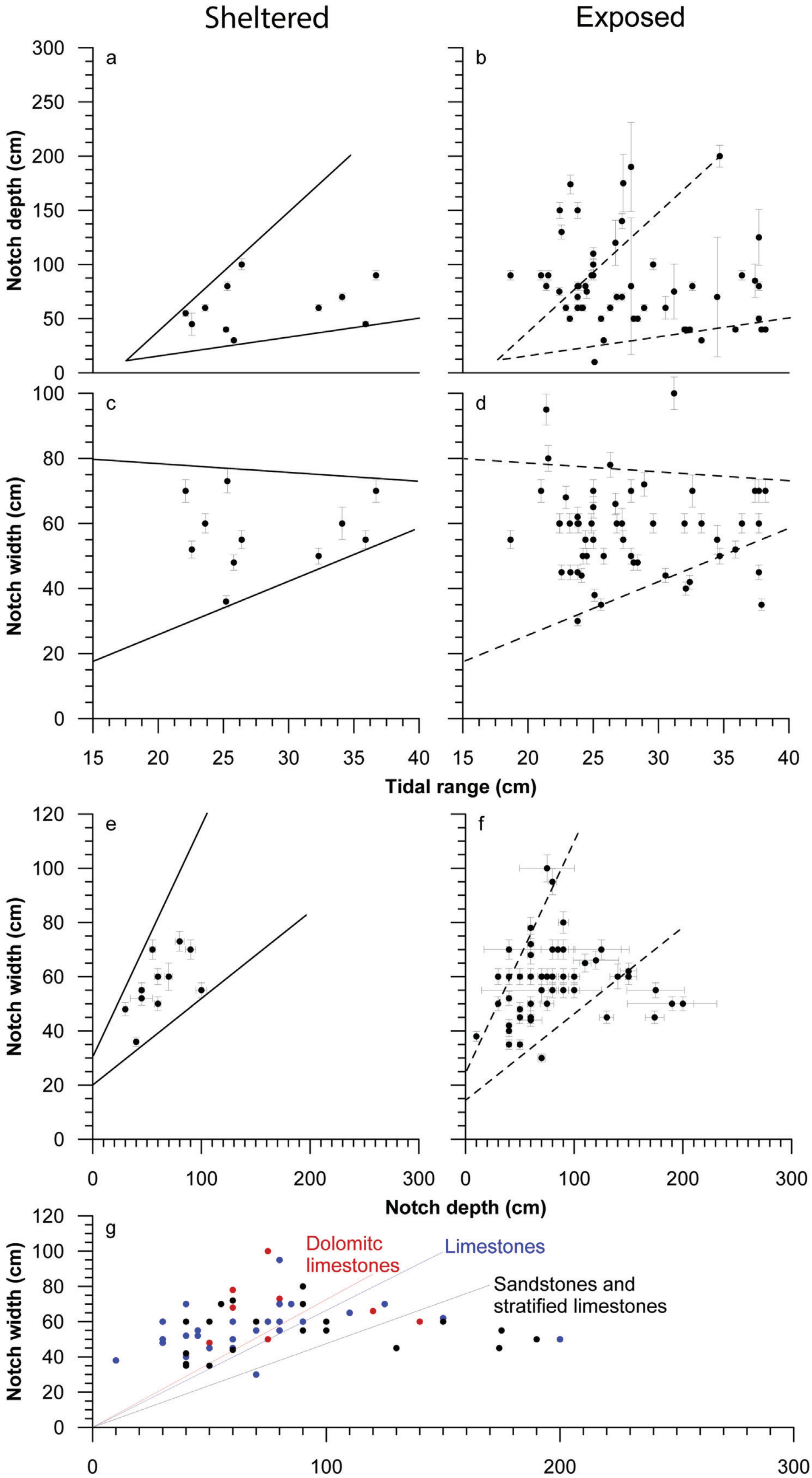

Fig. 8. Statistical diagrams. Relationship between tidal range and average depth of sheltered (**a**) and exposed (**b**) notches; relationship between tidal range and width of sheltered (**c**) and exposed (**d**) notches; relationship between average width and depth of sheltered (**e**) and exposed (**f**) notches; **g)** relationship between tidal notches and the lithology of the rock where they are carved.

