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## Climatic control on the formation of marine-notches in microtidal settings: New data from the northwestern Mediterranean Sea

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### Abstract

The genesis and distribution of marine notches around the microtidal Mediterranean basin has been widely debated in recent years. Here we provide new climate and geomorphological insights into the factors controlling notch formation based on the bathymetric distribution of marine notches found in Marseille Bay (NW Mediterranean). In this area, the notches exist (i) either near present mean sea level (msl); or (ii) at ~35 cm below the msl, but is absent at higher elevations along the same profile. We investigate the genesis of this unusual notch distribution using bio-geomorphological surveys, numerical modelling of nearshore hydrodynamics and palaeo-climatic data. This analysis shows that the submerged notch only occurs in those coastal sectors characterized by minimal or negligible hydrodynamics. Comparison with the millennial sea-level evolution shows that the present elevation of the submerged notch closely matches the sea-level stabilization that occurred during the Late Antique Little Ice Age (LALIA, ~1400 to ~1290 BP). During this period, the notch formed along the sheltered portions of the coasts despite minor wave mechanical action and bioerosion because the

sea-level stability concentrated the weathering erosion in the same portion of the cliff for ~400 years. The increased rates of sea-level rise over the last 1500 years hampered the formation of a younger notch in those sheltered sectors of the coast. On the contrary, changes in rates of sea-level rise did not affect the notch formation at the exposed sites where the mechanical action of waves coupled with intense bioerosion are the major control on the notch formation. These data further confirm that the preservation of a fossil submerged notch is not only ascribable to co-seismic subsidence but also to climatic factors. This has implications for the assessment of the paleo-seismicity of the Mediterranean region.

## **1. Introduction**

A peculiar geomorphological feature was found on the seaboard of the Frioul Archipelago coast, situated in the centre of Marseille Bay (NW Mediterranean). Along the archipelago's seaboard we observed a very unusual distribution of the marine notch. Over short distances (e.g., <250 m) the notch sometimes develops near present mean sea level (msl) while, in other areas, it develops at ~35 cm below the msl and is absent at higher elevations.

The aim of this paper is to explore the causes that controlled this peculiar geomorphology, which is very rare in the Mediterranean. We coupled bio-geomorphological surveys with hydrodynamic modelling in order to understand the drivers of notch formation (or non-formation) in the area. The results were further compared with a statistical reconstruction of the relative sea-level evolution and palaeo-Sea-Surface-Temperature data in order to explore possible climatic controls on notch formation.

Marine notches are indentations cut in steep calcareous cliffs at or near sea level (Pirazzoli, 1986; Antonioli et al., 2015; Trenhaile, 2016). Their genesis and distribution in the Mediterranean have been widely debated in recent years (e.g. Evelpidou et al., 2012; Antonioli et al., 2015; Trenhaile, 2016). A major issue is related to the current formation of tidal notches. On the basis of a number of Greek case studies, Evelpidou et al., (2012) stated that present-day tidal notches are no longer forming

because of the post-industrial acceleration of sea-level rising rates. In particular, this acceleration exceeds the thresholds for natural marine bioerosion, leading to the disappearance of tidal notches. Antonioli et al. (2015) challenged this hypothesis on the basis of the analysis of 73 Mediterranean coastal sites. They argued that the development of tidal notches as a mere consequence of midlittoral bioerosion (as per Evelpidou et al., 2012) is a simplification that can lead to misleading results because important roles in notch formation can also include wave action, the rate of karst dissolution, salt weathering and wetting and drying cycles. The results of this study indicate that midlittoral bioerosion can enhance notch formation and, in particular cases, also be the main process of notch formation and development (Antonioli et al., 2015).

The peculiar distribution of the notch along the Frioul Archipelago coasts offers a unique possibility to understand the mechanisms of formation, which can be ascribed to chemical dissolution processes in the intertidal zone, wetting and drying cycles, biological erosion or wave action or, most likely, a combination of these factors. Tectonically, this coastal sector is documented to be very stable and a high-resolution proxy-based sea-level history for the last four millennia is available for the area (Vacchi et al., 2021).

## **2. Methods**

### **2.1 Study area**

The Frioul Archipelago is located off the town of Marseille in the NW Mediterranean Sea (Figure 1A). This archipelago is composed of two main islands (Figure 1B): Pomègues (89 ha) and Ratonneau (95 ha), now artificially connected, and a third minor island called If (3.5 ha).

Almost the totality of the archipelago's coastline comprises plunging cliffs carved into Lower Cretaceous limestones (Collina-Girard, 2014). Beaches are almost absent with the exception of some gravel to pebble deposits found in the inner part of the several deep and fjord-shaped narrow bays, locally known as *calanques* (Collina-Girard, 2014). Semi-arid conditions (mean annual rainfall < 350 mm of per year) and the exposure to strong and frequent NW and SE winds (53 days per year > 60

km/h) significantly influence the micro-climate of the archipelago (Bonnet et al., 1999; Baumberger et al., 2012) known as the driest stretch of the Mediterranean French coast.

The coastal area is tectonically stable as suggested by the negligible historical seismicity (Billi et al., 2011; Noquet, 2012). Tectonic stability is further confirmed by the present elevation of the last interglacial shoreline (e.g., ~125 ka, Cerrone et al., 2021) while GPS-derived vertical rates suggest that the Marseille bay is presently characterized by stability to minor subsidence ( $<0.5 \text{ mm a}^{-1}$ , Noquet et al., 2016).

