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Research Article

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 with no notch present at higher elevations on the same profile. We investigate the genesis of this unusual notch distribution using bio-geomorphological surveys, numerical modelling of nearshore hydrodynamics and palaeo-climate data. This analysis shows that the submerged notch only occurs in 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 in sheltered areas of the coast, despite minor wave mechanical action and bioerosion, because relative sea-level stability concentrated 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 sheltered sectors of the coast. By contrast, changes in sea-level rise rates did not affect notch formation at exposed sites where the mechanical action of waves coupled with intense bioerosion were the major control on 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 palaeo-seismic assessments of the Mediterranean region.

1. Introduction

A peculiar geomorphological feature was found on the seaboard of the Frioul Archipelago, 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 processes controlling 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; Evelpidou and PIrazzoli, 2013; Antonioli et al., 2015). 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

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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 other factors can also play a role in notch formation including 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).

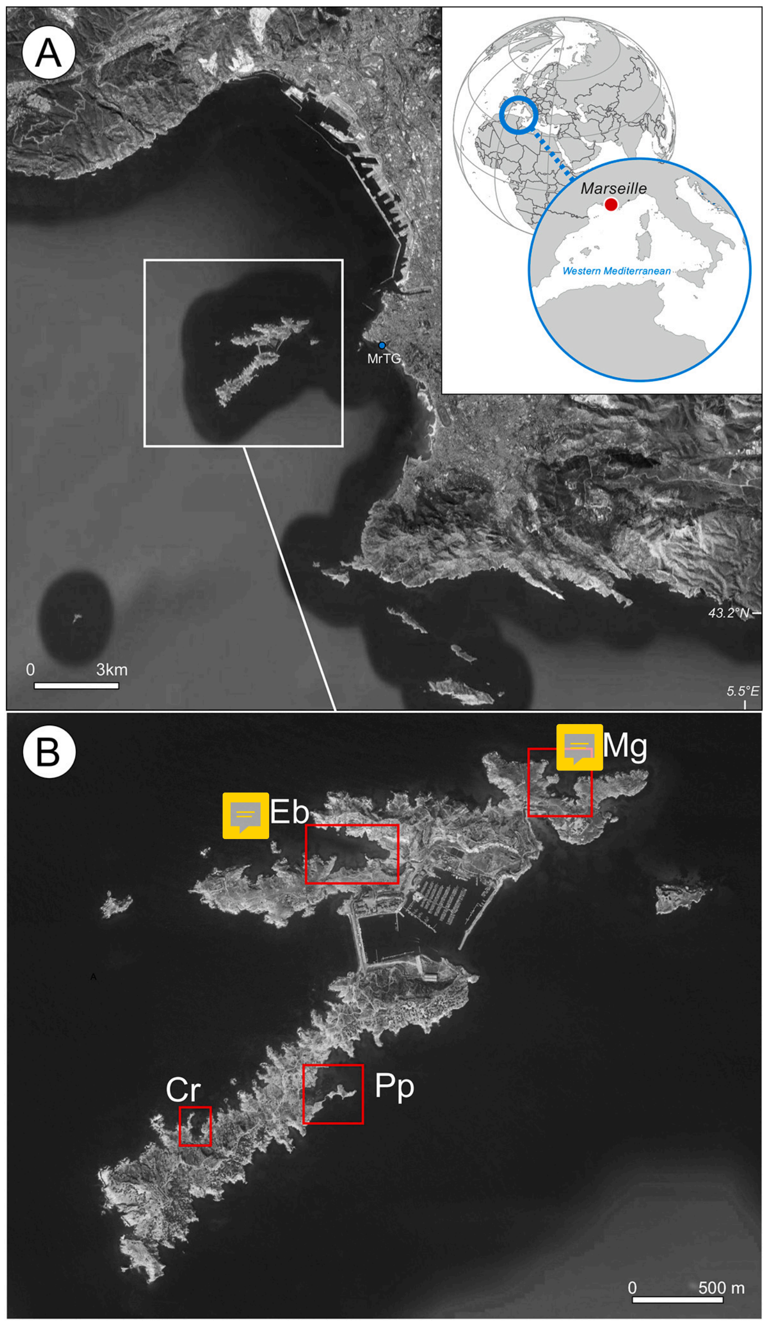

Fig. 1. A) Geographical location of the Frioul archipelago within Marseille Bay. Blue dot indicates the location of the Marseille tide gauge (MrTG). B) Coastal sites investigated in this study. Cr is *calanque* de Crine, Pp is Pointe Pomégue, Eb is *calanque* de Eoube, Mg is *calanque* du Mogiret. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Study area

The Frioul Archipelago is located off the town of Marseille in the NW Mediterranean Sea (Fig. 1A,B). This archipelago is composed of two main islands (Fig. 1C): 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). 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 mm a^{-1}, Nocquet et al., 2016).

Fig. 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 SeaLevel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Bio-geomorphological survey

We carried out two snorkelling surveys in July and September 2018 in order to map 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 (Fig. 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, Fig. 