4.3. *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 impact) and an indirect (rim growth) action on notch development. At each site, we investigated the relationship between rim thickness (measured at the notch base), and wave energy (kw/m) reaching the coast. We excluded from computation the sites located in sheltered settings.

It is evident from Fig. 5d there is a direct correlation between rim thickness and wave energy. In general, the higher the wave energy hitting the coast, the thicker is the rim. At some sites (Badisco, Biddiriscottai, Cala Fuili, Fig. 6), and also at sites from outside the Mediterranean area (Fig. 9b, Barbados) one or more

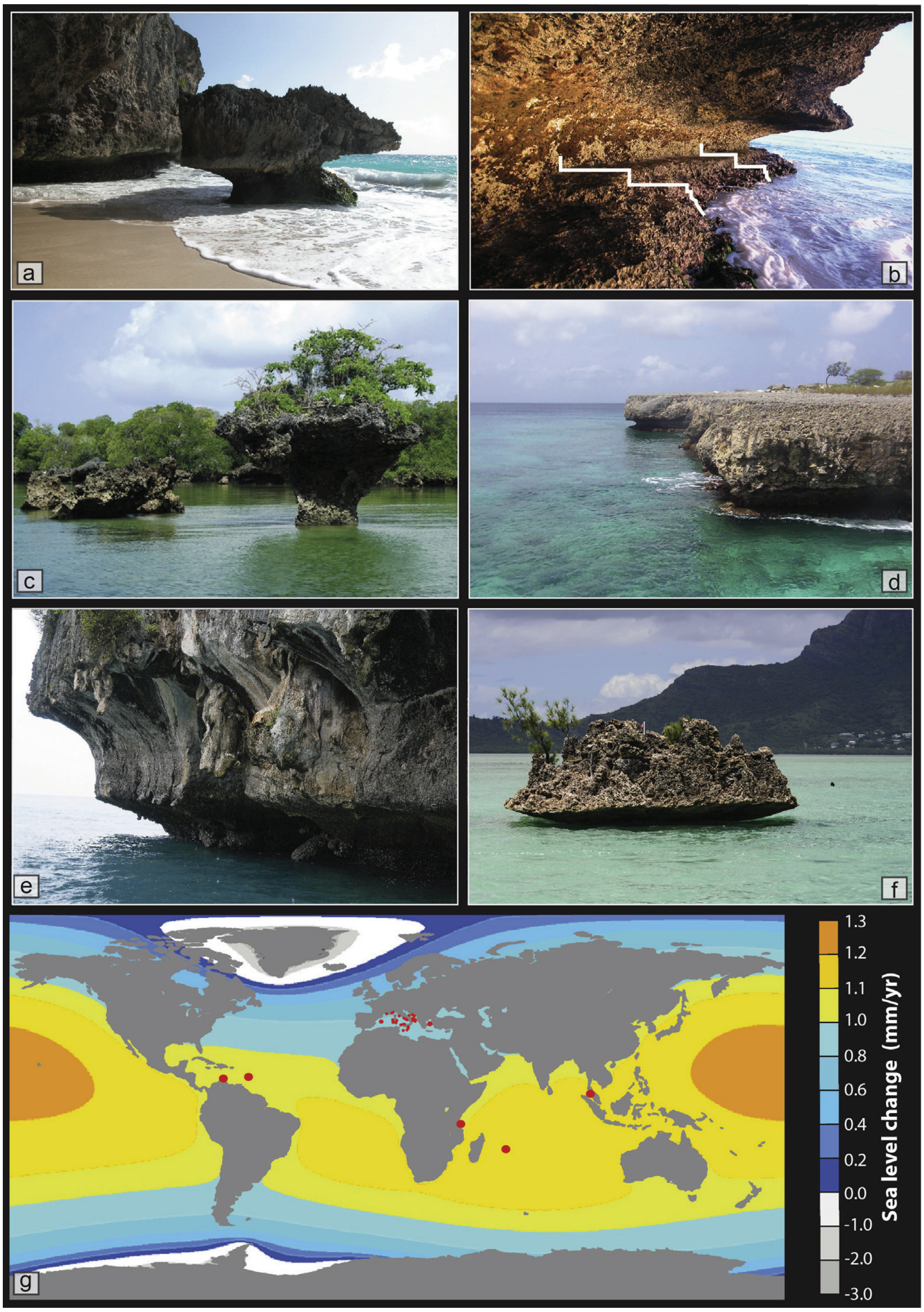

Fig. 9. Extra Mediterranean tidal notches: **a)** Barbados, notch width: 140 cm, **b)** Barbados, presence of reef steps, **c)** Zandibar, notch width: more than 400 cm, **d)** Bonaire, Netherland Antille, notch width: 100 cm, **e)** Thailand: a smoothed mid Holocene (Sheffer et al., 2012, +2.6 m 5.5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

Table 4
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 and 7 we used the original local tide gauge data.

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

steps (10–12 cm in size) in the *Lithophyllum* rim has been observed, whose origin is still to be understood.

5. Discussion

5.1. Model of notch evolution

In order to explore the relations between the shape of the notch and the Holocene sea-level rise, we developed a conceptual model of notch evolution through time. This model takes into account the variability in the rate of Holocene sea-level rise (including isostatic adjustment effects, Fig. 10a). According to this model, we suggest that the shaping of the MTN started when sea level rise rate sharply decreased, 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, and is independent of the location (and thus from the glacio-isostatic component). As an example, we show in Fig. 10a 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 and 6.8 ka cal BP; 0.6 and 1.42 mm/yr between 6 and 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).

Therefore, the tidal notch was firstly shaped 6.8 ka. ago. This is in agreement with the database published by Boulton and Stewart (2015) (Fig. 10b), where the oldest uplifted notches are always younger than 6.5 ka. Fig. 10a shows that at coastal sites with relatively uneven glacio-isostatic contribution, the oldest MTN is predicted to be located at different 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, the rate existing before 6.8 ka (Fig. 10a).

