Transgressive rocky coasts in the geological record: Preserved or eroded? Insights from Miocene granitic rocky shorelines and modern examples.

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ABSTRACT

Most of modern shorelines are in net erosion. Among these, rocky shorelines are commonly punctuated, with alternating high relief cliffs an 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 hollows 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 Corsica, Spain and Norway. The excellent preservation of the ancient examples offers a unique 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, and under storm-affected, low wave energy conditions along lithological, structural and weathered "weakness" zones. 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.

Keywords: rocky shorelines, granitic basement, pocket beaches, joint-cut hollows, conglomerates, transgressive

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 meters 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 hollows. 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 hollows 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 hollows 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, northern Austria, and compares them to modern systems in 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 hollows 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 (Sheppard, 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 for approximately 500 m2 and exposes 3 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. These images 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. These models were exported and imported into LIME, a 3D interpretation software (Buckley et al., 2019) which was used to map the geometry and extent of the unconformities and the different geomorphological features. Additionally, 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. 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. 3). The Bohemian Massif is a Proterozoic-Palaeozoic crystalline high. In the Austrian sector, the south-eastern boundary of 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. It is characterized by numerous tectonically induced domes and ridges of the Thaya granite (600-570 Ma) which parallel several N-S Miocene extensional faults. 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, characterized 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 hollows 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 hollows, where it crops out above the sedimentary infill (Fig. 4B). The hollows are bounded by smooth and subvertical surfaces with opposing dips (Fig. 4B and C). Two hollows are exposed at the western section which are separated by a small granitic promontory (Fig. 4B). The one at the left is 6 m wide and 10 m deep whereas the one in the right is 3.7 m wide and 7.5 m deep. The same geometry is observed at the eastern section (Fig. 4C) which exposes a 5 m wide and 6 m deep hollow. The infill of these hollows 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. 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 more than 500 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 characterized by a 1 m thick basal conglomerate overlain by 3 m of fining upwards, coarse to fine-grained sandstones (Fig. 5C and D). 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.

4.1.2. Interpretation

The composition of the clasts suggests the underlying granitic basement is the main sediment source. Their 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 hollows and pocket beaches within a rocky shore (Fig. 6). The subvertical and smooth surfaces that bound the hollows in the western and eastern sections of the quarry are interpreted as the result of erosion of conjugate fault or fracture planes. The wider and scoop-shaped depression observed in the middle section is interpreted as a preserved pocket beach. The lateral thinning of the deposits towards the margins of the pocket beach indicates a termination against a palaeo-relief, probably two headlands, one in each margin. 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 hollows 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 areas 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 hollows 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 hollows 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 mostly 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 definitively possible to interpret how much of the shape is inherited or created due to wave reworking, the lack of spherical particles points towards low flow competence, not consistent with these particles being rounded on the beach, and supporting the interpretation of a low to moderate energy environment. The different morphology of the incisions along with the interpretations about the energy conditions suggest deposition occurred in narrow and elongated joint-cut hollows, which passed laterally, along the shore, towards wider pocket beaches. These pocket beaches where bounded by large headlands that absorbed much of the wave energy during normal conditions. It is inferred, based on the observation of modern analogues (see below), that the occurrence of the pocket beaches is often coincident with major faults that experienced higher erosion rates than the surrounding coastline (Fig. 7E and F). This would generate a preferential erosion of this section creating a wider and deeply incised embayment (Fig. 6, 7F**)**

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 hollows cut along the bedrock (Fig. 7A-D). Both areas are characterized by a mean significant wave height around 0.5 m (Soukissian et al., 2017;

Norwegian Coastal Administration, 2022). Occurrence and development of hollows 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, hollows 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.

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 characterized by alternating pocket beaches, 200-300 m wide and large headlands that host multiple hollows 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 hollows in the coast of Capo di Feno.