## 2.2 Bio-geomorphological survey

We carried out two snorkelling surveys in July and September 2018 in order to map the occurrence of the marine notches along Frioul's coastline. After a preliminary survey, we focused our analysis on four coastal sites where the morphologies were particularly well preserved (Figure 1B). These are the *calanques* of Crine (Cr), Pointe Pomègues (Pp), Eoube (Eb), and Morgiret (Mg). These sites, situated on both Pomègues and Ratonneau islands, were selected in order to have different geomorphological contexts and a wide range wave exposure. During each survey, we performed two underwater transects at each site. The first in the outer portion of the *calanque* (very exposed to the open sea) and the second in the inner part (very sheltered from the open sea, Figure 2A). All measurements were carried out with a metric rod and taken during calm sea. The times of the measurements were also noted in order to benchmark the elevational data to the mean sea-level derived from the Marseille tide-gauge station (<http://refmar.shom.fr/en/marseille>) which is placed in front of the archipelago at less than 2 km of distance. The final accuracy is  $< 5 \text{ cm}$ . According to Antonioli et al., (2015) and Furlani et al., (2014, 2018) we measured the following morphometric parameters of the notches: i) the notch width which is the average vertical extent of the notch; ii) the inward notch depth which is the average horizontal extent of the notch; iii) the roof elevation which is the average elevation of the top of the notch with respect to the mean sea-level (msl); iv) the floor elevation which is the elevation of bottom of the notch with respect to the msl. During the survey,

we further measured water temperature at each site (accuracy  $\pm 0.1$  C°) in order to check for the presence of freshwater springs in proximity to the measured notch (Furlani et al., 2014). These data furnished a matrix for multivariate statistical analyses (PCA and cluster analysis), which are presented in the results section.

During the surveys, we further mapped the biological zonation of benthic organisms occurring on the cliff from the supratidal to the subtidal zone (e.g., Gatti et al., 2012). The vertical distribution of the different benthic associations was also measured with a metric rod and benchmarked to a common datum for the geomorphological survey.

### 2.3 Late Holocene sea-level evolution

The relative sea-level (RSL) dataset available for the Marseille Bay coastal sector mainly derives from radiocarbon-dated samples of fossil *Lithophyllum byssoides* rims (Laborel et al., 1994). This coralline red alga forms thick rims occurring in the upper portion of the tidal frame (Verlaque, 2010). Fossil rims, presently submerged, are recognized excellent sea-level indicator along the Mediterranean coast (Laborel and Laborel-Deguen, 2005; Faivre et al., 2019). Additional high-resolution sea-level data were derived from fossil fixed biological indicators found on the maritime structures of the ancient harbour of Marseille (Morhange et al., 1999; see Supplementary 1). These RSL index points allow high-resolution RSL reconstructions in the Mediterranean area (Morhange and Marriner, 2015; Khan et al., 2015). The evolution of the RSL positions and the variability of the rates of RSL change were derived from the recent analysis performed by Vacchi et al., (2021, see Supplementary 1). These data were obtained by apply an empirical-Bayesian spatio-temporal statistical model applied to a dataset of index points. The methodology is detailed in Vacchi et al., (2021).

### 2.4 Numerical wave model

State-of-the art numerical modelling suite Delft3D (Lesser et al., 2004) was used to compute wave heights at the different locations around the Frioul archipelago. Although establishing realistic engineering-grade computations was not the main objective of this study, the modeling strategy assumed here complies with the goal of gaining schematic insights into wave dynamics for northern, western and southern sides of the archipelago.

That is why simulations were only undertaken with the Delft3D-WAVE module, which relies upon the well-known third-generation wave model Simulating WAVes Nearshore (Holthuijsen et al., 1993; Booij et al., 1999; Ris et al., 1999). SWAN is based on the discrete spectral action balance equation and is fully spectral (in all directions and frequencies), allowing the model to simulate random, short-crested waves in coastal regions with deep, intermediate and shallow water. Various physical processes are explicitly considered in Delft3D-WAVE, like refraction due to depth, bottom friction, as well as depth-induced wave breaking.

#### *-Grid, bathymetry and boundary conditions*

Delft3D-WAVE is forced with wave data taken from Cerema's ANEMOC-2 database (Atlas Numérique des Etats de Mer Caiques et Côtiers; Tiberi-Wadier et al., 2016), made of wave hindcasts from 1979 to 2010. This numerical atlas was produced with TOMAWAC, a third-generation spectral wave model (Benoit *et al.*, 1996) forced with wind data from the Climate Forecast System Reanalysis (NOAA; Saha *et al.*, 2010), and calibrated against buoys and satellite measurements. Hourly wave data from 1994 to 1998 taken from the ANEMOC-2 database are subsampled to 3-hourly wave data as input for Delft3D-WAVE. As shown by Kulling and Sabatier (2016); Sabatier et al. (2017); and Kulling (2017), when compared to the full 30-year timespan covered by ANEMOC-2, 1994, 1996 and 1998 are close to a so-called typical “normal” year, whereas 1995 and 1997 are considered as “positive anomalies” (regarding waves heights).