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 situated <3 km from the archipelago (Fig. 1B). The final accuracy is <5 cm. Based on the methodology outlined by 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 the bottom of the notch with respect to the MSL. During the survey, we also measured water temperature at each site (accuracy ±0.1C°) 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 also mapped the biological zonation of benthic organisms occurring on the cliff from the supratidal to the subtidal zone (e.g., Gatti et al., 2012). Furthermore, the vertical distribution of the different benthic associations was 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 in the mid to upper part of the tidal frame (Verlaque, 2010). In the Mediterranean, presently submerged fossil rims, are excellent sea-level indicators (Laborel and Laborel-Deguen, 2005; Faivre et al., 2013; 2019). Additional high-resolution sea-level data were derived from fixed biological indicators found on the maritime structures of the ancient harbour of Marseille (Morhange et al., 2001; see Supplementary 1). These RSL index points allow high-resolution RSL reconstructions in the Mediterranean area (Morhange and Marriner, 2015; Khan et al., 2015; Vacchi et al., 2016). The RSL history and the temporal evolution of RSL rising rates were derived from the recent analysis performed by Vacchi et al., (2021, see Supplementary 2A,B). These data were obtained using 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

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

That is why simulations were only undertaken with the Delft3D-WAVE module, which is based upon the well-known third-generation wave model Simulating WAves Nearshore (Holthuijsen et al., 1993; Booij et al., 1996; 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.

2.4.1. 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), comprising 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 wave heights).

Like in previous work dealing with numerical models extending from deep water to the nearshore (Kulling et al., 2016; Boudet et al., 2016; Kulling, 2017), two bathymetric datasets were used to derive the bottom morphology in Delft3D-WAVE. From the coast down to 30/40 m depth, the seabed morphology is taken from the Litto3D® database of Shom (French National Oceanographic Service), 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, 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 averages from 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 (Fig. 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 (cf. Furlani et al., 2014) ranges from ~5 to ~12 cm above

Table 1
Grids locations and resolutions used in Delft-3D-WAVE for the study.

Site	Coarse grid resolution (min. x max. Cell side length)	Fine grid resolution (min. x max. Cell side length)
Crine	~25x27m	~7x7m
Eoube	~46x73m	~23x23m
Morgiret	~69x80m	~33x34m
Pomègues	~94x115m	~21x21m

Table 2
Mean values of the biological, morphometric and hydrodynamic parameters collected during the field surveys. NRP is the notch retreat point, NW is the notch width, NID is the notch inward depth, NRE is the notch roof elevation, NFE is the notch floor elevation. Hsig is the significant wave height. The A transects were performed in the outer part of the different calanques while B transects were performed in the inner part (see Fig. 2A).