4.2.2 Interpretation

The hollows 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 hollows 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 hollows and pocket beaches described on modern granitic rocky shorelines are interpreted as being potentially analogous 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. On the other side, there is a general agreement that these accumulations respond to high-energy events, including landslides and gravitational collapses, and that cliffs backing shore platforms are an important sediment source for boulders. Additionally, these 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). The base of the formation is chaotic and consists mainly of non-imbricated angular and subangular boulders up to 143 tons and, in minor proportion, smaller rounded to subrounded boulders. There, the accumulations 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, given that many cobbles and boulders where probably already rounded due to chemical and physical weathering before being further reworked by waves. The effect of chemical and physical weathering on producing rounded granite boulders 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 (Pradhan et al., 2022). The presence of faults and fractures in granitic and crystalline basements has a direct influence on the development of deep weathering profiles, 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 meters 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 hollows are interpreted as wave-eroded faults and fracture planes. The geometry and dimensions of the joint-cut hollows in the modern examples (1-4 m wide and 1-10 m high) is very similar to the incisions observed in the western and eastern sections of the Limberg Quarry (3.7-7.5 m wide and 6-10 m high), supporting the interpretation of these being former joint-cut hollows within an ancient rocky shoreline. Consequently, we suggest that the joint-cut hollows 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 hollows 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 meters) passing upwards towards much finer-grained fossil-rich carbonates with variable amounts of gravels, indicating marine reworking of the underlying basement. The geometry and length of the unconformity at the middle section of the Limberg Quarry (500 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 subcrops of basement. 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 characterized by sedimentary strata lying on top of a low relief unconformities (Johnson, 2006). Their morphology differs from that observed in modern systems, where heterogeneous rocky coastlines are characterized by steep and tall cliffs showing alternating headlands, joint-cut hollows and numerous pocket beaches. This suggests that despite being common in modern rocky coasts, pocket beaches and joint-cut hollows 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 mainly characterized by glacio-eustatic sea level cycles of high magnitude (e.g., 40-60 meters-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 meters-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 sub-horizontal 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 el 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 hollows, 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 hollows 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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FIGURES AND FIGURE CAPTIONS