Like in previous work dealing with numerical models extending from deep water to the nearshore (Kulling et al., 2016; Boudet *et al.*, 2017; Kulling, 2017), two bathymetric datasets were used to

derive the bottom morphology in Delft3D-WAVE. From the coast down to 30/40m depth, bottom morphology is taken from the Litto3D® database (Shom, 2018a), using topo-bathymetric aerial LiDAR measurements from 2012 (LADS MkIII and RIEGL VQ-820-G lasers combined, see Aleman *et al.*, 2015). Beyond this range, computations rely on bathymetric surveys from 1977 (Shom, 2018b), originating from the Base de Données Bathymétrique du Shom (BDBS). The model domain consists of several curvilinear grids designed with RGFGRID in order to compute wave propagation from deep water (ANEMOC-2 outputs) to the nearshore. We performed a numerical simulation for the northern, western and southern sides of both Pomegue and Ratonneau islands. Thus Delft3D-WAVE grids cover all the investigated *calanques* and finer grids are nested into coarser ones (Table 1): it allows more detailed wave computations at the edge and inside each *calanque*.

### 3. Results

#### 3.1 Bio-geomorphological survey

Results of the snorkelling survey carried out in the four sectors of the Frioul Archipelago are presented in Table 2. The morphometric values are averaged between the two surveys (July and September 2018) with a final vertical error of < 5 cm. At the exposed site, we observed an asymmetric notch characterized by an absent floor and a well-developed roof-top (Figure 2B). The average elevation of the roof varies between ~30 to ~15 cm msl at exposed sites. The average elevation retreat point of the roof notch (cfr. Furlani *et al.*, 2015) ranges from ~5 to ~12 cm above msl (Table 2 and Figure 2C).

The average inward depth of the notch showed a maximal value of ~80 cm and the whole roof notch profile (from the retreat point to the roof) is covered by a biological rim dominated by *Lithophyllum byssoides* (sometime forming the typical *trottoir* up to ~5 cm thick) and *Ellisolandia elongata*.

*E. elongata* became dominant at lower elevations, in particular between the msl and ~-25 cm. Below this level, we observed a transition in the benthic assemblages which are dominated by *Dictyota*



*dichotoma*, *Jania rubens* and *Botryocladia botryoides*. Presence of *Amphiroa rigida*, turf-forming algae, crustose coralline algae and sparse *Lithophaga lithophaga* was also observed.

At sheltered sites, we observed the absence of a notch at the present msl (Figure 2D). Instead we observed a notch located below the msl. The roof of the notch is located at ~-12 to ~-15 cm msl while the retreat point was measured between ~-37 and ~-35 cm (Figure 2E).

The floor of the notch (present but less developed than the roof) occurred at average elevations of ~-48 to ~-51 cm msl. The inward depth notch did not exceed ~50 cm.

The biological coverage at and above the msl is extremely scarce and is only characterized by the scattered presence of *Patella* spp. and by a biofilm up to ~20 cm above the msl (Figure 2D). Biological coverage increases significantly on the roof of the notch. In particular, the band between ~-10 to ~-20 cm is dominated by crustose calcareous algae and sparse *Ellisolandia elongata*. At lower depths, we observed a progressive decrease of crustose calcareous algae and a gradual increase of a sciafic biological association dominated by foliose *Peyssonnelia* sp., *Mesophyllum lichenoides* and *Lithophyllum stictiforme*, associated with small hydroids and turf-forming algae. This biological zone characterizes the whole width of the notch and extends up to depths of ~100 cm.

Water temperature did not show significant differences between sites. In July, we surveyed the changes in temperature between the exposed and sheltered sites and found that it was within 0.1 °C. In September, we observed a maximum difference of 0.3 °C between the exposed sites and the sheltered ones (Table 2).

### 3.3 Wave modelling

The mean results of the numerical wave modelling are provided in Table 1. The complete output of the model is provided in Supplementary 2. The data indicate a significant difference between the  $H_{sig}$  values recorded at the exposed sites and those recorded in the sheltered ones. The simulation clearly shows that all the sheltered sites are characterized by minimal wave influence with mean  $H_{sig}$  values of between 0.04 and 0.12 m and maximal  $H_{sig}$  values which do not exceed 1.1 m. At exposed sites,

the numerical model output indicates that mean  $H_{sig}$  are up to 80% higher than in the sheltered ones with maximal  $H_{sig}$  values comprised between 0.9 and 3.2 m (Table 1).

### 3.3. Statistical analysis

To compare and contrast the notches on Frioul's exposed and sheltered coasts, we performed multivariate statistical analyses on a data matrix comprising the following measurements: T (°C) July 2017, T (°C) September 2017, Notch retreat point, Notch depth, Roof elevation,  $H_{sig}$  (mean),  $H_{sig}$  (max). In the first instance, we performed a Principal Components Analysis which clearly differentiated the exposed and sheltered notches into two separate groups. PCA axis 1 explains >93% of the variability in the data and is loaded by the variables "Notch retreat point", "Notch depth" and "Roof elevation" (Figure 3). The morphological differences between the exposed and sheltered notches of Frioul were further reinforced by a Paired group cluster analysis (similarity index = Euclidean).