Site	Biological association	NRP (cm)	NW (cm)	NID (cm)	NRE (cm)	NFE (cm)	Hsig (mean)	Hsig (max)	T (C °) July	T (C °) Sept.
Crine A	Exposed	18		80	30		0,28	2,01	19,3	21,7
Crine B	Sheltered	−35	63	47	−15	−48	0,04	0,51	19,5	21,9
Eoube A	Exposed	5		41	15		0,13	0,87	19,3	21,7
Eoube B	Sheltered	−37	67	50	−16	−51	0,05	0,57	19,3	21,7
Morgiret A	Exposed	15		78	28		0,24	1,79	19,3	21,7
Morgiret B	Sheltered	−34	65	40	−15	−50	0,07	0,51	19,3	21,7
Pomegues A	Exposed	12		68	28		0,31	3,17	19,3	21,7
Pomegues B	Sheltered	−35	60	43	−12	−48	0,12	1,1	19,4	21,9

MSL (Table 2 and Fig. 2C).

The average inward depth of the notch showed a maximum 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* (Fig. 3). *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 *Dictiota dichotoma*, *Jania rubens* and *Botryocladia botryoides* (Fig. 23. 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 present MSL (Fig. 2D). However, 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 (Fig. 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 (Fig. 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 elongate* (Fig. 3). 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 down 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).

3.2. Wave modelling

The mean results of the numerical wave modelling are provided in Table 2. The complete output of the model is provided in Supplementary 1. 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 2).

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, Hsig (mean), Hsig (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" (Fig. 4). 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 Supplementary 2A). In the last 4.0 ka, maximal sea-level variation did not exceed ~1.75 ± 0.3 m (Fig. 5A). During this time-span, we observed variability in the sea-level rising rates which range from ~1.1 mm/y to ~ − 0.1 mm/y (Fig. 5B, Supplementary 2B). In particular, we observed rising rates of up to ~0.6 mm/y from ~3.5 to ~2.3 ka BP which were followed by a RSL deceleration which bottomed out between ~1.5 to ~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 (Fig. 5B). Younger data indicate that RSL rising rates transitioned to positive values in the last ~1.1 ka BP with significant rising rates observed in the last ~0.3 ka BP (up to~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, submerged marine notches are often reported in tectonically active coastal areas such as the Aegean Sea (e.g., Evelpidou et al., 2011; Kolaiti and Mourtzas, 2016; Karkani and Evelpidou, 2021) or in areas characterized by particular hydrological conditions and/or tectonic activity such as the mid to northern Adriatic Sea (Furlani et al., 2014; Marriner et al., 2014; Faivre and Butorac, 2018).

To the best of our knowledge, Marseille Bay and the surrounding *calanques* (see Antonioli et al., 2017) are presently the only Mediterranean region showing the occurrence of a notch developing at or slightly above msl at exposed sites and another one developing below msl (e.g., ~ − 35 cm) at sheltered sites. Such variability cannot be ascribed to ground movements related to differential tectonic activity for two main reasons: i) no major faults are reported in the Frioul area (Nocquet and Calais, 2004; Noquet, 2012); and ii) the submerged notch and the one measured at the present msl often occur on either side of the same cliff (see Fig. 2).