As sea level rose from its position 6.8 ka ago to the present level, cliffs slowly retreated and tidal notches tracked the sea level rise (Fig. 10c). In 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. This may be 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 rapid dissolution and destruction of the rocky coast is testified by the characteristic “nose” (Figs. 10c and 6). Where the organic rim (mainly coralline algae and Vermetid reefs) covers the bedrock and shelters it from dissolution and abrasion, the cliff retreat is halted, as documented by the morphology of fossil notches dating more than 6 ka 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 larger width (10–15 cm) than the modern notch. This difference is attributed to the existence of a rim which conceals the floor of present notches and partly alter its size (Fig. 2g, f).

As shown in Fig 10c, the notch evolution allows a retreat of the cliff of at least 3 m or more for the last 6.8 ka.

5.2. Sites where the notch is missing

In rare occasions the MTN does not form (e. g. where beds have vertical dips, Fig. 11a), or it is not preserved (it is discontinuous when carved in bioclastic calcarenites, Fig. 11c,d, where it attains a 4–5 m depth and then collapses) in carbonate rocks. 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 local biocoenosis 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 continuously 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 suggests that important springs or fresh water flows existed during the MIS 5, although this hypothesis is contrasted by the observation that the island perimeter was similar to the present one based on the development of the Last Interglacial notch. This conundrum needs still to be resolved.

5.3. Present-day formation of the notch

Based on work carried out along Greek coastlines (Euboea gulf, Corinth gulf, Cycladic islands), Evelpidiou et al. (2012) have argued that the tidal notch has been ‘drowned’ because of bioerosion (at rates between 0.3 and 1.28 mm/yr) cannot cope with the rate of sea-level rise during the last century (~1.4 mm/yr). Conversely, we have shown that the current notch is present in the vast majority of stable carbonate coasts in the central Mediterranean. We believe that the different results and interpretation between Evelpidou et al. (2012) and this paper arise from methodological aspects,