### 3.4 Late Holocene sea-level evolution

The RSL record for the bay of Marseille is composed of 32 SLIPs covering the last ~4.6 ka BP (see appendix 1). In the last 4.0 ka, maximal sea-level variation did not exceed  $\sim 1.75 \pm 0.3$  m (Figure 3A). During this time-span, we observed variability in the sea-level rising rates which range from  $\sim 1.1$  mm/y to  $\sim -0.1$  mm/y (Figure 4B). In particular, we observed rising rates of up to  $\sim 0.6$  mm/y from  $\sim 3.5$  to  $\sim 2.3$  ka BP which were followed by a RSL deceleration which reached its bottomed out between  $\sim 1.5$  to  $\sim 1.1$  ka BP when the RSL data show evidence of substantial stability characterized by rates of  $-0.1$  mm/y. During this period, the RSL was between  $-0.4$  and  $-0.3$  m msl (Figure 4A). Younger data indicate that RSL rising rates transitioned to positive values in the last  $\sim 1.1$  ka BP with significant rising rates observed in the last 0.3 ka BP (up to  $\sim 1.1$  mm/y).

## 4. Discussion

The marine notches of the Frioul archipelago show an unusual geomorphology compared to other areas of the Mediterranean Sea. For instance, presence of submerged marine notches is often reported in tectonically active coastal areas such as the Aegean Sea (e.g., Evelpidou et al., 2011; Kolaiti and Mortzas, 2016; Karkani and Evelpidou, 2021) or in areas characterized by particular hydrological conditions and/or tectonic activity such as the Gulf of Trieste and Istria (Furlani et al., 2014; Marriner et al., 2014; Faivre and Butorac, 2018).

Marseille Bay is presently the only Mediterranean area showing the occurrence of a notch developing at or slightly above msl on exposed sites and another one developing below msl (e.g., ~-35 cm) on sheltered sites. Such variability cannot be ascribed to ground movements related to differential tectonic activity for the two main reasons: i) no major faults are reported in the Frioul area (Noquet and Calais, 2004; Noquet, 2012); ii) the submerged notch and the one measured at the present msl often occur on either side of the same cliff (see figure 2)

Our data, which are based on bio-geomorphological surveys and numerical modelling, provide fresh insights into the mechanisms controlling the bathymetric variability of marine notches in the Marseille area. In fact, the results of the multivariate analysis clearly subdivided in two groups (>93% of the variance) the notches of the Frioul according to their exposed or sheltered position. In all the exposed sites of the archipelago, the notch is currently forming in the same way as several other Mediterranean coastal areas (Antonioli et al., 2015). At these sites, the biological cover in the intertidal and shallow subtidal zone show the typical association of exposed Western Mediterranean rocky shores with the development of thick rims of *Lithophyllum byssoides* (Laborel et al., 1994; Schembri et al., 2005; Verlaque, 2010). The major wave influence at these sites is also confirmed by the numerical model which indicates significant wave heights of up to 2 m along the exposed seaboard of the Archipelago. By contrast, at the sheltered sites characterized by i) the virtual absence of wave influence (mean  $H_{sig} < 0.07$  m and maximal  $H_{sig} < 0.6$  m) and ii) by a very low density of biological cover in the intertidal zone (with an absence of *Lithophyllum byssoides* rims) the notch is absent at present msl but occurs underwater.

In light of these factors, what is the origin of the submerged notch? Is it a currently forming notch or the relict of a past sea-level position?

#### 4.1. Formation of the submerged notch

Antonioli et al., (2017) described a similar notch distribution in the *calanques* of Sormiou and Port Miou located less than 20 km from the Frioul archipelago. Here, the exposed cliffs are characterized by a well-developed “roof notch” (crf. Antonioli et al., 2015) while they observed the presence of a submerged tidal notch in the inner part of these long and narrow bays. Antonioli et al., (2017) speculated that the underwater notch is currently forming and that its origin is controlled by coastal spring water that stratifies above marine water. This freshwater layer may play a key role in the chemical dissolution of limestone, as suggested by Furlani et al. (2014) in the northern Adriatic Sea. However, the authors did not report *in situ* measurements of water temperature or salinity for either Sormiou or Port Miou.

Based on our data of the Frioul archipelago, such a hypothesis is difficult to corroborate for two main reasons: i) the Frioul area is the most arid area of metropolitan France (mean annual rainfall < 350 mm of per year; winds 53 day per year > 60 km/h; Baumberger et al., 2012) and the hydrological network of the archipelago is non-existent; ii) our surveys did not show significant variability in the water temperature between the exposed and the sheltered sites in both of our July and September surveys. This suggests the absence of submerged freshwater springs which are generally characterized by colder water (Furlani et al., 2014).

On the basis of our analyses, we provide alternative explanation for the origin of this submerged notch (Figure 5B). Comparison with the millennial sea-level evolution shows that the present elevation of the underwater notch (~35 cm) closely matches the sea-level stabilization that occurred during the Late Antique Little Ice Age (LALIA, ~1400 to ~1290 BP, Buntgen et al., 2016) when a general cooling of the Mediterranean climate triggered a significant deceleration of the sea-level rising rates which characterized the last 4.0 ka BP (Vacchi et al., 2021). Around 1500–1250 BP,

Mediterranean Sea Surface Temperatures cooled rapidly by around  $0.27^{\circ}\text{C}$  (Marriner et al., 2022). Oscillations of sea-level rising rates are controlled by the differential response of the Mediterranean to cooling/warming episodes, as demonstrated by the variability of sea-level rise rates observed in the Common Era (Faivre et al., 2019; Vacchi et al., 2021). The stabilization driven by the LALIA cooling is evident in the Marseilles' sea-level record (Figure 3B and Appendix 2) which shows negligible or slightly negative rising rates from 1.5 to 1.1 BP when the paleo-sea level was at  $-36 \pm 18$  cm.