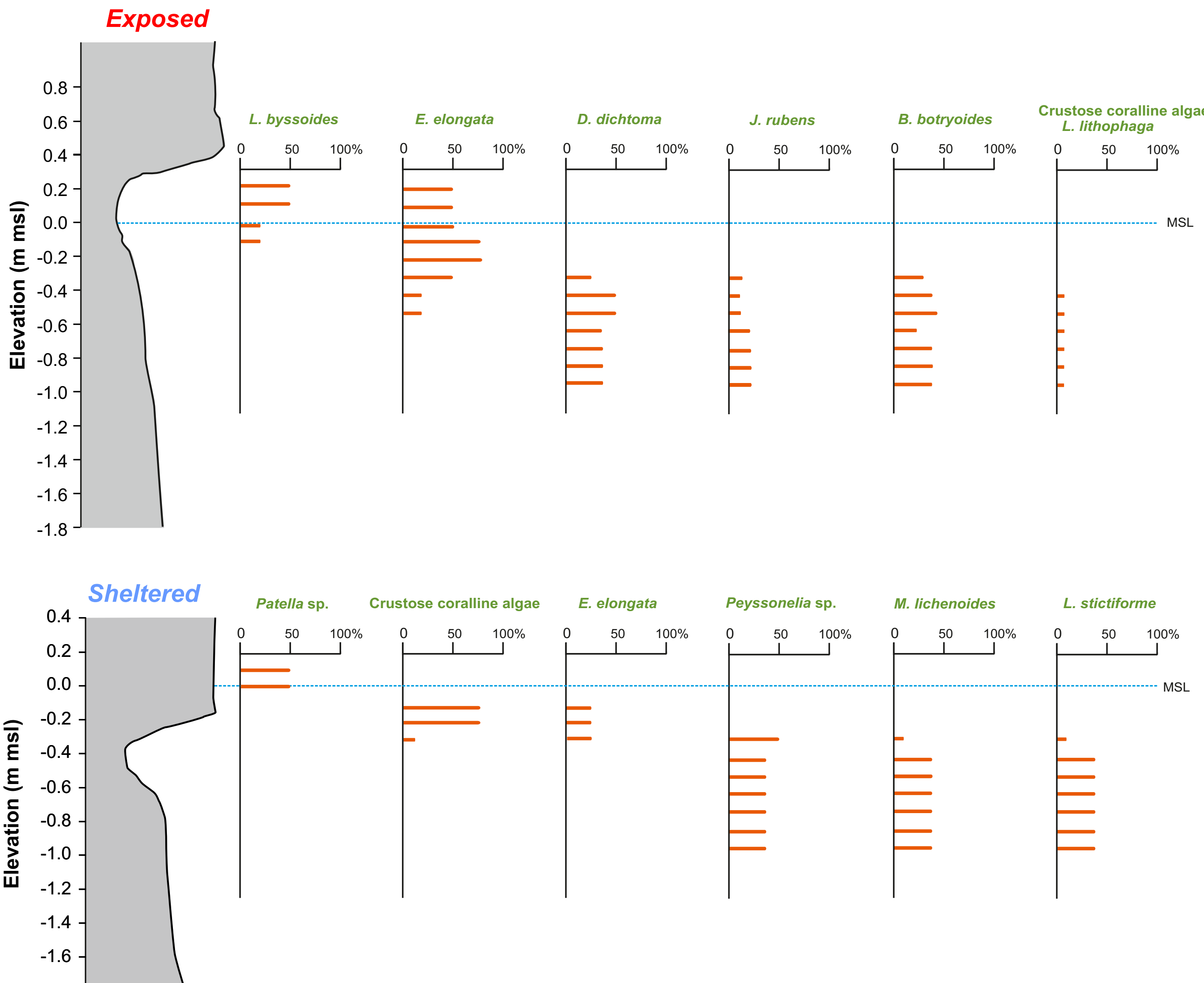

Fig. 3. Biological cover along the exposed and sheltered areas of the Frioul coast. Main taxa are reported as relative abundances. MSL is the Mean Sea Level.