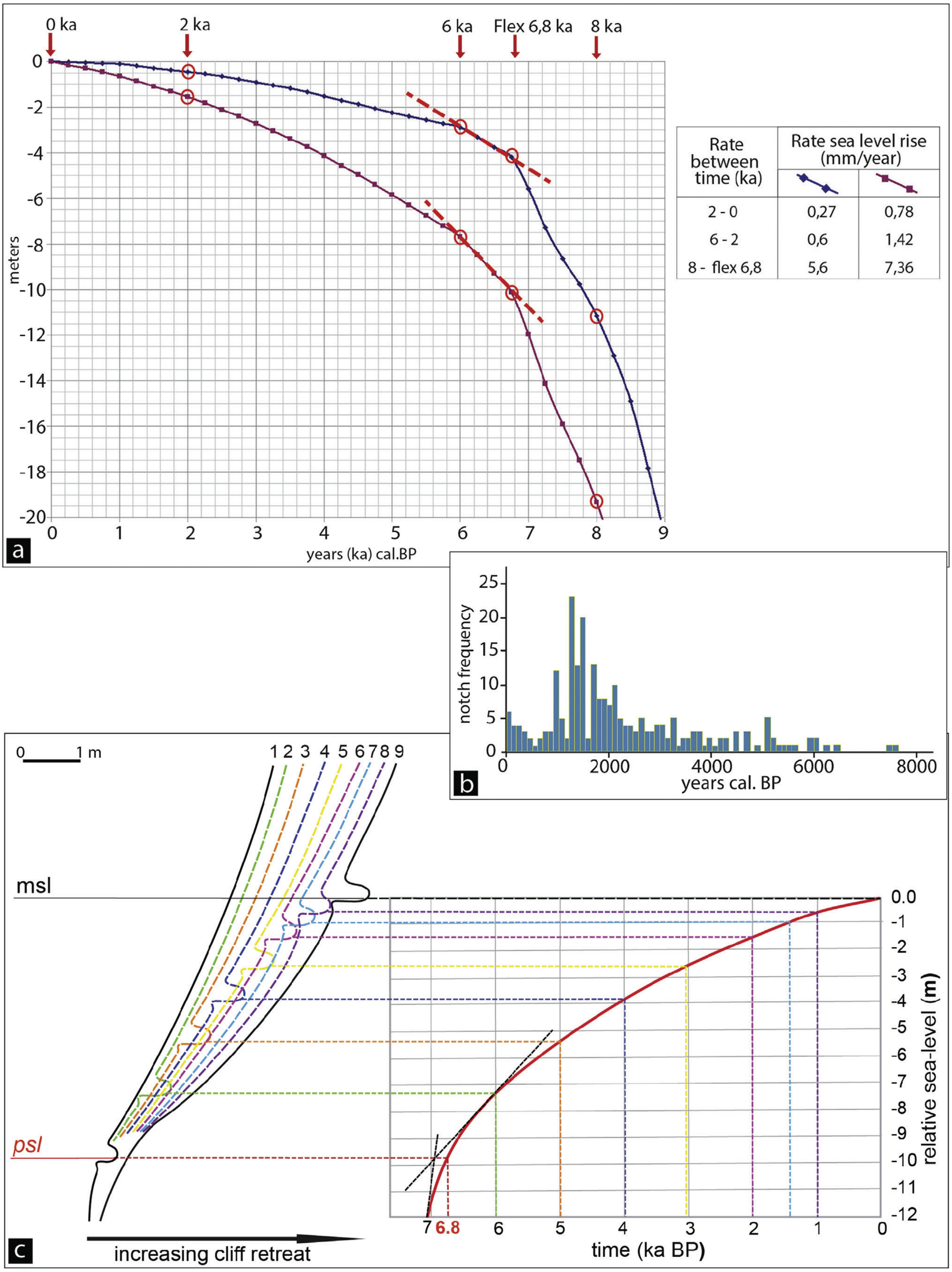

Fig. 10. **a)** Sea level rise rates from 8 ka cal BP to the Present using the predicted sea level rise curves (Lambeck model, 2011) with maximum (Cagliari, purple line) and minimum (Trieste, blue line) isostatic subsidence values. The inflection at 6.8 ka marks the change of rise. **b)** Frequency of notches formation from 8 ka to 0 ka (modified from Boulton and Stewart, 2015). **c)** Model of tidal notches formation from 6.8 ka to the present. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

from the uneven role attributed to specific processes concurring in notch formation, and from the proper choice of the investigated area.