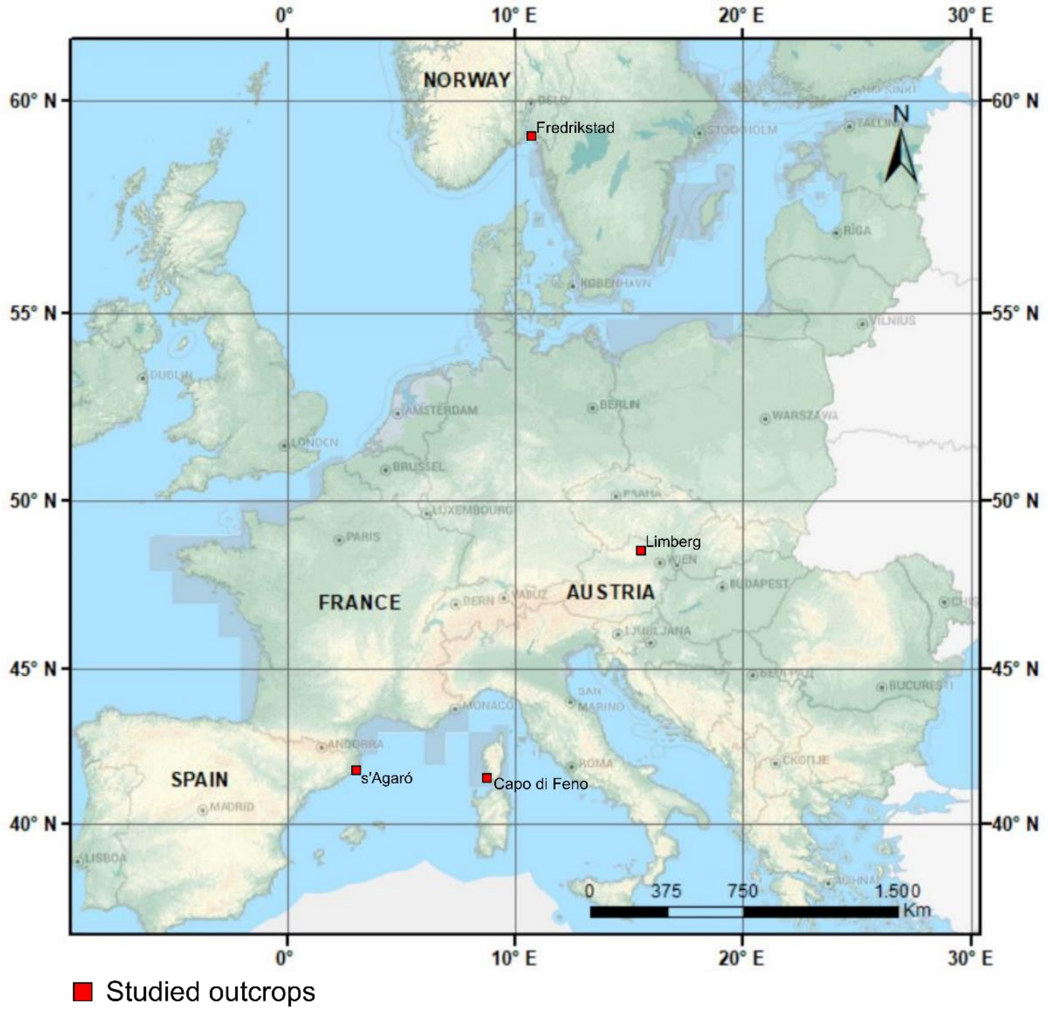

Figure 1. Digital elevation model of Europe with the main countries and outcrops studied. (modified map from www.mapsforeurope.org)

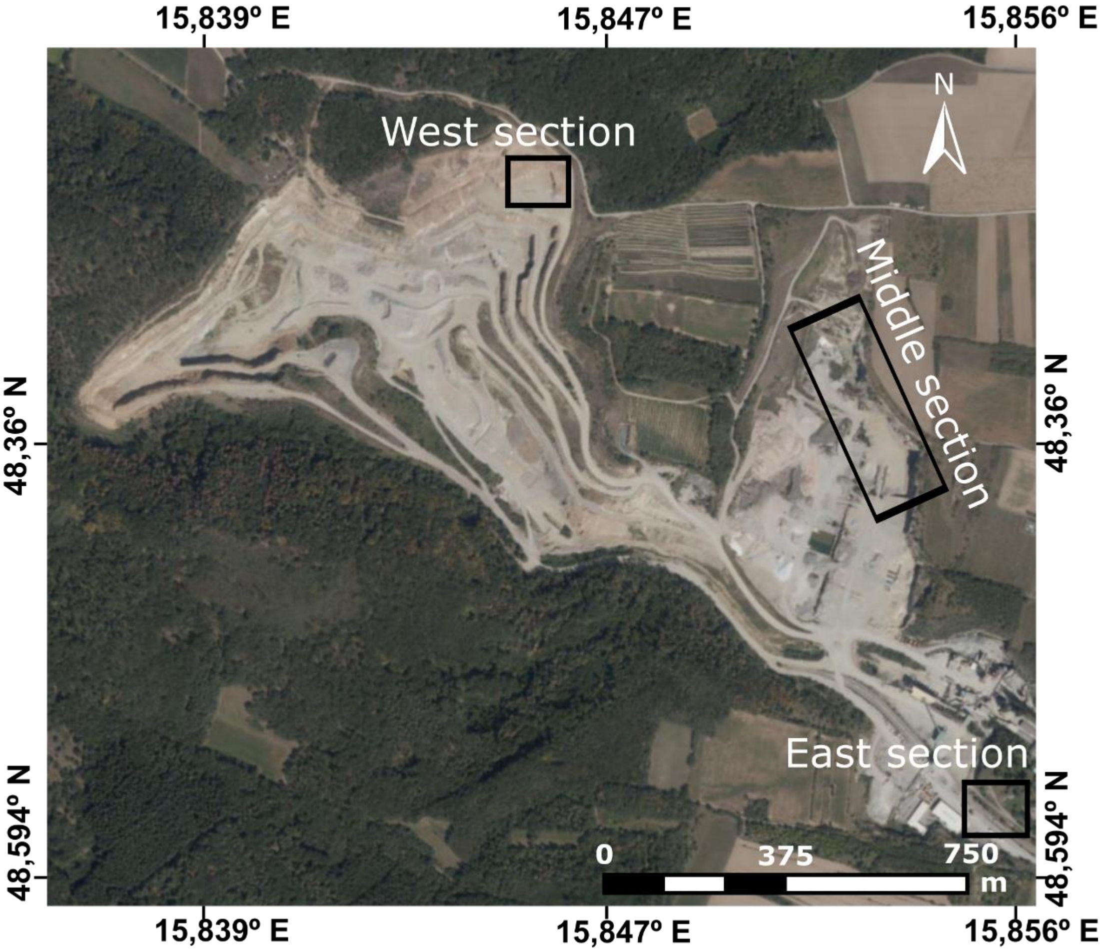

Figure 2. Orthophoto with the location of the Limberg Quarry. Three sections have been studied in this work, one at the west, one at the east and another one in between (middle section) (orthophoto from www.basemap.at).