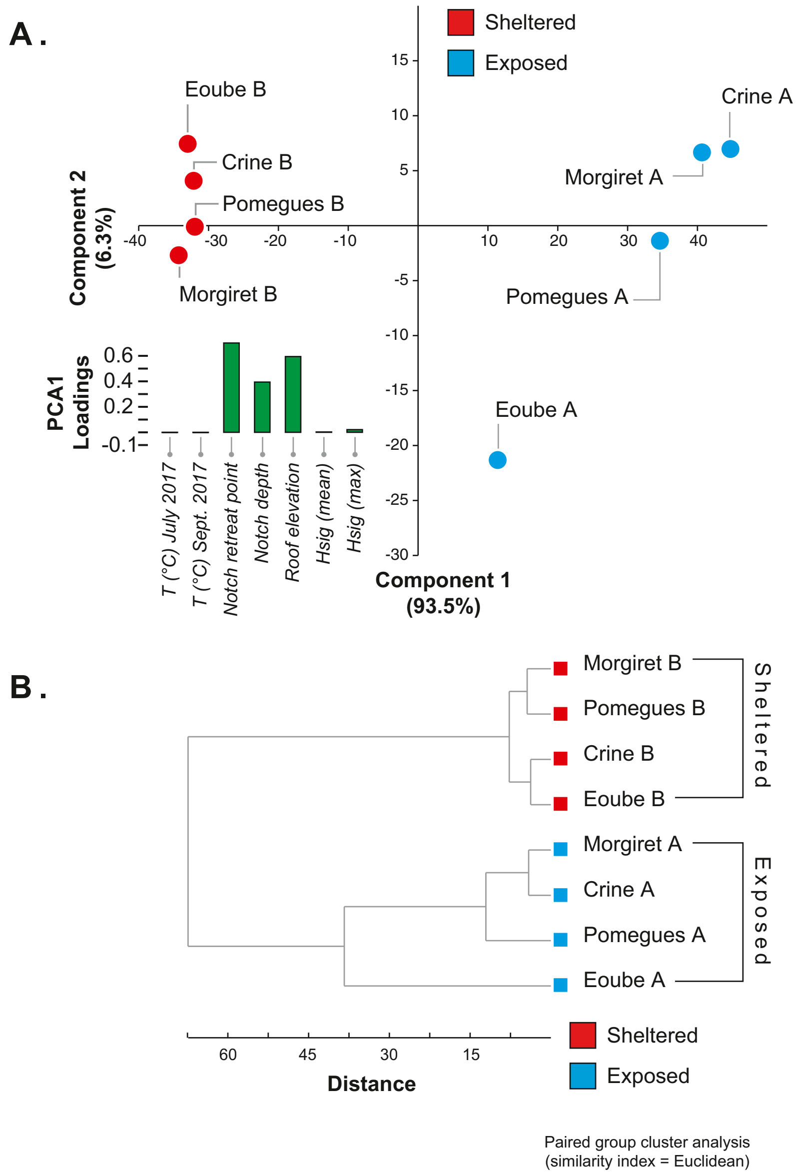

Fig. 4. Multivariate statistical analyses of the geomorpgological notch data (A) Principal Components Analysis. (B) Paired group cluster analysis (similarity index = Euclidean).

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 analyses clearly categorized the notches of the Frioul into two groups (>93% of the variance) according to their exposed or sheltered position. At 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). 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. Climatic control on the formation of the submerged notch

Antonioli et al. (2017) described a similar notch distribution in the *calanques* of Sormiou and Port Miou located <20 km from the Frioul archipelago. Here, the exposed cliffs are characterized by a well-developed “roof notch” (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)