For this reason, we consider the underwater notch of the Frioul archipelago to be a relict landform which formed during a ~400-year period of sea-level stability driven by the general cooling of the NW Mediterranean Sea (Figure 5B). During this period, the notch formed along the coast of the archipelago because the sea-level stability enhanced erosion (Evelpidou et al., 2012; Trenhaile, 2016). On the sheltered parts of the coast, the absence of significant wave mechanical action and low bio-erosion were not conducive to notch formation. At these sheltered sites, the dominant notch-forming processes probably involved karst dissolution, salt weathering and wetting and drying cycles.

In the last 1000 years BP, data show that sea-level rising rates transitioned to positive values of up to  $0.5 \text{ mm}^{-1}$  in the pre-industrial era (e.g., before 1850 CE) accelerating up to 1.1 in the last 150 years (Figure 3B). In this time-span, we observed a different geomorphological response of the coasts of the Frioul archipelago. At the exposed sites, the cumulative action of mechanical wave erosion, bio-erosion and chemical processes led to the progressive formation (still active now) of a marine roof notch which continued developing in equilibrium with the rising sea level (Figure 5A). For the roof notch, the term “visor” has been proposed by Evelpidou et al. (2011) which ascribes erosion to dissolution by a freshwater spring undercutting a limestone cliff at sea level. Our data are not in agreement with this genesis for the roof notch because we did not observe the presence of freshwater springs at either the sheltered or exposed sites along the Frioul archipelago. The roof-notch shape at exposed sites is more likely controlled by the minimal sea-level variation (i.e, 35 to 40 cm) occurring in the last 1.5 ka in this sector of the Mediterranean Sea which is controlled by minor isostatic-driven

land subsidence ( $\sim 0.25 \text{ mm a}^{-1}$ , Spada and Melini, 2022). This probably hampered the formation of the notch floor which remained, for the whole period, in the most erosionally active part of the cliff subject to both mechanical and bio erosional processes. The south of France was also characterized by significant storm activity during the LALIA and the Little Ice Age, which would have further accentuated mechanical erosion processes in exposed areas of the Frioul coastline (Sabatier et al., 2012; Shah-Hosseini et al., 2013; Degeai et al., 2015).

At the sheltered sites, the relative absence of wave mechanical action and bio-erosion (intrinsically correlated) were not conducive to the formation of the notch in the last millennium. The absence of these major erosional processes also influenced the shape of the notch which, in contrast to the exposed-site notch, presents both the roof and the floor. The floor has probably been preserved due to the increase of sea-level rising rates in the last millennium which significantly lowered the erosion rates observed in the previous  $\sim 400$  years of relative sea-level stability. These data agree with those recorded by Faivre et al., (2019) in the northern Adriatic, where a relict submerged tidal notch formed during the post-Roman sea-level stabilization.

Our data further confirm the complexity of factors affecting notch formation, notably along the microtidal Mediterranean coast. We have demonstrated that sea-level stability represents an important factor for notch formation only at very sheltered sites. By contrast, our data indicate that, in the presence of bio-erosional and wave mechanical processes, marine-notch formation can occur with rising rates  $> 1 \text{ mm a}^{-1}$  confirming the results reported by Antonioli et al., (2015) and Trenhaile (2016). Furthermore, our data show that marine notches can be preserved when submerged without co-seismic events (see Faivre et al., 2019) but only in those sectors characterized by negligible hydrodynamics and minor GIA signal (e.g., characterized by minimal RSL variations in the last 4.0 ka). This has important implications for the assessment of the paleo-seismicity of the Mediterranean area.

## 5. Conclusions

Trenhaile (2016), demonstrated that notch morphology is the product of both regional (e.g., changes in sea level and climatically-induced variations in erosional efficiency) and local factors related to slope gradient and geological factors including the bedrock resistance to erosion and the morphology of the rock strata. The peculiar distribution of the marine notch of Marseille Bay provides new insights into the local mechanisms mediating this key landform of carbonate coasts. Our data indicate that sea-level stability is an important factor for notch formation only at sheltered sites. By contrast, mechanical wave action seems to be the major factor in controlling notch formation, at least in the microtidal Mediterranean settings. Future research should focus on a wider range of *in situ* geochemical measurements to explain notch formation and evolution. In particular, it is fundamental to better quantify the role of chemical factors such as karst dissolution, salt weathering and wetting and drying cycles on notch formation. The Frioul archipelago, with its peculiar notch distribution, represent an ideal site for this kind of analysis. Finally, our findings indicate that the occurrence of submerged marine notch cannot be ascribed only to tectonically-driven ground movements but their origin can also be related to climatic factors.