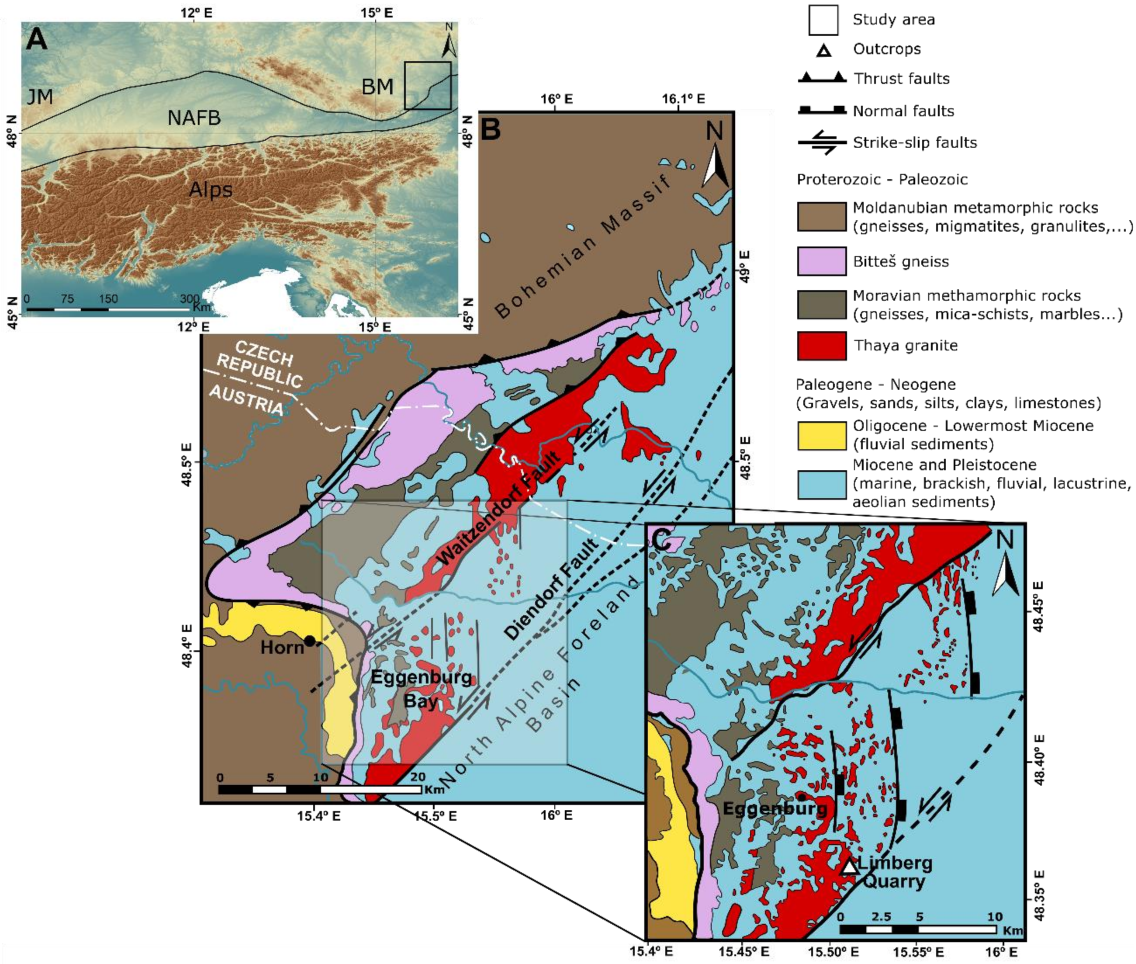

Figure 3. (A) Digital elevation model of the Alps (JM: Jura Mountains, BM: Bohemian Massif, NAFB: North Alpine Foreland Basin) (data from www.land.copernicus.eu). (B, C) Geological maps of the south-eastern margin of the Bohemian Massif in Lower Austria showing the studied outcrops, local structures and stratigraphy (modified from Roetzel et al., 1999 and Roštínský and Roetzel, 2005).

