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Transgressive rocky coasts in the geological record: Insights from Miocene granitic rocky shorelines and modern examples

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ABSTRACT

Rocky shorelines are commonly punctuated, with alternating high relief cliffs and incised embayments which host "pocket beaches". While multiple cases of ancient rocky shorelines associated with low relief ravinement surfaces have been documented in the geological record, deposits formed in pocket beaches and joint-cut coves are more rarely described. This poses the question "are high relief rocky coastlines and their associated deposits not preserved or have they been previously overlooked? Here we document exhumed examples of ancient granitic rocky shoreline systems of diverse morphologies from the Early Miocene of northern Austria, and compare them with modern systems in UK, Corsica, Spain and Norway. The preserved ancient examples offer a good opportunity to characterize these sedimentary systems, provide diagnostic criteria for their recognition and discuss the main controls on their occurrence and preservation in the rock record.

From their stratigraphic and sedimentological analysis, and its comparison with modern examples, we interpret that these rocky shorelines form and get preserved during rapid rates of combined tectonic and eustatic sea-level rise, along lithological, structural and weathered "weakness" zones affected by normal low wave energy conditions interrupted by storms. These results provide a mechanism for predicting their potential occurrence and distribution during transgression of rocky coasts, with implications for exploration around structural highs and coastal management.

1. Introduction

Rocky coasts form around 72 % of modern shores (Nyberg and Howell, 2016). These are dominated by wave erosion of uplifted coastal areas with sediment accumulation limited to small embayments called pocket beaches. Pocket beaches usually range from tens of meters up to 1000 m wide (Bowman et al., 2009, 2014). It is also common to find more local and narrow systems cut in fractured and jointed bedrocks, which we differentiate from pocket beaches and refer to as joint-cut coves or incisions, in genetic or descriptive terms, respectively. In these systems, sediment is typically derived locally and the rates of supply and accumulation are low when compared to prograding deltas and clastic shorelines which are supplied by sediments derived from large fluvial catchments (Regard et al., 2022). Pocket beaches and joint-cut coves occur in areas along the rocky coastlines that have experienced greater erosion, either due to lithological contrasts or due to structural complexity, where a high density of fractures and faults makes cliffs more prone to erosion (Sunamura, 1992; Kennedy et al., 2014; Trenhaile, 2016). This differential erosional pattern produces zones of more resistant bedrock, acting as headlands, which bound embayments, excavated in the less resistant bedrock. Pocket beaches and joint-cut coves are very common along most modern rocky coasts and their deposits are typically composed of conglomerate material that ranges from granule up to boulder size, with variable amounts of sand and mud (Brunel and Sabatier, 2007; Bowman et al., 2009; Klein et al., 2010; Balouin et al., 2014; Sammut et al., 2017; Randazzo et al., 2021; Lapietra et al., 2022). Although the geometry, sediment distribution and evolution of these systems are well documented in modern examples (Trenhaile, 2001, 2005) they are rarely reported in ancient systems (Johnson, 1992, 2006). This poses questions regarding their recognition and preservation potential in the geological record: Are they mostly absent or simply overlooked? If they are present, what are their diagnostic criteria and the conditions that favour their preservation? This study focuses on the characterization of newly discovered Lower Miocene rocky shoreline sedimentary systems, linked to a granitic basement, in the south-eastern margin of the Bohemian Massif, in Limberg,

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northern Austria, and compares them to modern systems in UK, Corsica, Spain and Norway (Fig. 1). The aim is to provide a detailed description of their diagnostic features, consider their depositional geometries and discuss the factors that controlled their occurrence and preservation.

The accurate identification of pocket beaches and joint-cut coves adds important information to reconstructing the paleogeography and nature of unconformities in areas that have experienced net erosion and for which there is little or no sedimentary record (Shepard, 2006; Rousse et al., 2012).

2. Methods

In order to achieve these objectives, detailed fieldwork was carried out in Miocene sedimentary rocks cropping out in an active granite quarry, the Limberg Quarry, in northern Austria (Fig. 1), which extends horizontally for approximately 1.125 km^2 and exposes 3 WNW-ESE/ NW-SE vertical sections, one at the west, one at the east and a middle section (Fig. 2). Detailed sedimentary logging was carried out, one log at each section, recording information on grain size, roundness, sorting, sedimentary structures and fossil content. This was complemented with UAV-acquired images, which were subsequently used to create virtual outcrops and orthomosaics. These images, with a 4096 × 2160 pixel resolution, were first imported and georeferenced into Agisoft PhotoScan, a photogrammetry software used to reconstruct the geometry of the outcrops and create 3D texturized models based on the identification of common points between images. Given that the virtual outcrops are georeferenced, the thickness of the sedimentary logs was calibrated against the thickness observed in the virtual outcrop through the same log trajectory in order to correct small errors in the field measurements. The sedimentary logs were then digitized in Inkscape, an opensource vectorial drawing software. Additionally, the UAV images, the virtual outcrops and the orthomosaic were interpreted in Inkscape too. To complement the study in Austria, modern analogue examples of granitic rocky coastlines in Spain and Norway were also studied in the field, where detailed sedimentological descriptions were done, consisting of grain size, roundness, sorting, sedimentary structures and fossil content. Additionally, satellite images were used to study the map view and structural controls on the distribution of the different parts of these sedimentary systems. The large-scale sedimentary characteristics and the morphology of the modern examples in Corsica were described using solely satellite images and available bathymetric maps in ArcGIS.

3. Geological setting

The emplacement of the Alps during the Eocene-Miocene Alpine orogeny created the North Alpine Foreland Basin (NAFB), a subsiding SW-NE basin bounded by the Jura Mountains to the west and the Bohemian Massif to the east (Kuhlemann and Kempf, 2002; Sharman et al., 2018) (Fig. 3A). The Bohemian Massif is a Proterozoic-Palaeozoic crystalline high. In the Austrian sector, the south-eastern boundary of