Firstly, the bioerosion rate estimates are very few and scattered, when compared to the capillary distribution of available tide-gauge data worldwide, and thus generalizing erosion rates obtained in different areas for a specific area may be biased. In addition, the Authors neglect any possible contribution from different processes at local and regional scale, and namely tectonics and isostatic movements. However, the Greenland Ice Sheet contribution to the relative sea-level rise is significant and produces different responses at distant coasts with respect to the rising eustatic sea (e.g. Fig. 10a). In turn, this may have varied feedbacks on the rate of local processes, such as mechanical erosion and bioerosion.

Probably, the most important aspect creating different observations and interpretations relates to the tectonic setting of investigated sites. Greece is located on an active subduction zone and back-arc basin, where tectonic processes are very rapid and widespread. Coastal studies have shown that the Greece coastlines exhibit significant vertical tectonic movements, with abrupt transitions between subsiding, uplifting and stable sectors (Vacchi et al., 2012; Anzidei et al., 2014; with references). In contrast, Italy, apart from Calabria and the northern Adriatic sea can be considered stable or affected by very low tectonic motions at least since the MIS 5.5 (Ferranti et al., 2006, 2010; Antonioli et al., 2009). We believe that tectonic stability is a mandatory condition for a correct investigation of the origin of notches.

6. Conclusions

Careful measurement of the tidal notch geometry coupled to quantitative and qualitative investigation of processes occurring at the intertidal zone in the central Mediterranean Sea has revealed that the genesis of the notch is, rather than the effect of a single mechanism, the result of several processes that concur with different rates to the lowering of the cliff. As an example, we showed that the depth of the notch increases in exposed with respect to sheltered coastal sites. In addition, notches have slightly larger average concavity on rocky headlands and pillars, than on extended cliffs, because on the former, exposed settings, dissolution and abrasion occur with enhanced energy. On the other hand, the width of the notch seems correlated to the tidal range, and not to exposure to incoming waves. These observations suggest that exposure to wave action and tidal range are intimately intertwined in notch genesis and evolution, but act in different modes.

Another example regards the role played by encrusting organisms. While bioerosion is surely an important factor in notch development, we also show that bioprotection by the encrusting cap 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 competing processes are not enough to initiate notch formation.

However, one of the main factors leading to notch development is the existence of submarine fresh-water springs which enhance rock dissolution. Although the quantitative contribution of each single process cannot be disentangled because of the existence of mutual feedbacks between them, we stress that only an integrated appraisal of all these processes can explain the appearance and size of tidal notches at different sites. Considering only one process (Evelpidou et al., 2012) may lead to wrong conclusions.

Notwithstanding the current sea-level rise at 1.24 mm/yr in the Mediterranean Sea, the presence of the modern notch is confirmed by our observations. We explained the genesis of the modern notch with a process involving continuous carving of the notch during cliff retreat (Fig. 10c). During its evolution over the last 6.8 ka, tidal notches have undergone a continuous change in shape tracking the sea level rise and isostatic (negative) movements causing the cliff

