerged; those located along the coast between Marsiglia and Balzi Rossi (Italy), are normal tide notches. The rias morphology and the large presence of spring water at sea surface can drive the formation of the observed submerged morphologies that are not originated by vertical tectonics.

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The coast of Tindari shows uplifted and submerged roof notches that can be dated between 6.5 and 5 ka cal BP. Here, the submerged notches may have been carved by pebbles abrasion when their bottom was at a higher elevation (abrasional notch). This speculation is supported by the notch width, which is larger than in other coasts with similar tidal range, as reported in Antonioli et al. (2015).

Finally, along the southeastern coast of Tavolara Island (Italy), that falls in the tectonically stable region of Sardinia, we discovered four isolated mushroom shaped rock formations (see S2), revealing the presence of marine tidal notches at −25 m that mark the position of a fossil coastline. We speculate that their origin is related to a marine transgression that took place during the MIS 5 and likely during the MIS 5.1 or MIS 5.3, in agreement with the estimated position of the past global sea level for that specific age.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2017.02.037.

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