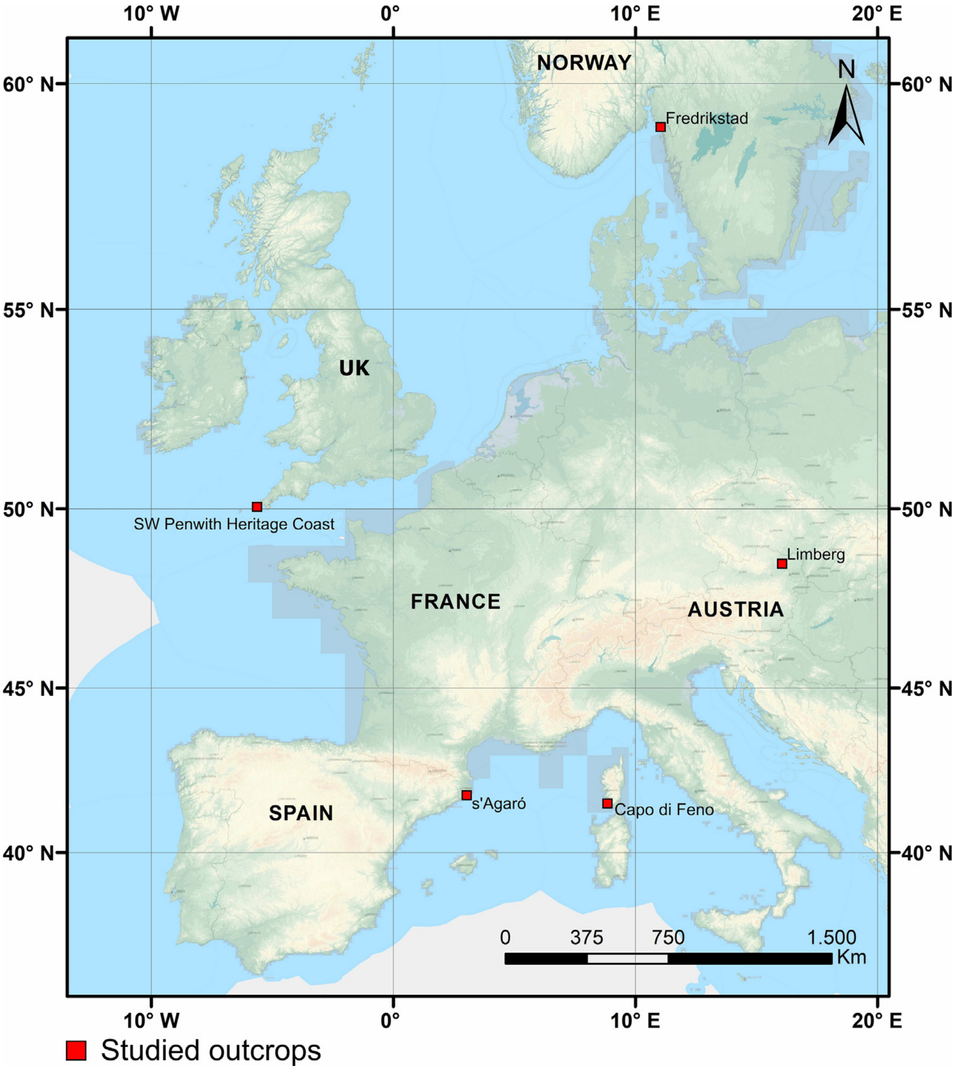

Fig. 1. Digital elevation model of Europe, between 13° W and 20° E, with the main countries and outcrops studied. (modified map from www.mapsforeurope.org).

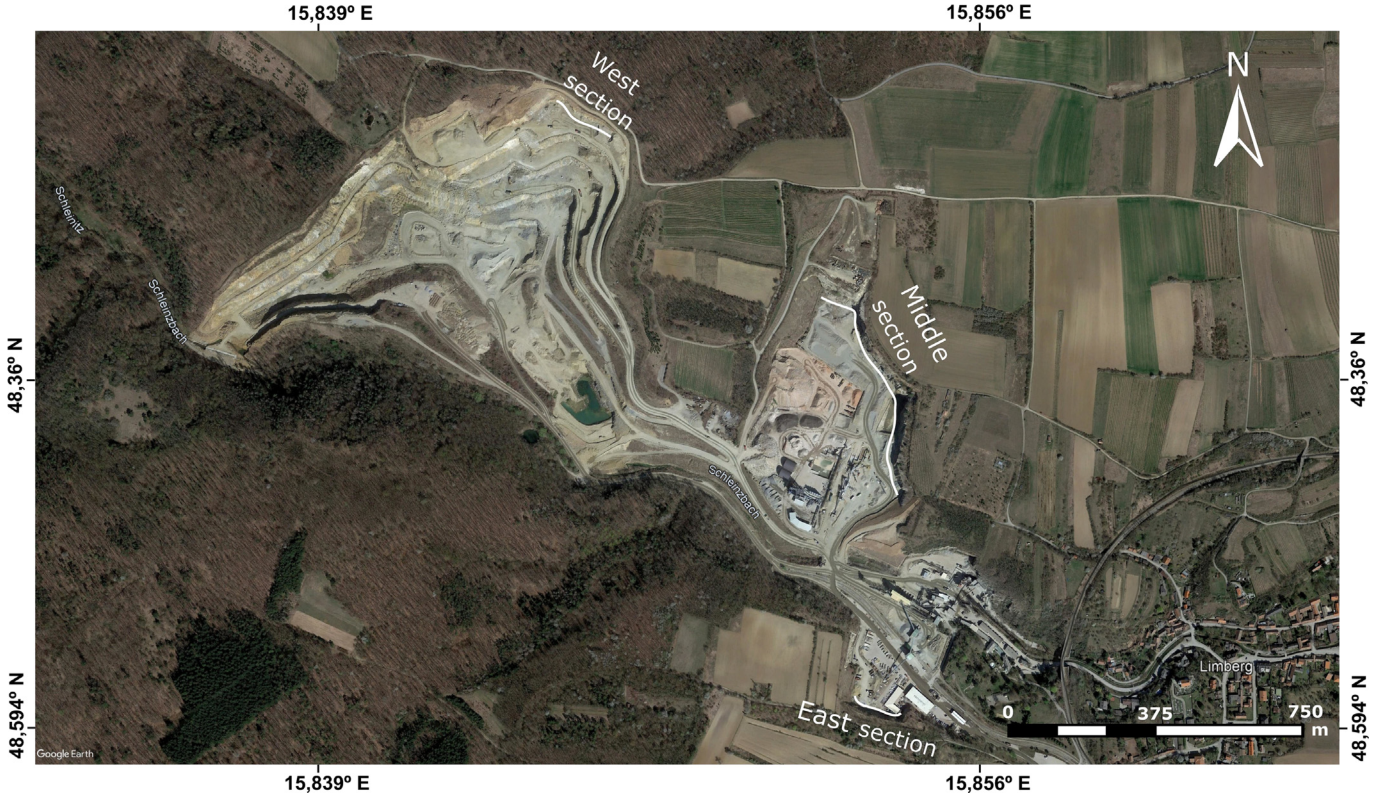

Fig. 2. Orthophoto with the location of the Limberg Quarry. Three sections have been studied in this work (solid white lines), one at the west, one at the east and another one in between, the middle section. (orthophoto from Google Earth imagery catalogue).

the Bohemian Massif is controlled by two regional structures, the Diendorf and Waitzendorf faults, a pair of SW-NE parallel-trending faults of Permian age that had a significant phase of sinistral strike slip movement during the Miocene (Roštínský and Roetzel, 2005). Between these two faults, the Eggenburg Bay developed (Fig. 3B): an Early Miocene bay characterised by numerous tectonically induced domes and ridges of the Thaya granite (600–570 Ma) which acted as small islands which paralleled several N-S Miocene extensional faults and fractures (Roštínský and Roetzel, 2005; Nehyba and Roetzel, 2021). Additionally, the Eggenburg bay was sheltered at the SE by a large SW-NE striking basement elevation which paralleled the Diendorf Fault (Fig. 3C). Additionally, it is observed that the Limberg Quarry was part of a small cape with a WNW-ESE /NW-SE orientation. The studied area in the Bohemian Massif was transgressed during the late Eggenburgian and early Ottnangian stages of the Early Miocene (Harzhauser and Piller, 2007). The first transgression created accommodation that led to the deposition of coarse grained, basement reworked granitic marine clastic rocks of the Burgschleinitz Formation. This was followed by a second cycle, characterised by proximal calcareous sandstones of the Zogelsdorf Formation and distal pelitic claystones of the Zellerndorf Formation (Roetzel et al., 1999; Grunert et al., 2010).