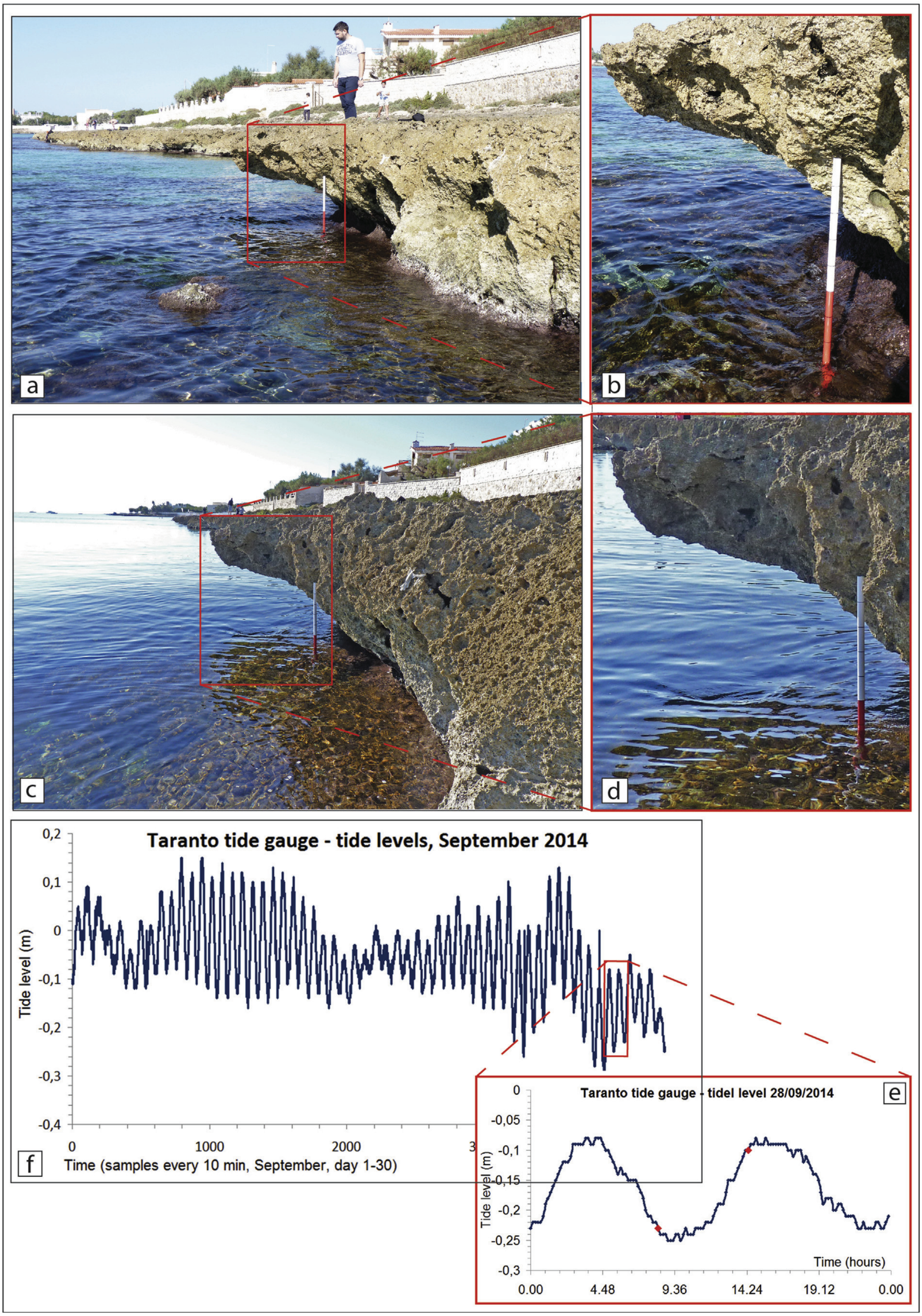

Fig. 12. Tidal range measured on the Taranto – San Vito notch (site 68 Table 1 and S1. Measured on 09/28/2014 at 10.00 am (a,b), and 16.30 pm (c,d). Observations are in agreement with the instrumental data collected at the nearest tide gauge located at Taranto. Plots show the daily tide during the observations (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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

retreat. This is the reason why submerged tidal notches are not detected in stable sites, and, conversely, tidal notches are found in uplifting (Fig. 2h) or subsiding (Fig. 2d) coasts.

The width of the Last Interglacial and the modern notches is similar, suggesting that at the vast majority of investigated sites, where both notches are present, processes have not changed during the last 125 ka. This observation indicates that long-term and large-scale oceanographic and geological processes rather than short-term processes are effective in the genesis of the notch. Finally, the local tide amplitude is always less than the tidal notch width, and the maximum notch concavity does not correspond to the maximum tidal ranges (Fig. 12).

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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.quascirev.2015.03.016.

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