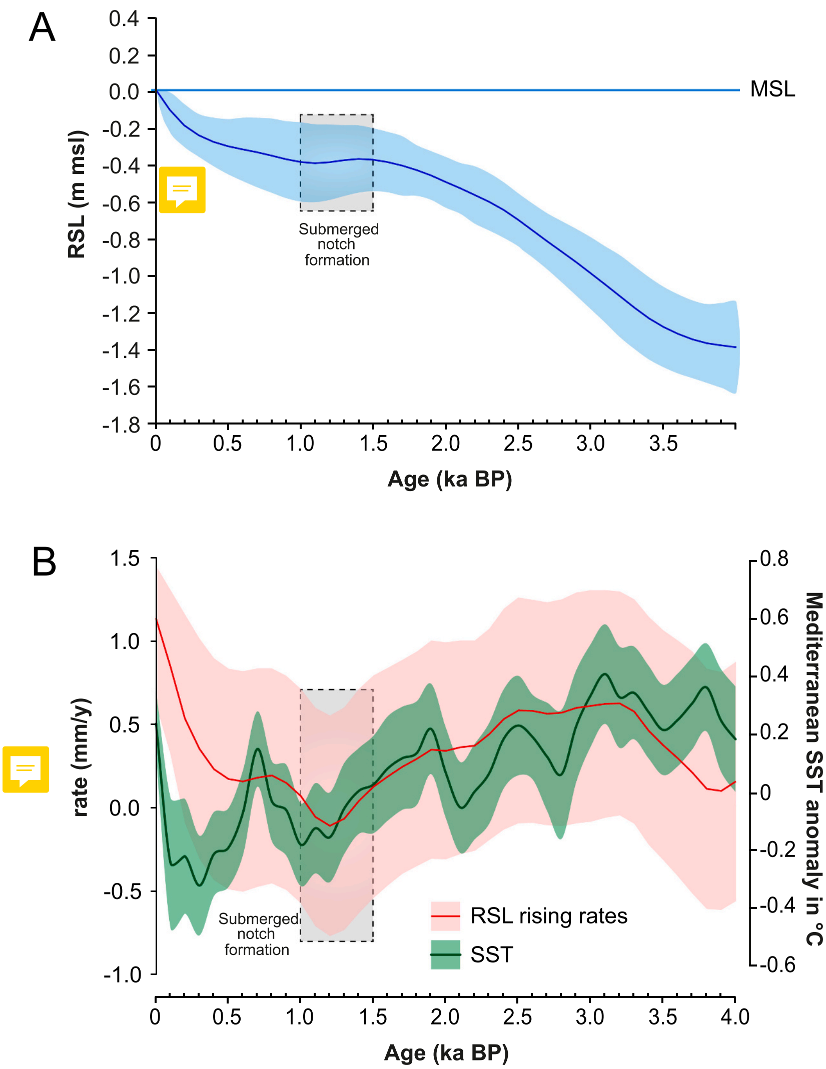

Fig. 5. Spatio-temporal reconstruction of the RSL position (A) the rates of sea-level change (B) and Mediterranean SST anomalies (B) for the last 4.0 ka BP in the Marseille Bay area (Marriner et al., 2022).

and there is no hydrological network on the archipelago; ii) our surveys did not show significant variability in the water temperature between the exposed and the sheltered sites in either our July or 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 an alternative explanation for the origin of this submerged notch (Fig. 6). 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, Büntgen et al., 2016) when a general cooling of the Mediterranean climate triggered a significant deceleration of RSL rising rates (Vacchi et al., 2021). Around 1500–1250 BP, Mediterranean Sea Surface Temperatures cooled rapidly by around 0.27 °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., 2013; Vacchi et al., 2021). The stabilization driven by the LALIA cooling is evident in the Marseilles' sea-level record (Fig. 5B and Supplementary 2B) which shows negligible or slightly negative rising rates from 1.5 to 1.1 BP when the paleo-sea level was at −36 ± 18 cm.

For this reason, we consider the underwater notch of the Frioul archipelago to be a relict landform which was shaped during a ∼ 400-year period of sea-level stability driven by the general cooling of the NW Mediterranean Sea (Fig. 6). 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 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 RSL rising rates transitioned to positive values of up to ∼0.5 mm^{-1} in the pre-industrial era (e.g., before 1850 CE) accelerating up to ∼1.1 mm^{-1} in the last 150 years (Fig. 5B). During this time, 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 (Fig. 6). 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-