4. Results

4.1. Miocene rocky shoreline deposits and their morphology

4.1.1. Limberg Quarry description

In the Limberg Quarry, the Miocene sedimentary succession studied is lying unconformably on top of a granitic basement. The sections at the west and east of the quarry preserve narrow-erosional incisions which are mainly filled with conglomerates and sandstones of the Burgschleinitz and Zogelsdorf formations (Fig. 4A, B and C). The clasts in the conglomerates are exclusively composed of granite. The backface of the conglomerate deposits rests on the granite surface, as observed in the uppermost part of some incisions, where it crops out above the sedimentary infill (Fig. 4B). The incisions are bounded by smooth and subvertical surfaces with a N-S strike and dipping oppositely at 70–80° (Fig. 4B and C). Two incisions are exposed at the western section which are separated by a small granitic promontory (Fig. 4B). The one at the left is 6.5 m wide and 10 m deep whereas the one in the right is 3.7 m wide and 7 m deep. The same geometry is observed at the eastern section (Fig. 4C) which exposes a 5 m wide and 7.5 m deep incision. The infill of these incisions shows a consistent fining-upward trend, which allows subdividing them into a basal part, more encased, and an upper part which seals the incisions (Fig. 4A). The basal part is dominated by clast-supported pebble-to-boulder conglomerates with variable amounts of medium-to-coarse pebbly sandstones as matrix. The conglomerates are poorly to moderately sorted, subangular to well rounded, displaying discoidal or blocky shapes and local imbrication (Fig. 4A West and B). Additionally, some boulders contain fossilized barnacle colonies attached to their surfaces (Fig. 4D). The upper part is finer grained and the facies are more variable between sections. At the western section it is dominated by very poorly sorted medium-to-coarse sandstones with high amounts of matrix-supported subangular to subrounded pebble-to-boulder conglomerates. At the eastern section it is dominated by sharp based, fine grained, well to very well sorted, calcareous fine sandstones. At the middle section, between the western and eastern sections (Fig. 2), and at an equivalent stratigraphic position, there is a more extensive conglomeratic deposit onlapping onto the basement (Fig. 5A and B). This deposit fills a scoop-shaped erosional surface 430 m wide and 8 m deep. The sedimentary infill thins towards the margins of this depression. The unconformity surface is relatively flat and smooth, except for some local highs, 1–2 m high, around which deposits pinch out. The succession is characterised by a 1 m thick basal conglomerate overlain by 3 m of fining upwards, coarse to fine-

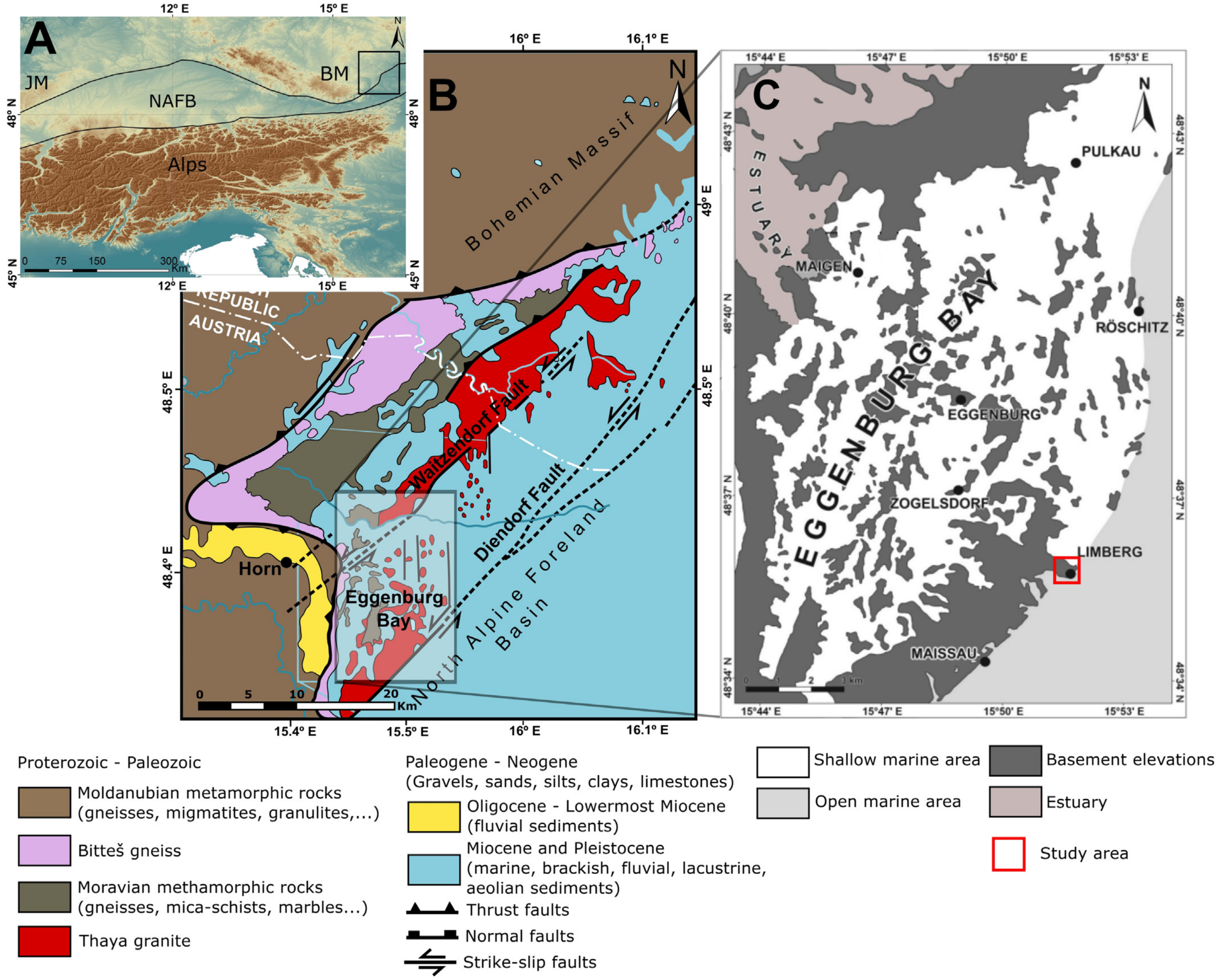

Fig. 3. (A) Digital elevation model of the Alps (JM: Jura Mountains, BM: Bohemian Massif, NAFB: North Alpine Foreland Basin) (data from www.land.copernicus.eu). (B) Geological map of the south-eastern margin of the Bohemian Massif in Lower Austria showing the Eggenburg bay, local structures and stratigraphy (modified from Roetzel et al., 1999 and Roštínský and Roetzel, 2005). (C) Paleogeographical reconstruction of the Eggenburg Bay during the Eggenburgian (Early Miocene). The study area formed part of a large SW-NE trending basement elevation which separated the rather restricted shallow marine Eggenburg Bay from the open marine outer area. Note the local WNW-ESE cape morphology of the Limberg Quarry during the Eggenburgian (modified from Nehyba and Roetzel, 2021).

grained sandstones (Fig. 5B and C). The basal part is predominantly conglomeratic with thin interbeds of well sorted coarse-to-very coarse grained sandstone. The conglomerates are rich in matrix, composed of coarse-to-very coarse sandstone, and are dominated by poorly-to-moderately sorted pebbles (2 to 4 cm) and cobbles (7 to 10 cm). Boulders (up to 60 cm) are also locally observed. The clasts are mostly sub-angular to sub-rounded with associated minor amounts of angular cobbles. Some of these angular clasts tend to be imbricated and concentrated at specific levels. The conglomerates fabric is structureless, except for the upper part of the package where we see the development of thin, 10 cm thick, normally graded layers consisting of discoidal pebbles and ostreid shells displaying horizontal orientations. Some of the conglomerate clasts preserve fossilized marine barnacles and serpulid tubes incrusted on its surface. The upper part of the succession is dominated by 3 m of structureless to cross-stratified well-to very well-sorted coarse-to-fine sandstones. Thin shell-rich laminae are common. Sandstones are predominantly structureless although towards the top of the package there is a characteristic interval, 0.5–1 m thick package with well-developed wavy or hummocky cross stratification (Fig. 5B and C).