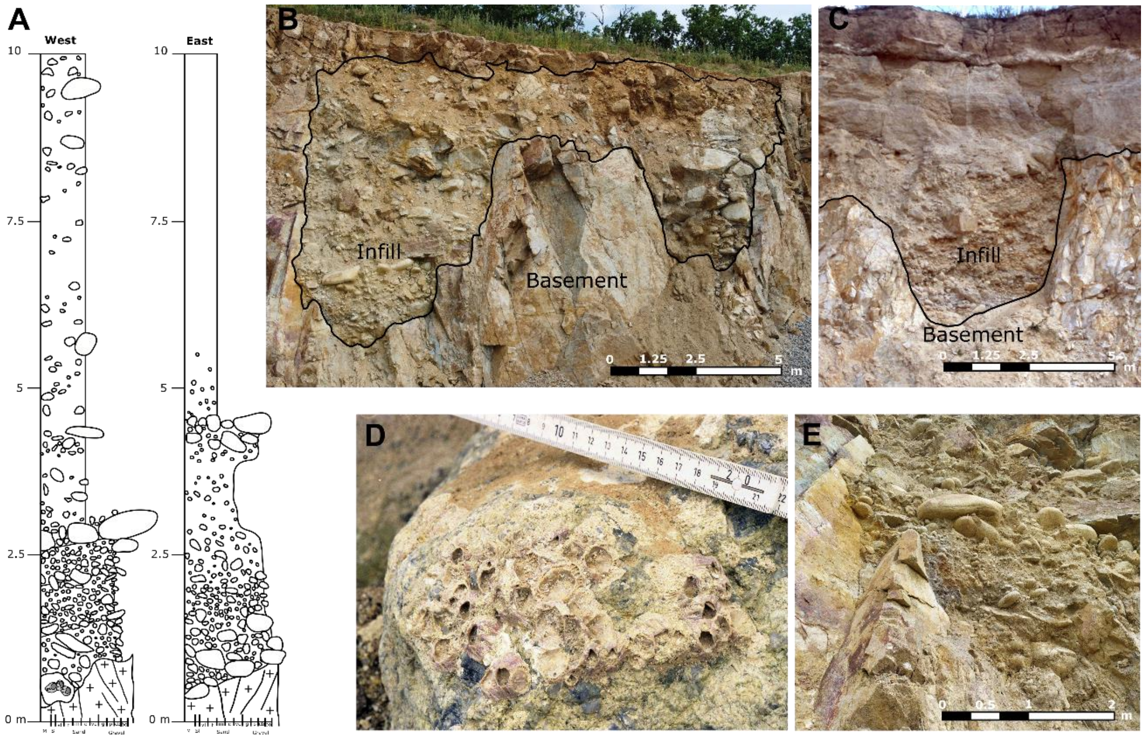

Figure 4. (A) Stratigraphic logs of the western and eastern sections of the Limberg Quarry hollows. Note that both show a marked fining-upwards trend with a basal part dominated by poorly-to-moderately sorted conglomerates and an upper part composed of variably sorted sandstones. (B, E) Western section of the Limberg Quarry hollows and detail of its sedimentary infill. Note imbricated boulders at the base of the hollow. (C) East section of the Limberg Quarry hollows, note the sharp contact between conglomerates and sandstones. (D) Example of barnacles attached to a boulder surface.