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## **Data availability**

All the data used for the analysis of this study are posted to a trusted repository and are available under Creative Commons Attribution 4.0 International at the following link: <https://doi.org/10.5281/zenodo.6816954>

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## Figures caption

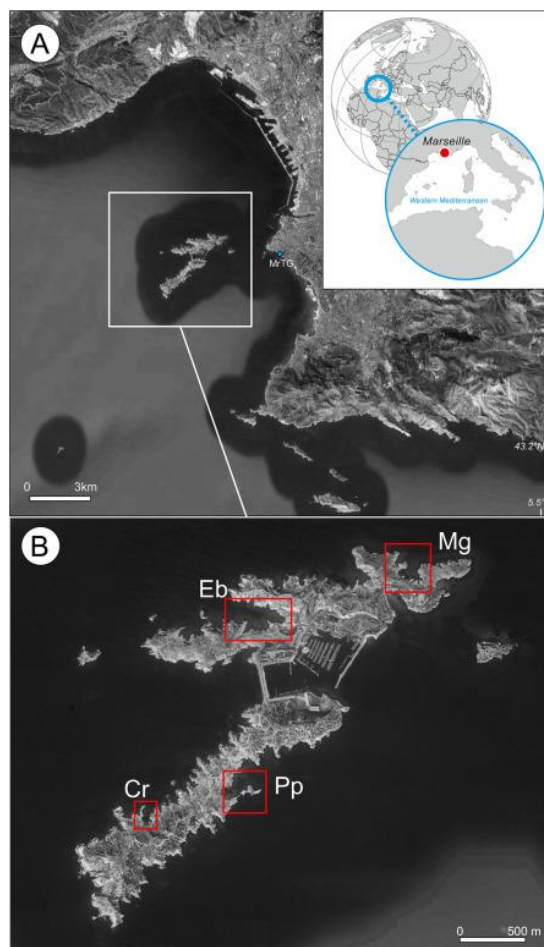


Figure 1. A) Geographical location of the Frioul archipelago within Marseille Bay. C) Coastal sites investigated in this study. Cr is *calanque de Crine*, Pp is *Pointe Pomégue*, Eb is *calanque de Eoubé*, Mg is *calanque du Mogiret*.



Figure 2. (A) Photograph of one of the study sites (Crine). The red line indicates those areas located in the outer part of the *calanques* and characterized by the presence of the roof notch developing at present msl. The green line denotes those areas located in the inner part of the *calanques* and characterized by the presence of the submerged notch. The arrow indicates the direction of the main storm waves and swell. (B, C) Roof notch developing in the exposed sectors. (D) Absence of the notch along the cliffs located in the sheltered areas. (E) Submerged notch occurring in the sheltered sectors. Msl is mean sea-level.

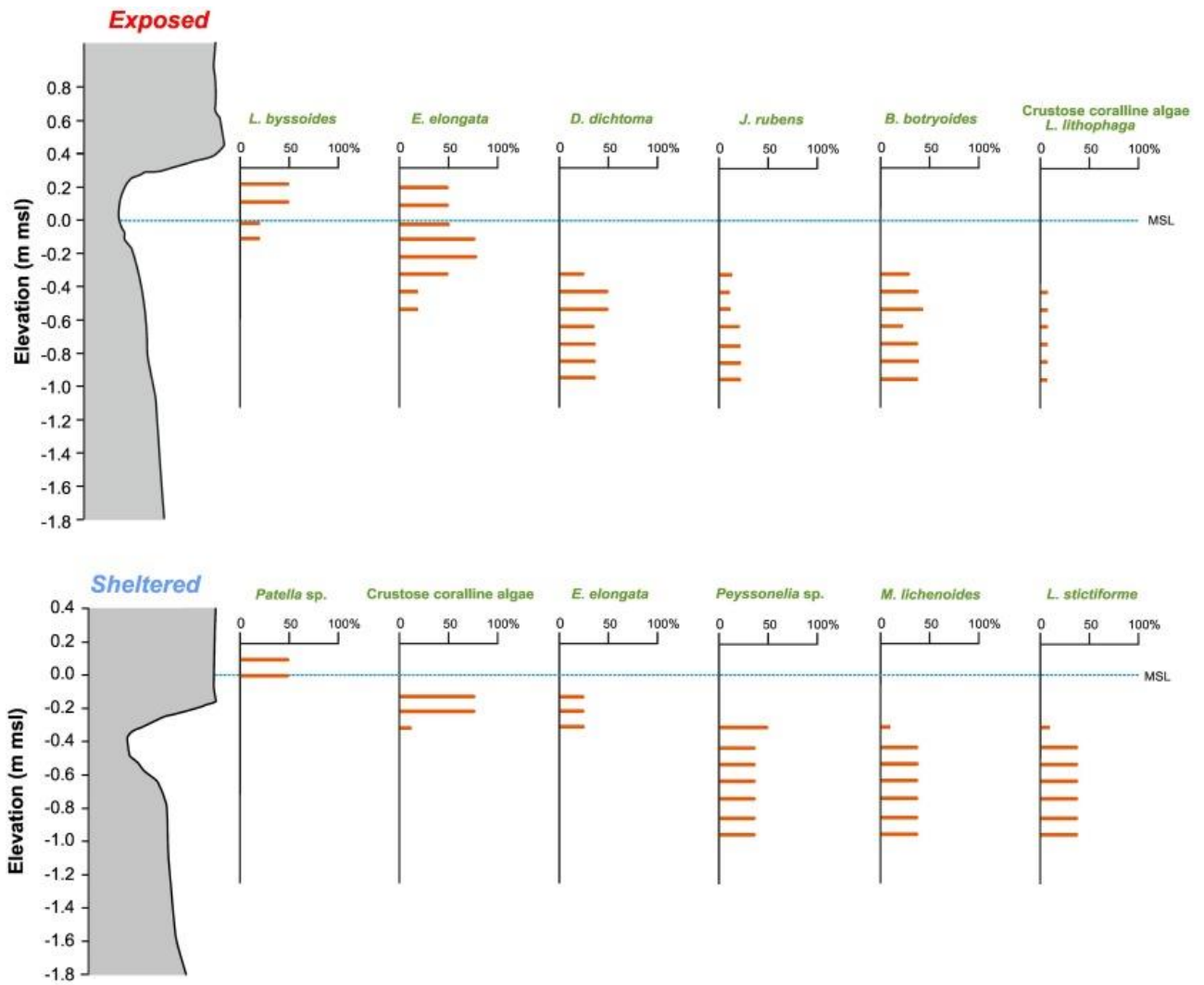


Figure 3. Multivariate statistical analyses of the geomorphological notch data (A) Principal Components Analysis. (B) Paired group cluster analysis (similarity index = Euclidean).