4.1.2. Interpretation

The lithological composition of the clasts suggests the underlying granitic basement is the main sediment source. The position of the deposits, attached to the face of the outcrop, along with the presence of marine fauna precludes a channelized fluvial origin. Instead, the geometry of the deposits, the fossil fauna and the conglomerate roundness suggest these are mostly wave-reworked marine deposits formed in narrow joint-cut coves and pocket beaches within a rocky shore. The subvertical and smooth surfaces that bound the joint-cut coves in the western and eastern sections of the quarry are interpreted as the result of erosion of conjugate fault or fracture planes. Comparing the N-S orientation of the fracture and fault system which hosts the deposits and the paleogeographical reconstruction of the Eggenburgian shoreline in Fig. 3C, it is interpreted that the Limberg Quarry was once a segment of a former W-E or WNW-ESE striking rocky shoreline. The current orientation of the studied sections with respect to the reconstructed paleoshoreline, indicates these are mainly vertical alongshore sections. The sea was located at the SW of the shoreline, at least in the western section, based on the recognition of the preserved cliff face which

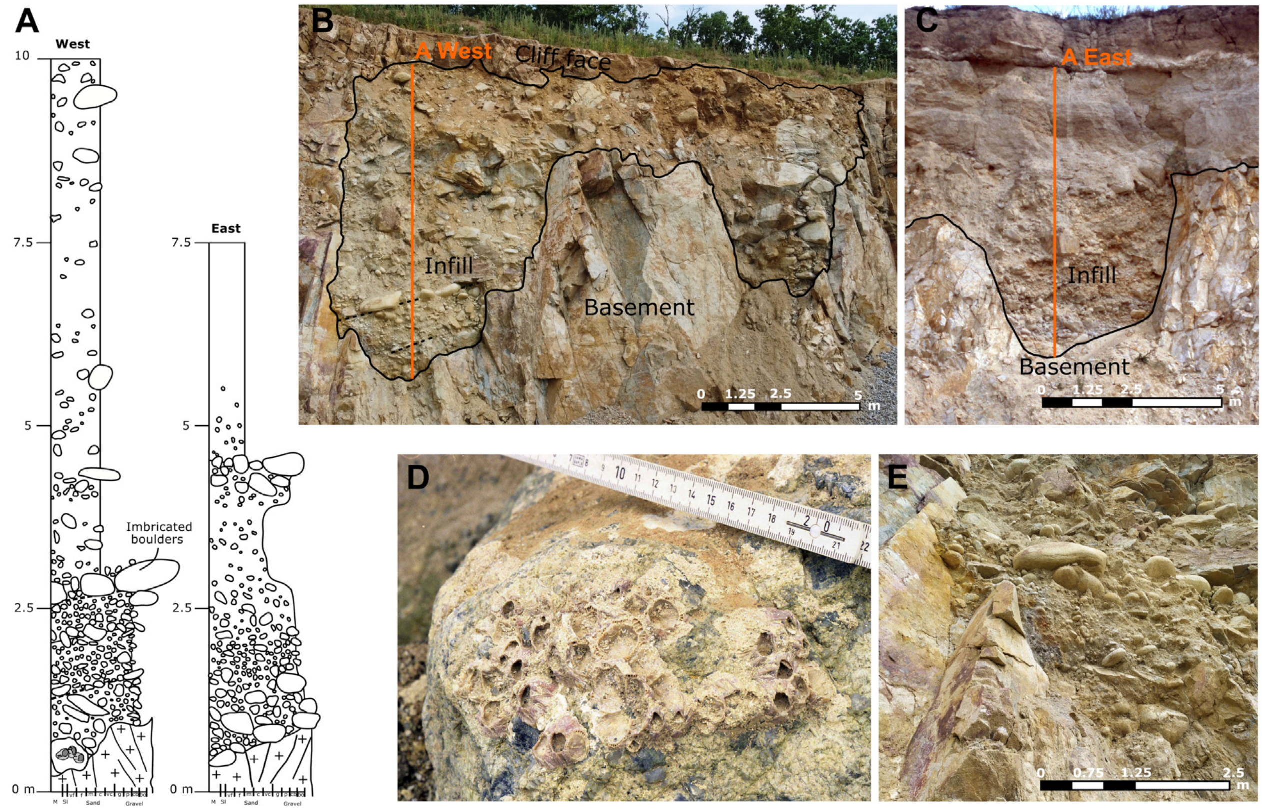

Fig. 4. (A) Stratigraphic logs of the western and eastern sections of the Limberg Quarry incisions (log trajectory depicted as vertical orange lines in B and C). Note that both show a marked fining-upwards trend with a basal part dominated by poorly-to-moderately sorted conglomerates and an upper part composed of variably sorted sandstones. (B) Western section of the Limberg Quarry incisions. Note imbricated boulders at the top of the basal conglomeratic interval in A (West) and B (dashed black lines). (C) East section of the Limberg Quarry incisions, note the sharp contact between conglomerates and sandstones. (D) Example of barnacles attached to a boulder surface. (E) Detailed up-view of the western incision sedimentary infill in B. Photos taken on August 2021.

crops above the sedimentary infill and backs the deposits. Lack of biostratigraphic data, three dimensionality and the absence of exposed cliff faces in the middle and eastern section hinders a confident interpretation about the position of the sea with respect to the shoreline and the age correlation between sections. It is assumed, only for exemplification purposes, that the sea was located SW of the different sections and that they were all connected along a rather rectilinear coastline, however it could be different, with a seaward edge at the NE and more complex configurations given the ancient cape morphology of the study area in Fig. 3C. The wider and scoop-shaped depression observed in the middle section is interpreted as a preserved alongshore section parallel to a former pocket beach. The sub-horizontal disposition of the depression indicates that post-depositional tilting is null or negligible. The lateral thinning of the deposits towards the margins of the pocket beach suggests a termination against a palaeo-relief. The conglomeratic infill is interpreted to be originally sourced from a combination of 1) remnant products of chemical-physical weathering, like spheroidal forms and corestones, 2) gravitational collapse of particles, 3) ripped out fragments as a consequence of marine erosion, and to a lesser extent 4) fluvial or alluvial sediments which accumulated at stream mouths and were subsequently redistributed alongshore. The origin of the joint-cut coves in the Limberg Quarry is likely the result of marine erosion, faulting, inherited weathered relief or a combination of them.

The stratigraphic sequence in the three sections studied shows a well-developed upward-fining stacking pattern, consistent with an overall transgressive trend, and interpreted to result from a relative sea-level rise and consequently recording a vertical transition into a deeper and lower energy depositional environment. As described, the upper part of the succession shows a significant facies variability throughout the different sections; in the eastern section it is dominated by fine-grained and well-sorted sandstones. This is interpreted to suggest that during transgression, the reliefs at the eastern section of the Limberg Quarry had less height and were drowned earlier than the joint-cut coves in the western section. The transgression generated a rapid disconnection from any nearby source area and consequently the sedimentation was finer grained than in the western section. In contrast, the upper part of the succession in the western section is dominated by coarser-grained material. This suggests reliefs there remained exposed for a longer period of time and kept supplying gravels and coarse sand as they were being eroded. The presence of preserved reliefs outside the joint cut-coves and the sharp contact between the conglomerates and the overlying sandstones in the eastern section indicates that this flooding was relatively rapid, reducing the time that the cliffs were eroded and protecting them from wave bevelling. The poor-to-moderate sorting of the basal conglomerates in the studied outcrops, their moderate roundness and the high amount of sand between the clasts suggests a low-to-moderate energy environment that was unable to sweep the sand particles. High energy storm events are interpreted to have occurred episodically based on the recognition of imbricated boulder intervals. The recognition of hummocky-swaley cross stratified fine sands could also be interpreted as a potential indicator of storm influence (Duke, 1985). The shape and the width of many boulders and cobbles is interpreted to be partially inherited from the spacing between the fracture network and the faults that affect the granite basement. Chemical and physical weathering along and between these structures was more intense, weakening the surrounding rock until it was relatively easy to erode by waves. Although it is not possible to interpret how much of the shape is inherited or created due to wave reworking. The different morphology of the incisions along with the interpretations about the energy conditions suggest