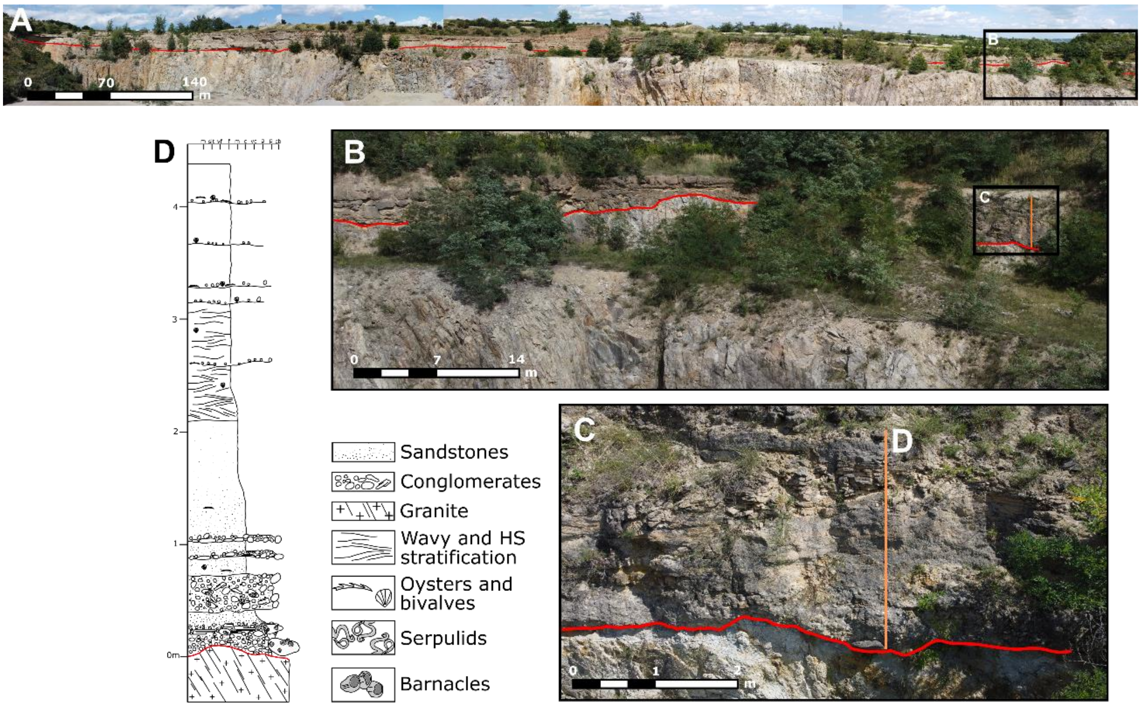

Figure 5. (A) Photopanel of the middle section showing the extent of the scoop-shaped erosional unconformity. Note how the succession thins towards the margins suggesting a nearby termination. (B) Detail of the basal erosional surface, note the local high and how the sediments onlap around it. (C and D) Logged section showing the stratigraphic succession and the sedimentary log, respectively. Note the well-developed finning-up trend, consistent with a transgressive succession.

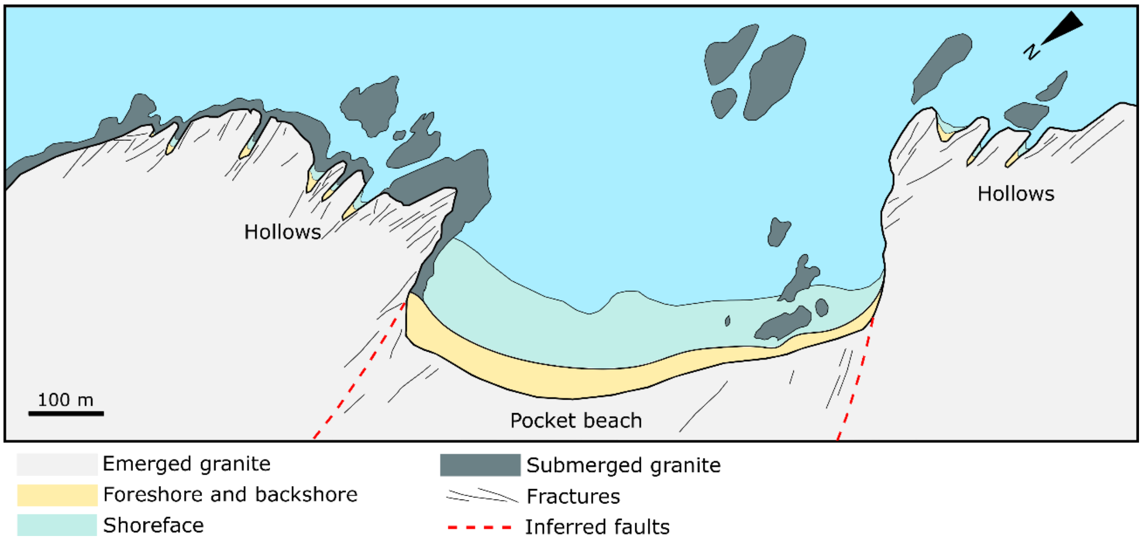

Figure 6. Paleogeographic reconstruction of the Limberg Quarry shore. Hollows are observed at the western and at eastern section, while a pocket beach developed between in the middle section. This configuration is frequently observed in modern rocky shorelines, hollows develop along bedrock fractures, in sections of the coastline that occupy a more seaward position and are therefore more exposed. 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 that tend to experience higher erosion rates than the fractures that bound the hollows.