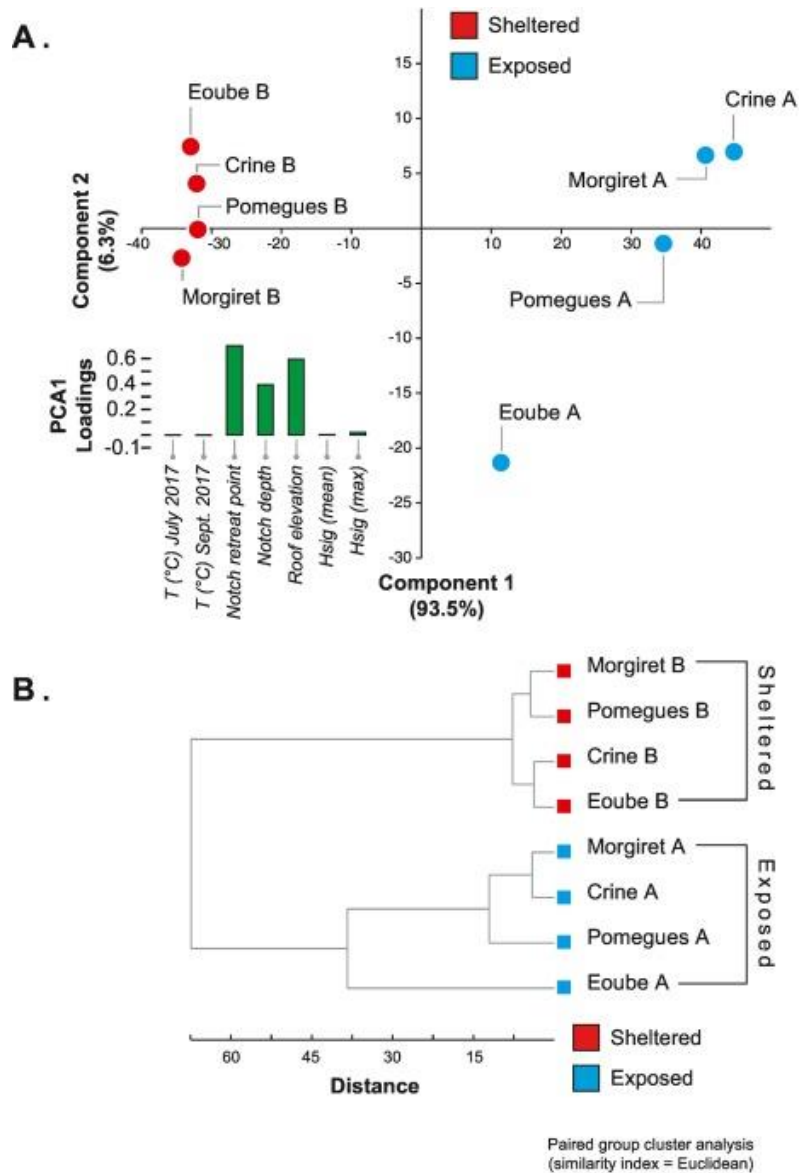


Figure 4. Spatio-temporal reconstruction of the RSL position (A) the rates of sea-level change (B) and Mediterranean SST anomalies (B) for the last 4.0 ka BP in the Marseille Bay area.