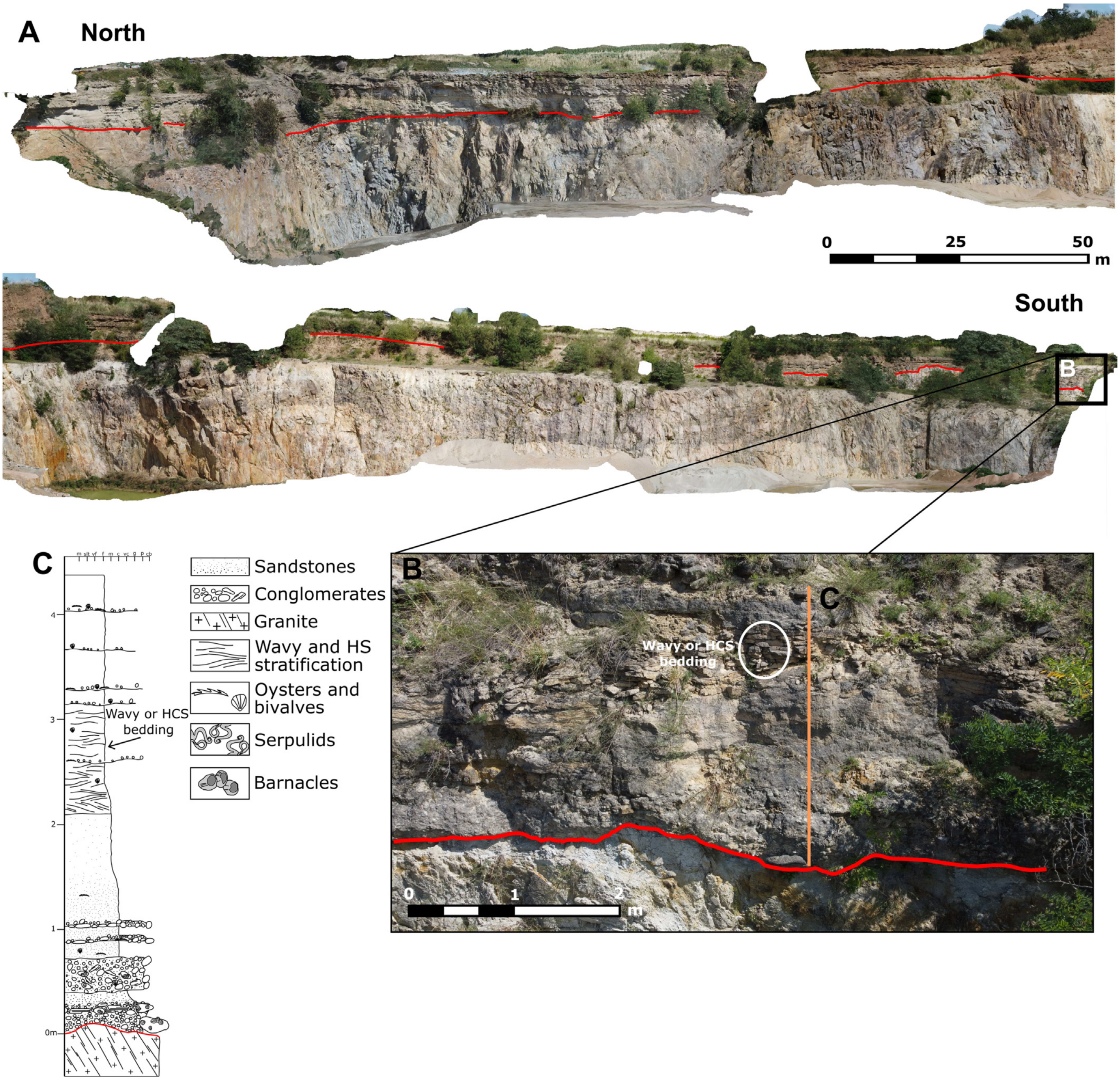

Fig. 5. (A) Orthomosaic of the middle section showing the extent of the scoop-shaped erosional unconformity. Note how the succession thins towards the margins suggesting a nearby termination and the local thinnings around small shallow basement highs at the South. (B and C) Logged section showing the stratigraphic succession and the sedimentary log, respectively. Note the well-developed finning-up trend, consistent with a transgressive succession. Photos taken on August 2021.

deposition occurred in narrow and elongated joint-cut coves, which passed laterally, along the shore, towards wider pocket beaches (Fig. 6A). It is inferred, based on the observation of a potentially analogous modern granitic coastline in Porthcurno, SW Penwith Heritage Coast, UK, that joint-cut coves are mostly found along headlands, and that pocket beaches tend to occur in sheltered and embayed areas between headlands (Fig. 6B). This configuration, in alternating headlands and bays, is often controlled by the lithological or structural heterogeneities found along the coast, with pocket beaches occupying areas between major faults or lithological contacts, which tend to experience higher erosion rates than the surrounding headlands. The lateral thining of the deposits in the middle section, and the scoop shaped morphology of the unconformity, would suggest that the middle section in the Limberg Quarry was bounded by two headlands, both at the North and South, showing a similar configuration to the example in the SW Penwith Heritage Coast (See Supplementary Materials section for detailed examples of the area).

4.2. Modern granitic rocky shorelines at s'Agaró, Spain; Fredrikstad, Norway and Capo di Feno, Corsica

4.2.1. Description

The coast at s'Agaró in Spain and Fredrikstad, Norway, are highly indented granitic rocky shorelines which host numerous narrow joint cut-coves cut along the bedrock (Fig. 7A–D). Both areas are characterised by a mean significant wave height around 0.5 m (Soukissian et al., 2017; Norwegian Coastal Administration, 2022). Occurrence and development