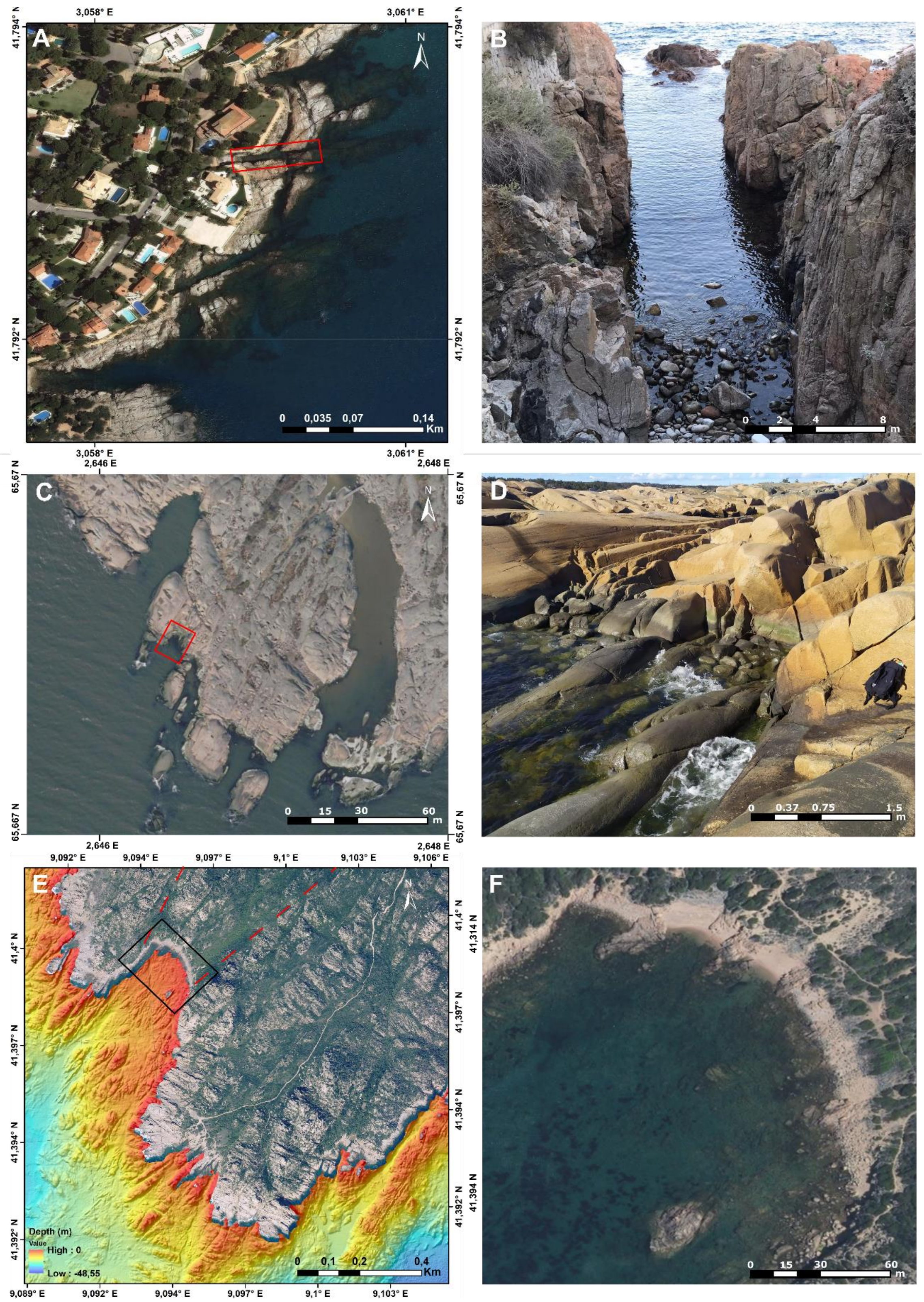

Figure 7. Modern hollows at s'Agaró (A, B) and Fredrikstad, Norway (C, D). Hollows are mainly developed along fractures and faults (orthophoto in A and C from www.icgc.cat and

www.norgebilder.no). (E) Composite image of Capo di Feno, Corsica, showing the alternating hollows 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.