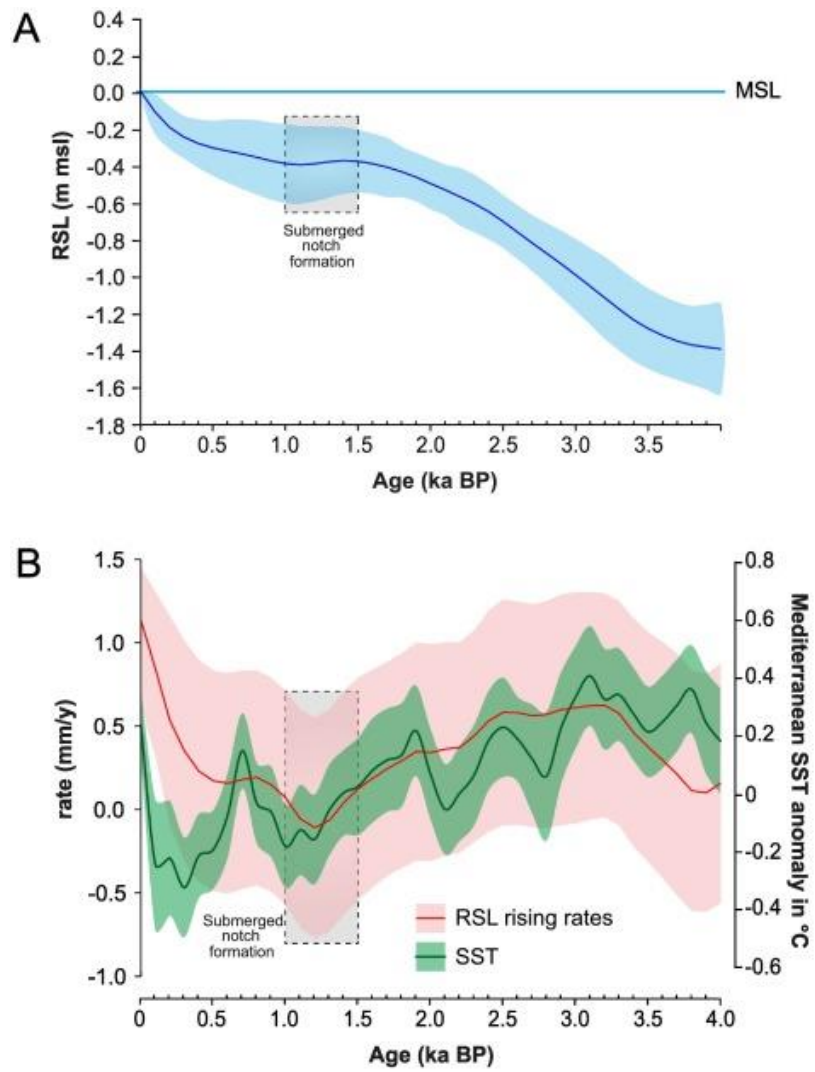


Figure 5. Morphological model to explain the differential notch evolution observed in the Marseille Bay area. Pmsl is the paleo mean sea level. Msl is the present mean sea level.



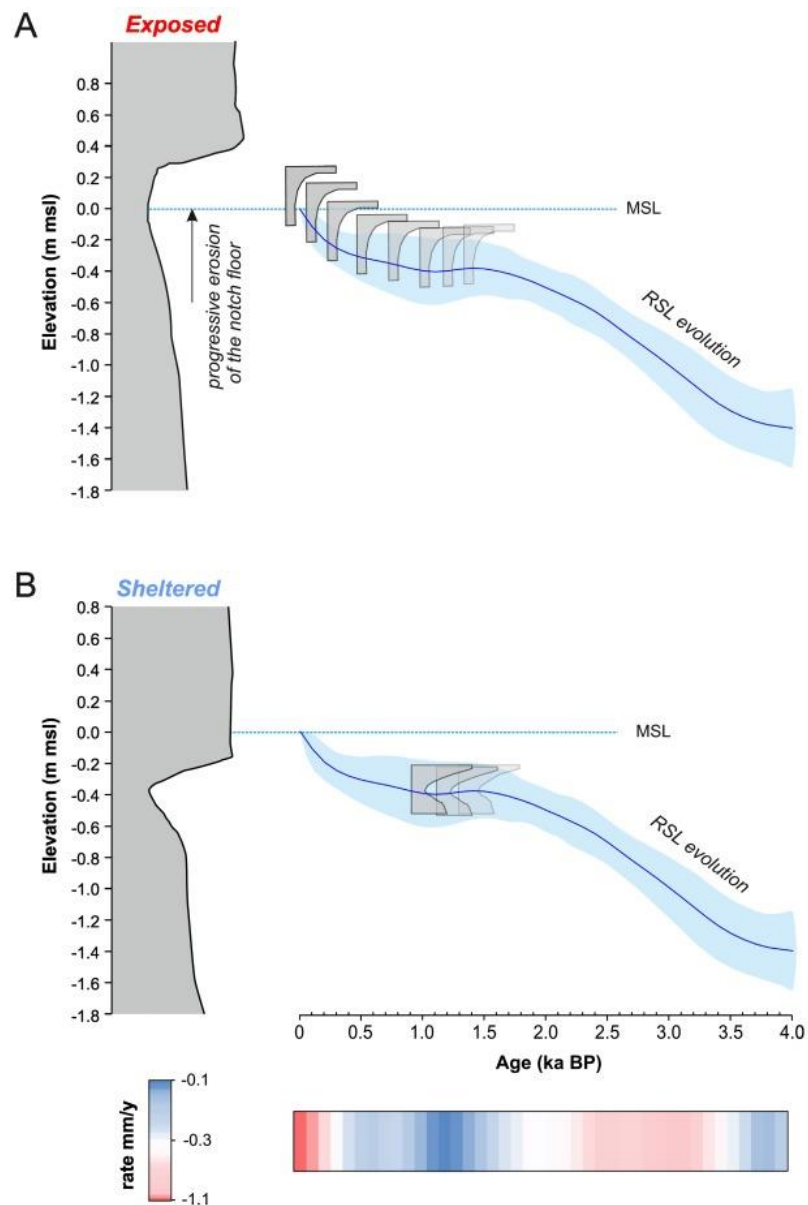


Fig. 6. Morphological model to explain the differential notch evolution observed in the Marseille Bay area. RSL is the Relative Sea Level. MSL is the present Mean Sea Level.

**Supplementary 1.** a) RSL data used for the statistical analysis of sea-level evolution. B) output of modelled sea-level positions and rates for the Marseille bay, data from Vacchi et al., 2021.

**Supplementary 2.** Complete output of the hydrodynamic modelling in the four calanques investigated in the study. For each site, the model output for shelterd and exposed sectors is provided.

Please refer to section 2.4 for the methodological explanation.