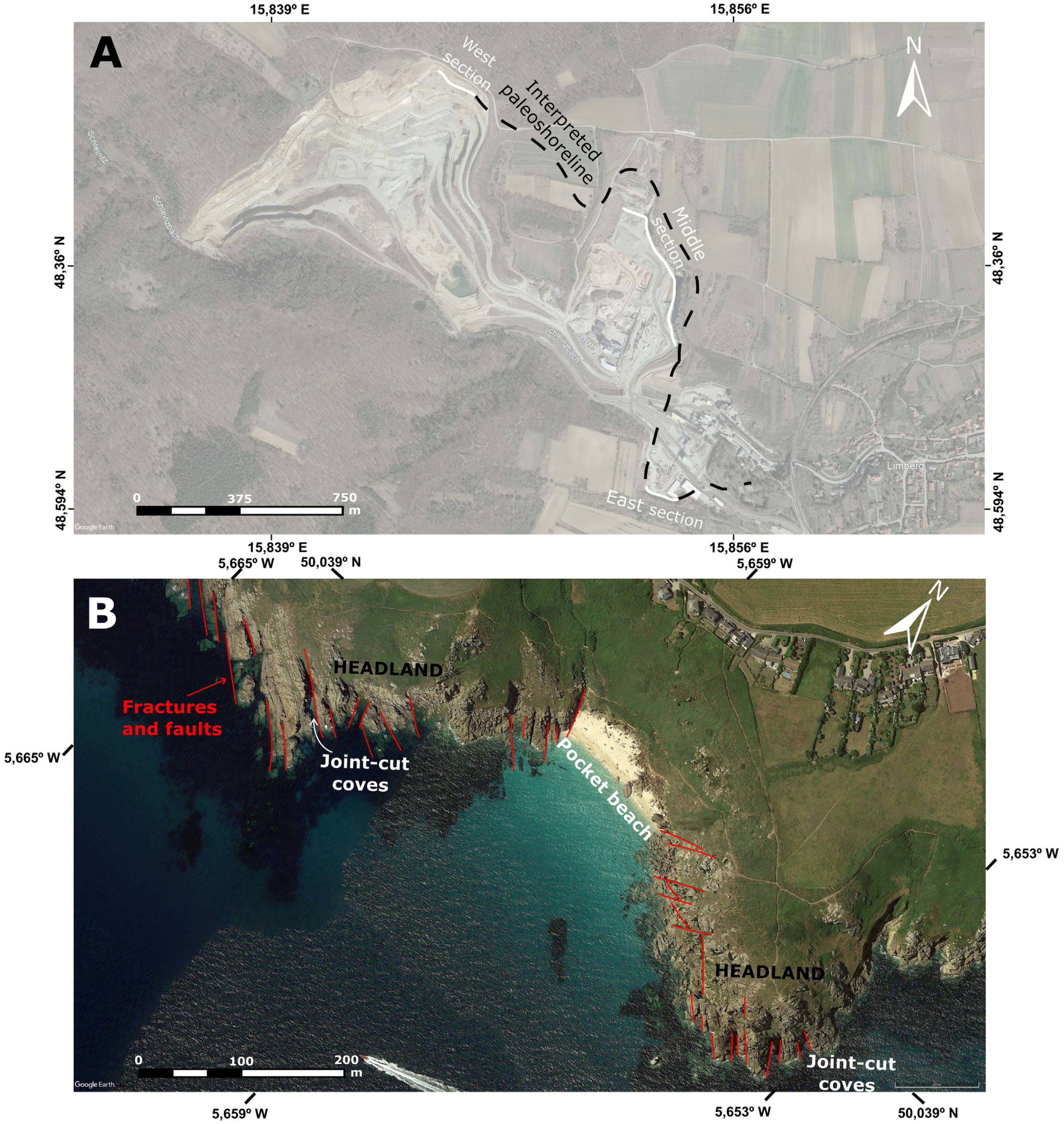

Fig. 6. (A) Interpreted paleoshoreline and correlation between the Limberg Quarry sections studied. Joint-cut coves are developed at the western and at eastern section, while a pocket beach developed in the middle section. (B) Interpreted modern granitic rocky coastline at Porthcurno, in the SW Penwith Heritage Coast, in the UK. The interpreted configuration of the Limberg Quarry paleoshoreline is frequently observed in modern rocky coastlines. Joint-cut coves develop along bedrock fractures, in sections of the coastline that occupy a more seaward position and are therefore more exposed, headlands. In contrast, pocket beaches develop between these sections, occupying less exposed and more protected areas bounded by headlands. Based on modern examples, it is inferred that the position of the pocket beaches could be coincident with major faults or lithological contacts, which tend to experience higher erosion rates than the fractures that bound the joint-cut coves.

of joint-cut coves is coincident with SW-NE oriented fractures, faults and dikes that cut through Hercynian and Neoproterozoic granitoids, respectively (Gattacceca et al., 2004; NGU, 2021). The bounding surfaces are smooth and steeply inclined. The cliffs at s'Agaró are up to 10 m high. The sedimentary infill comprises moderate-to-poorly sorted gravels, with subangular and subrounded boulders and cobbles. The sphericity of the clasts is low and most of them have a blocky shape (Fig. 7B). At Fredrikstad, joint-cut coves are 1 to 4 m wide, bounded by 1 to 2 m high promontories. The sedimentary infill of these depressions is dominated by clast-supported, moderate-to-poorly sorted gravels, with subangular, 40 to 60 cm long boulders which have a blocky shape with subrounded edges (Fig. 7D). Subordinate amounts of pebbles and boulders are also found, sometimes with small amounts of matrix in between, consisting of very coarse sand and granules.

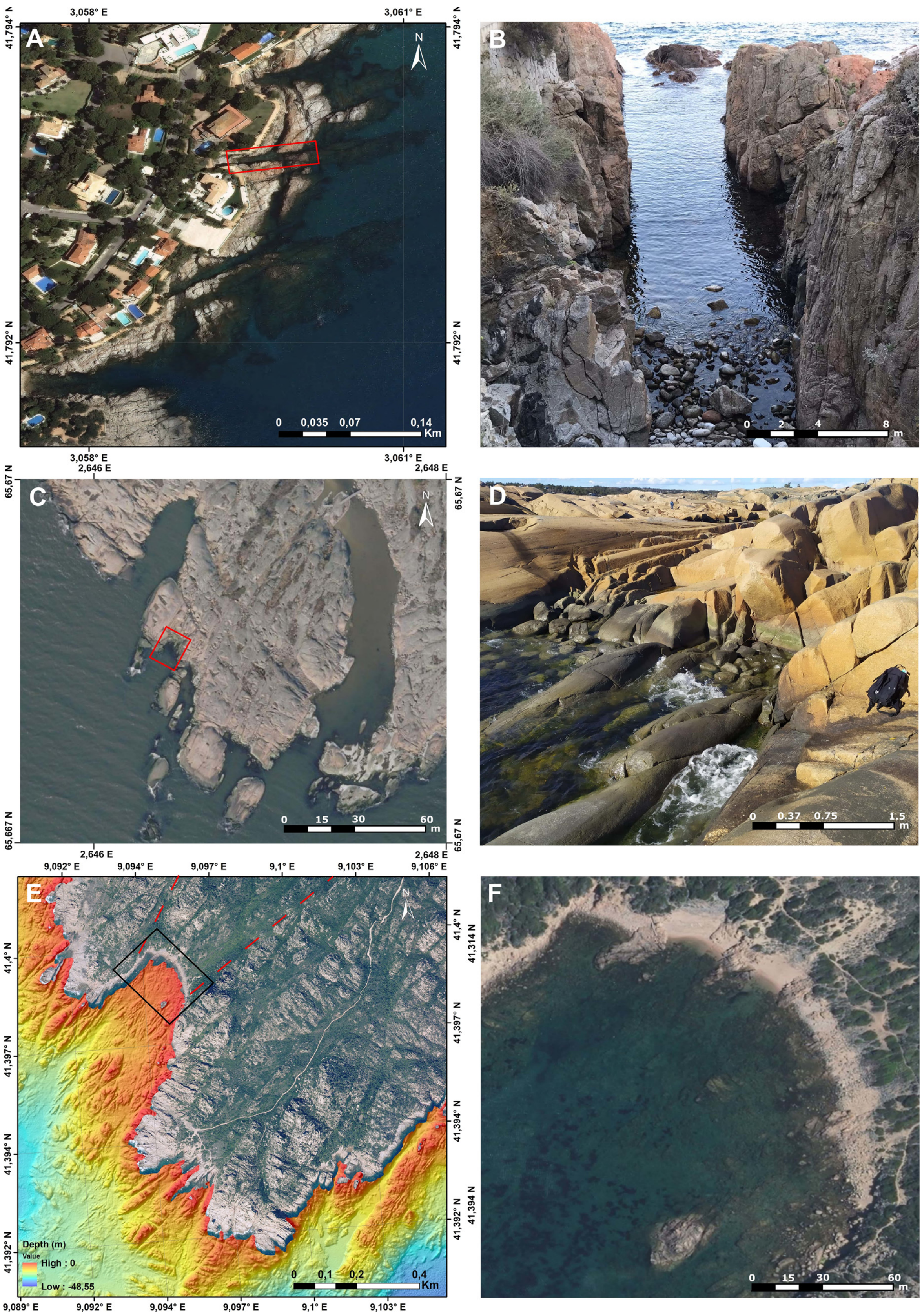

Fig. 7. Modern joint-cut coves at s'Agaró (A, B) and Fredrikstad, Norway (C, D). Joint-cut coves are mainly developed along fractures and faults (orthophoto in A and C from www.icgc.cat and www.norgebilder.no). All photos were taken on April 2022. (E) Composite image of Capo di Feno, Corsica, showing the alternating joint-cut coves and pocket beaches that form along the coastline and their underwater continuity (bathymetry from www.shom.fr, orthophoto from www.geoservices.ign.fr). (F) Satellite image from the pocket beach at Capo di Feno showing alternating patches of sandstone and conglomerate that terminate locally against small promontories.