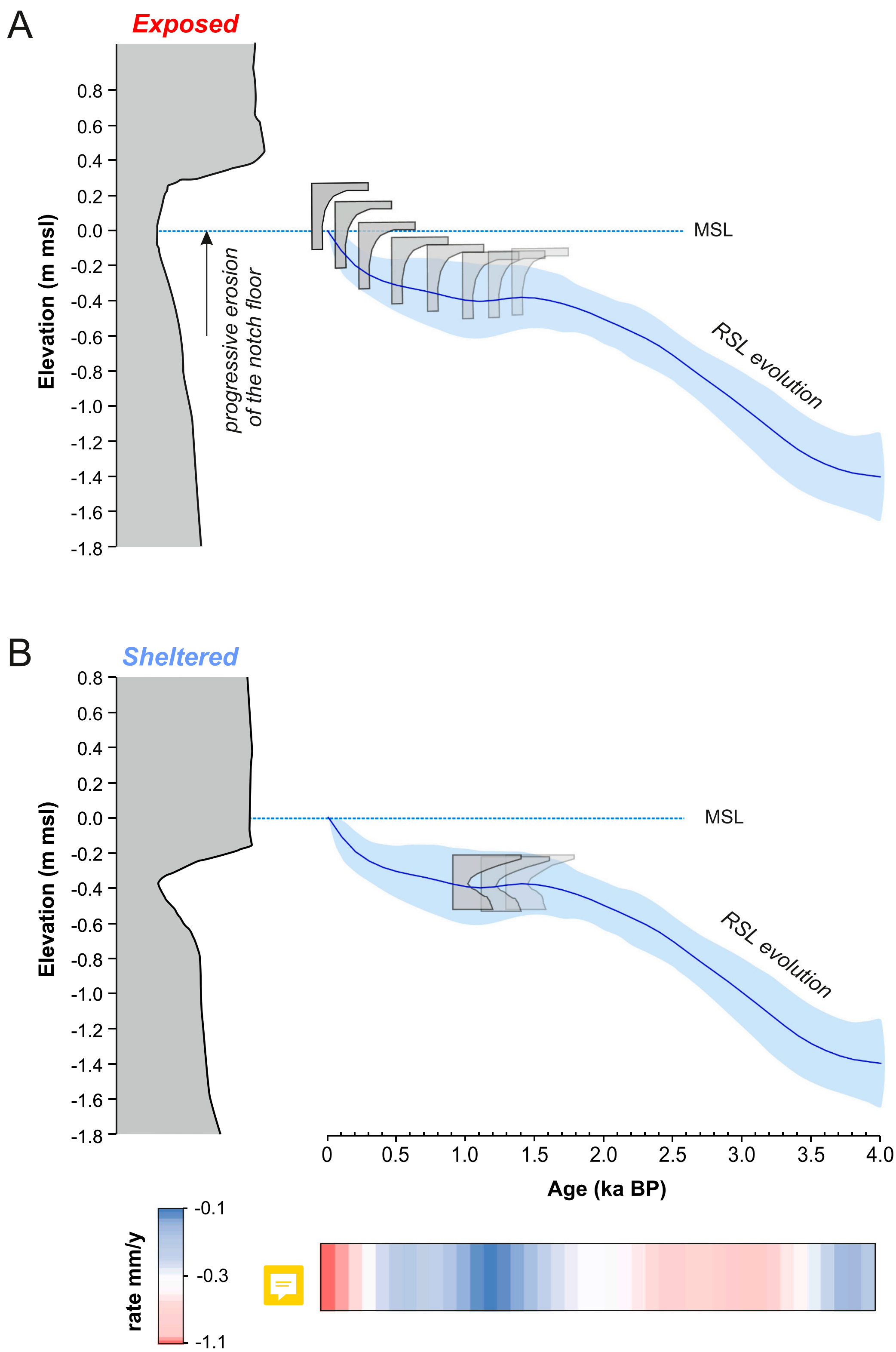

Fig. 6. Morphological model to explain the differential notch evolution observed in the Marseille Bay area. RSL is the Relative Sea Level. MSL is the present Mean Sea Level.

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 (~0.25 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 and 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 mechanical wave 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 ~400 years of relative sea-level stability. These data are in good agreement with those reported 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 mm^{-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 but only in those sectors characterized by negligible hydrodynamics and minor GIA signal (e.g., characterized by less than ~2.5 m of RSL variation 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 bedrock resistance to erosion and the morphology of rock strata. The peculiar distribution of the marine notch of Marseille Bay provides new insights into the local mechanisms mediating this key carbonate-coast landform. Our data indicate that sea-level stability is only an important factor for notch formation at sheltered sites. By contrast, mechanical wave action seems to be the major factor in controlling notch formation, at least in 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, represents an ideal site for this kind of analysis. Finally, our findings indicate that the occurrence of submerged marine notches cannot solely be ascribed to tectonically-driven ground movements but that their origin can also be related to climatic factors.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.margeo.2022.106929.

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

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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