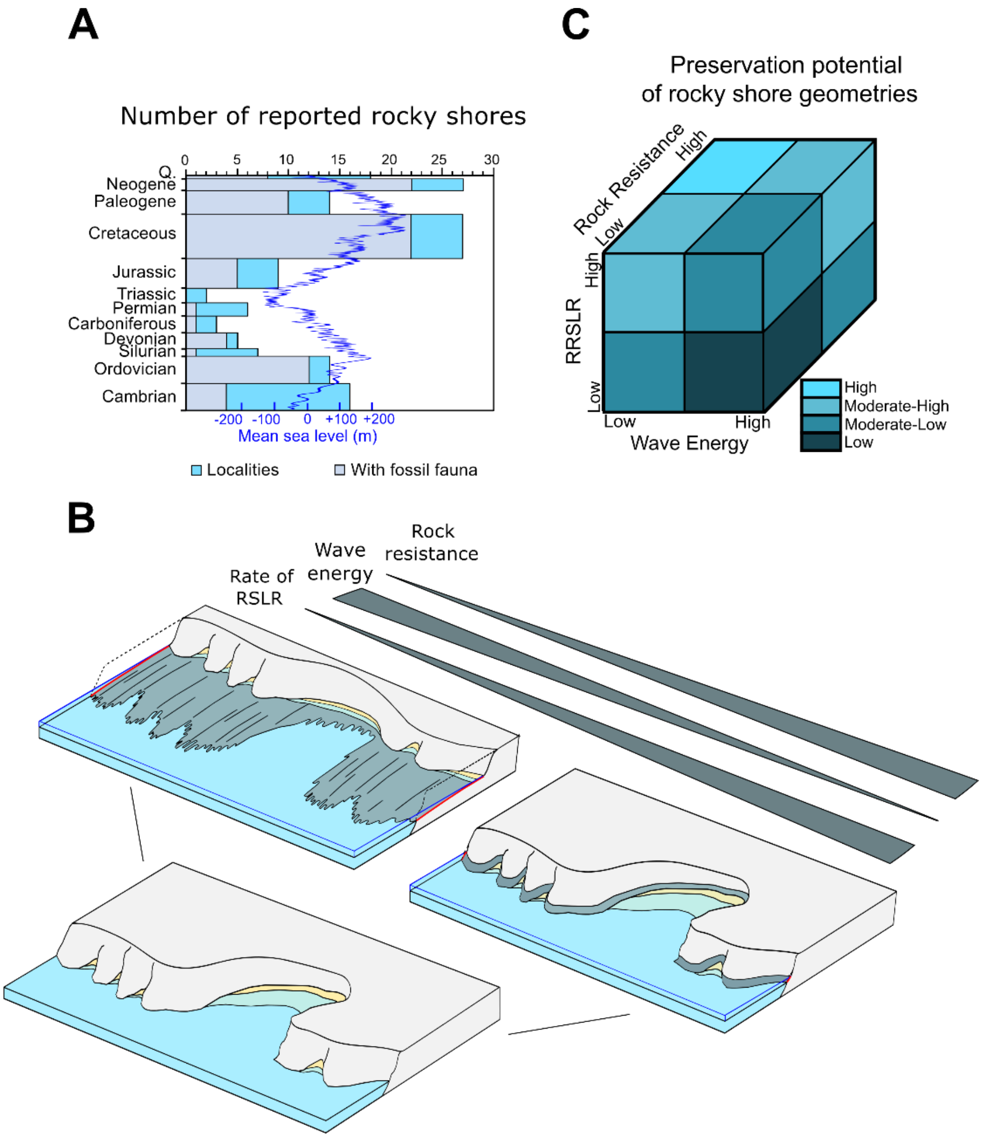

Figure 8. (A) Reported rocky shores vs global sea level curve (modified from Johnson (1992) and Haq and Al-Qahtani (2005)). (B) Schematic representation of a rocky shoreline evolution and its endmembers resulting from applying different values of rate of relative sea-level rise (RRSLR), wave energy and 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.