The area of Capo di Feno, in Corsica, is dominated by a mean significant wave height between 0.5 and 0.85 m (Soukissian et al., 2017). The coast is composed of Hercynian granitoids which are affected by SW-NE fault and fracture systems (Gattacceca et al., 2004). The area is characterised by alternating pocket beaches, 200–300 m wide and large headlands that host multiple joint-cut coves carved into the bedrock (Fig. 7E, F). The deposits vary from boulder to sand dominated, with alternating sand patches and thin veneers of cobbles and boulders that terminate laterally, along the shore, against small promontories (Fig. 7F). Study of satellite images shows that the occurrence of pocket beaches is coincident with the location of larger faults and fault zones. Pockets tend to form at the junction of, or between these structures (Dehouck et al., 2009). Additionally, the bathymetric maps show several offshore highs and depressions, 10 to 20 m deep and 10 up to 200 m wide. These features are very similar in geometry to the examples described and are aligned with the current location of pocket beaches and joint-cut coves in the coast of Capo di Feno.

4.2.2. Interpretation

The joint-cut coves at s'Agaró and Fredrikstad are formed where the granitic basement is easier to erode in areas between the unaltered bedrock. It is interpreted that the fault and fracture spacing within the cliffs has a clear control on the distribution of the sedimentary systems. The smooth and steeply inclined surfaces that bound the joint-cut coves are interpreted as wave eroded fractures and faults. The size of the boulders in both areas clearly matches the spacing between fractures up section, indicating that these are ripped out clasts that experienced low amounts of transport and wave reworking. The lack of sphericity in both cases, the poor-to-moderate sorting and the recurrence of outsized boulders at the base of the cliffs is indicative of a low-to-moderate energy environment with occasional storms and/or gravitational collapses. The small terminations observed within the pocket beach at Capo di Feno are interpreted as local highs around which the deposits pinch out. The offshore highs and depressions observed in the bathymetric maps are interpreted as former rocky shorelines preserved and incorporated as part of the modern-day Corsican submarine platform, supporting the idea that these environments can get preserved in the geological record.

5. Discussion

5.1. Comparison of ancient and modern examples

The joint-cut coves and pocket beaches described on modern granitic rocky shorelines are interpreted as being potentially analogous, at least geometrically, to the ancient Miocene example described in the Limberg Quarry. The sedimentary infill in both cases, dominated by clast-supported, poorly-to-moderately sorted, subangular-to-subrounded conglomerates with local outsized boulders and small amounts of very coarse sandstone and gravels as matrix, indicates low-to-moderate wave energy conditions with occasional storms and/or gravitational collapses. The influence of storms on the accumulation of coastal boulders has been previously discussed and documented in modern examples (Paris et al., 2011) and ancient examples (Dewey and Ryan, 2017). The review in Paris et al. (2011) emphasizes the role of storms and hurricanes as plausible alternatives to tsunamis in order to explain these accumulations, even do the sedimentological criteria for distinguishing between both types is still limited and case dependent. Additionally, cliffs backing shore platforms are regarded as important boulder sediment sources. Boulders can be further transported and reworked once on the shore, reaching offshore positions up to cliff-top positions, being boulder beaches commonly found at the cliff-platform junction. Ancient examples of boulder accumulations are described in Miocene rocky shores of the Matheson Formation in New Zealand (Dewey and Ryan, 2017). Boulder accumulations there are interpreted to be mainly driven by tsunamis given the lateral extent of the deposits (80 km) and its inland extent (5 km inland from the reconstructed Miocene shore). The origin of the boulders shape is commonly interpreted as the result of plucking and mass collapse of the cliffs when the clasts are angular and as recycled and wave reworked boulders when they are rounded. Even do they suggested that joint and fracture spacing in the basement controlled the detachment and supply of blocks and boulders, something that we do observe and interpret in the Limberg Quarry, we emphasize that the subrounded shapes of the granite conglomerates needs to be interpreted carefully, especially when trying to link this with an specific wave regime. The effect of chemical and physical weathering on producing rounded granite boulders, like the ones observed in the Limberg Quarry, is well documented by several authors (Ollier, 1971; Durgin, 1977; Vasile and Vespremeanu-Stroe, 2016; Twidale and Vidal-Romaní, 2020). These weathering products tend to concentrate forming rather flat profiles in homogeneous and non-faulted terrains or they can be distributed forming highly asymmetric and irregular profiles in heterogeneous and structurally complex basements as documented in the granitic and low-grade metamorphic terrains of the Aravalli-Delhi Mobile belt in NW India (Pradhan et al., 2022) and the sub-Cretaceous inclined peneplain of the South Swedish Dome, in Sweden (Lidmar-Bergström et al., 2017). The weathering profiles there are highly irregular and show deeply incised weathered basement zones, 10's up to 100 m deep, which developed preferentially through fractures and faults. As mentioned in the description and interpretation of the deposits, the smooth and subvertical surfaces that bound the joint-cut coves are interpreted as wave-eroded faults and fracture planes. Consequently, we suggest that the joint-cut coves in the Limberg Quarry are exploiting former deeply weathered fractured and faulted zones which were subsequently exposed, modified by wave action and occupied by the sea during transgression of the area. The influence of these deep weathering profiles on the development of coastal landforms is documented along the coast of Darwin, in northern Australia (Nott, 1994), where coastal valleys and pocket beaches develop preferentially cutting through the areas where the weathering profiles are deeper and occupy a lower stratigraphic position, whereas headlands are formed in between, in areas where the weathering profile is thinner and stratigraphically higher. In terms of basement composition and geometry, there are very few cases of ancient granitic rocky shorelines described that compare with the Miocene Austrian sections. The studied joint-cut coves and its sedimentary infill can be compared with ancient examples coming from the Late Pleistocene of the Seychelles (Johnson and Baarli, 2005; Johnson, 2006). There, the deposits are confined within narrow depressions and abutted against steep walls of Precambrian granites. Some of them are represented by 2 to 3 m thick fining upward successions consisting of basal subrounded to subangular granitic boulders (up to 1.5–2 m) passing upwards towards much finer-grained fossil-rich carbonates with variable amounts of gravels, indicating marine reworking of the underlying basement (Johnson and Baarli, 2005; Johnson, 2006). The geometry and length of the unconformity at the middle section of the Limberg Quarry (430 m wide, 8 m deep, wedging laterally and with local pinchouts around basement highs) is potentially analogous to the length and geometry of the pocket beach at Capo di Feno, 200–300 m wide, bounded by headlands and with alternating veneers of sediment terminating laterally against small basement subcrops. No examples of described ancient pocket beaches directly comparable with the ones studied were found in the literature.

5.2. Occurrence, preservation and implications

Approximately 150 ancient rocky shores are documented in Johnson (1992) (Fig. 8A). The majority are described from the Cenozoic, Late Cretaceous and Cambro-Ordovician periods and are mainly characterised by sedimentary strata lying on top of a low relief unconformity (Johnson, 2006). Their morphology differs from that observed in modern systems, where heterogeneous rocky coastlines are characterised by steep and

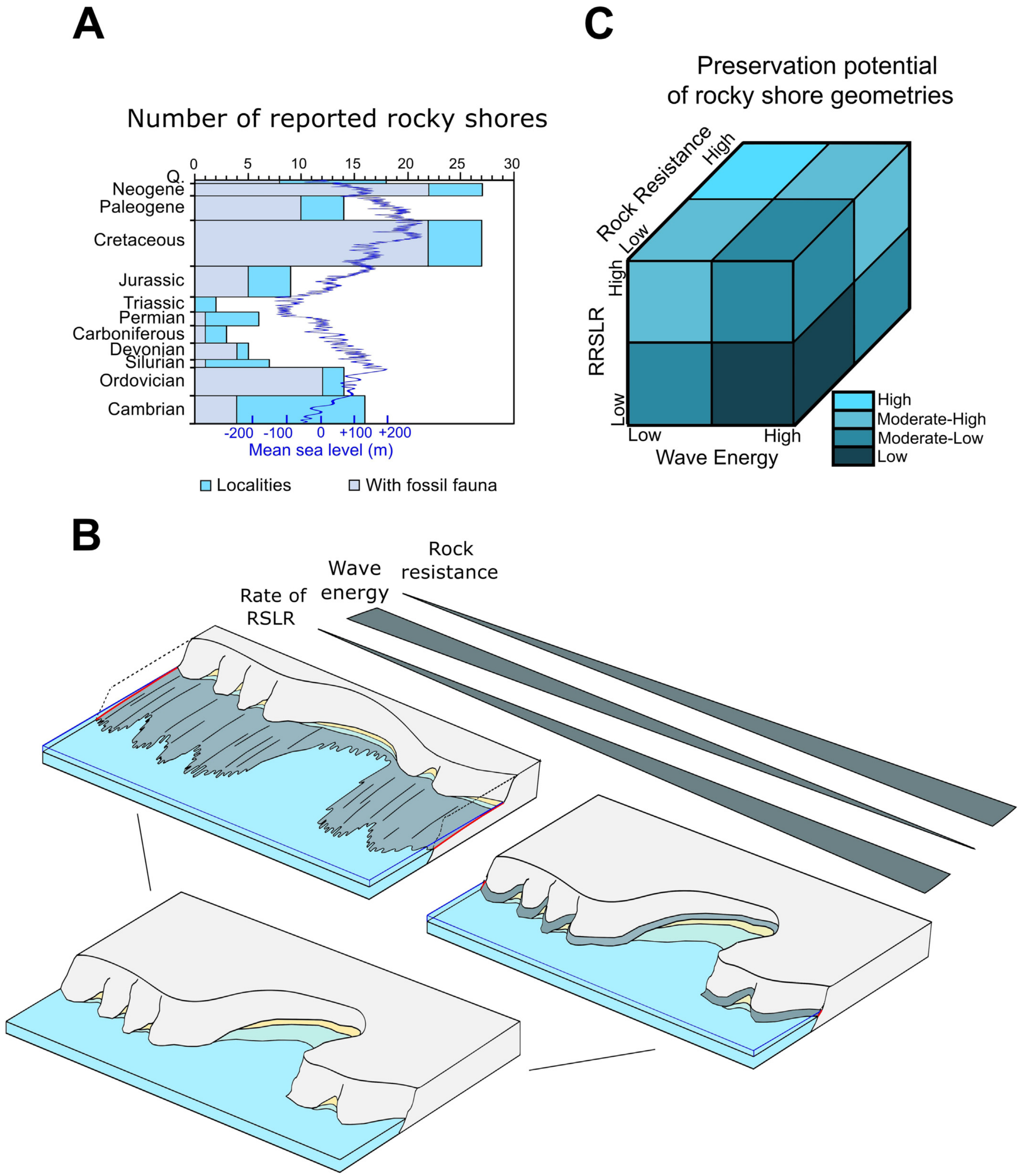

Fig. 8. (A) Reported rocky shores vs global sea level curve (modified from Johnson (1992), Haq et al. (1988) and Haq and Al-Qahtani (2005)). (B) Schematic representation of a rocky shoreline evolution and its endmembers resulting from applying different values of rate of relative sea-level rise (RRSLR), wave energy and rock resistance. (C) Matrix with the preservation potential of rocky shore geometries vs the different combinations of rate of relative sea-level rise, wave energy and rock resistance.

tall cliffs showing alternating headlands, joint-cut coves and numerous pocket beaches. This suggests that despite being common in modern rocky coasts, pocket beaches and joint-cut coves are not necessarily well preserved (or adequately recognized) in the rock record. It is therefore interesting to consider what factors control their preservation. Thus, we interpret that the high rates at which sea level rose during the Neogene and Quaternary could be one of the main factors controlling preservation of rocky shoreline geometries. The Neogene and Quaternary were icehouse periods (i.e., periods of the Earth with a fluctuating ice sheet cover) mainly characterised by glacio-eustatic sea level cycles of high magnitude (e.g., 40–60 m-Ma in Early Miocene up to 130 m-100Ka in Middle Pleistocene-Holocene) (Miller et al., 2020). These values are higher than the calculated 15–30 m-Ma for the Late Cretaceous-Eocene periods (Miller et al., 2005) and the estimated rates for the Mesozoic curves of Haq and Al-Qahtani (2005). Rapidly rising sea levels would quickly place the shoreline below wave base, decreasing the amount of time that cliff sections were eroded, and consequently increasing the preservation of rocky coastal reliefs. Static or slower rates of sea level rise allow longer periods of erosion and the development of subhorizontal wave cut platforms (Fig. 8B). In the case of the Bohemian Massif, rapid rates of relative sea-level rise were enhanced by fault-related subsidence favouring the preservation of the pocket beach geometries and their deposits. Additionally, wave energy and rock resistance are also interpreted as key controls on preservation of rocky shorelines. Low wave energy environments like the ones studied have less erosional capacity and take longer to peneplane any given cliff section. Finally, rock mechanical and chemical resistance to erosion is a function of lithology (Prémaillon et al., 2018). In the case of the granites on the Bohemian Massif, fractures and chemical weathering weakened the rock and locally enhanced faster erosion rates of the cliffs, which were compensated due to the low wave energy conditions and rapid rate of sea-level rise. As a consequence, we propose that erosion rate and preservation potential of rocky shoreline geometries and deposits is controlled by the resulting combination of rate of relative sea-level rise, mean wave energy and bedrock resistance (Fig. 8C). These observations suggest that the different sedimentary systems within a rocky shoreline and their deposits might be more common in the geological record than previously thought. This has potential implications for coastal management and subsurface hydrocarbon exploration around structural highs. Interest around structural highs has experienced a recent increase, especially in the Norwegian Continental Shelf, with multiples reservoir discoveries around the Utsira High and others (Rønnevik et al., 2017; Ottesen et al., 2022). Some of these highs are composed of granitic rocks which were exposed for a long period and drowned in the Late Jurassic-Early Cretaceous (Riber et al., 2015). Consequently, they became islands which experienced variable rates of marine erosion as they were being transgressed, potentially developing and preserving rocky shoreline deposits locally. Depending on the reservoir properties, ancient rocky shoreline deposits could have a positive impact, defining new reservoirs and increasing the extent of an oil field or have a negative impact on production, especially from fractured basement plays, where they can act as conduits or barriers to flow. The fact that they tend to develop preferentially following fractures, faults and lithological contacts can provide with a predictive model to study their distribution in the subsurface and in other less well-exposed transgressive successions.

6. Conclusions

The stratigraphic and sedimentological analysis of both ancient and modern rocky shoreline deposits associated with granitic basements has allowed us to provide diagnostic criteria for their recognition and discuss the main controls on their occurrence and preservation in the rock record. Rocky shoreline deposits are often abutted against steep basement walls and confined within narrow depressions, in the case of joint-cut coves, or much wider embayments, in the case of pocket beaches. Both types of sedimentary systems are represented by fining upward successions consisting of basal subrounded to subangular granitic boulders passing upwards towards much finer grained fossil-rich deposits with variable amounts of gravels, indicating marine reworking of the underlying basement. Our study suggests that these systems can have a higher preservation potential than what is commonly reported in the geological record. According to our results, in order to avoid erosion of the rocky shoreline deposits and subsequent development of subhorizontal wave cut platforms certain conditions need to be meet, which are: 1) rapid rates of relative sea-level rise under 2) storm-affected, low-wave energy environments affecting 3) relatively resistant cliffs. If such conditions prevail, then joint-cut coves and pocket beaches developed along fractured and weathered basement zones might get preserved. These results shed new information to better understand this type of environments and provide a mechanism for predicting their potential distribution and preservation during transgression of rocky coastlines, with potential applicability on subsurface exploration around structural highs, but also coastal management and under current and projected sea-level rise.

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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