Facies models for rocky shorelines and their application to transgressed basement highs in the North Sea.

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Abstract

Rocky shorelines form where basement highs are eroded and flooded during marine transgressive events. Despite the Mesozoic North Sea rift generated numerous platform margins and rotated fault blocks which acted as basement highs, rocky shoreline deposits have not been previously reported. In the rock record rocky shoreline deposits are usually represented by thin conglomerates overlying major unconformities, and are typically characterised by their ichnological aspects, rather than their depositional facies. This study uses the sedimentological aspects of modern and Miocene rocky shoreline conglomerates from Spain and Austria, to create facies models which are then applied to the recognition of rocky shorelines in the Mesozoic of the Central North Sea. Our results demonstrate that structureless, clast-supported, poorly-to-moderately sorted conglomerate deposits are associated with competent basement lithologies, which produce hard, resistant coastal cliffs in areas associated with volcanic centres which were previously overlooked in the subsurface. The basement lithologies in most of the

Central North Sea favoured the formation of smaller coastal cliffs, with less resistant lithologies that did not generate or preserve gravel size particles, precluding the preservation of Mesozoic rocky shores in much of the North Sea's stratigraphic record.

Shallow marine conglomerate deposits are usually associated with recessional coastal cliffs where preexisting geological formations are eroded to form rocky shorelines (Sunamura, 1992; Trenhaile, 2016). The sediments on these beaches originate from marine erosion of coastal cliffs with minor input from redeposited fluvio-deltaic and alluvial deposits typically entering the sea through small rivers and streams. The proximal portion of a rocky shoreface is usually characterised by gravels or a mixture of gravel and sand sized particles which accumulate in pocket beaches and joint-cut coves, typically forming relatively thin veneers on a bedrock unconformity (Bluck, 1967; Bowman et al., 2009; Hayes et al., 2010; Klein et al., 2010; Balouin et al., 2014; Sammut et al., 2017; Lapietra et al., 2022; Puig et al., 2023). Deposits become progressively sandier and more fossiliferous in a basinward direction. Previous studies on shallow marine conglomerates, and particularly, on conglomeratic rocky shoreline deposits, are relatively scarce and the significance of such deposits remains poorly understood (Johnson, 1992; Clifton, 2003; Johnson, 2006). The majority of previous studies have focused on the palaeontological and ichnological aspects of the basal unconformity or the overlying sandier deposits (Domènech et al, 2001; Santos et al., 2008; Santos and Mayoral, 2009; Brlek et al., 2016; Buatois and Encinas, 2011; Martinell et al., 2021). The identification of the rocky beach conglomerate deposits remains ambiguous in the absence of fossil data, which is a recurrent feature, since harsh conditions in the proximal portions of coarse grained gravel shorefaces and the absence of sandy substrates limits the preservation of benthic marine fauna typically used to infer marine depositional conditions (Dashtgard, 2008; Pemberton et al., 2012). Despite some works dealing with the lithological and sedimentological aspects, the conglomerates have received far less attention (Hart and Plint, 1989; Lescinsky et al., 1991; Hart and Plint, 1995; Gupta and Allen, 1999; Felton, 2002; Bluck, 2011; Rousse et al., 2012; Evans and Holm-Denoma, 2017). Sedimentary structures in conglomerates are often crude and poorly developed. Conglomerates can be formed in a variety of different sedimentary environments: glacial, fluvial, alluvial, lacustrine, shallow or deep marine (Barrell, 1925; Nemec and Steel, 1984; Higgs 1990; Mueller et al., 2000; Bennett et al., 2009; Stéphan et al., 2012; Strzelecki et al., 2017, Henriksen et al., 2018; Changmin et al 2020; Zhi et al., 2023), and there presence is definitive of any given environment, increasing the chances of misinterpreting their depositional environment in the absence of fossil data. There are only around 200 rocky shore cases described in the geological record (Johnson, 1992; 2006), all of them from outcropping onshore successions that are associated with low relief ravinment surfaces. The low number of reported examples may suggest that they are rarely preserved, however a recent study about the preservation potential of transgressed Miocene rocky shoreline morphologies and depositional systems demonstrated that they do occur (Puig et al., 2023). In addition to the onshore scarcity of examples, none have ever been reported from subsurface study cases, although the geological record registers a significant number of transgressed basement highs (Peacock and Banks, 2020). Building on these observations, the aim of this paper is to describe the characters of conglomeratic rocky shoreline deposits with the objective of identifying overlooked examples around subsurface basement highs in the North Sea. Furthermore, to explain the absence of rocky shoreline deposits on highs where they are not present.. To accomplish these objectives, we first studied modern gravelly shorelines in Spain, where information about the different depositional zones and sediment type was recorded and then used to complement the description and interpretation of three different Miocene rocky shore successions formed above sedimentary, metamorphic and igneous basement rocks (Fig. 1). The resulting observations were used to create facies models which were then applied to the Upper Jurassic and Lower Cretaceous systems in the Western Margin of the Central North Sea Graben (Fig. 2).

Geological setting

Rocky shoreline deposits form along recessional or erosional coastlines, which constitute 72% of modern-day coastal length (Nyberg and Howell, 2016). The Holocene continental configuration is highly fragmented, with approximately 734.000 km of measured cumulative coastal length (≈ 2.5 million km including small islands) (Liu et al, 2019). This length is slightly higher (10-15%) than the one calculated for the rest of the Neogene and Cretaceous periods (Johnson, 2006), two of the most prolific time intervals for the development and preservation of ancient rocky shores (Johnson, 1992). Rocky shores tend to proliferate during periods of continental and epicontinental flooding associated with rifting and continental break-up, foreland subsidence during orogens is also a driving mechanism. This is exemplified in the studied Miocene outcrops which form part of a complex Cenozoic rift system developed in Western Europe coincident with the late phases of the Alpine Orogeny in the Alps and the Pyrenees (Fig. 1) (Ziegler, 1992a).

The section studied in Tarragona, SE Spain, forms part of the Tarragona Sequence and was deposited during the Middle Miocene in the Valencia Trough, an extensive Neogene system of horst and grabens (Roca and Desegaulx, 1991; Domènech et al., 2001; Etheve et al., 2018).

The Tortonian-to-Messinian Azagador Member studied in Sorbas, S Spain, and the Burdigalian Burgschleinitz Formation in Limberg, N Austria, were deposited in intermontane and foreland basins developed during the structuration of the Betic cordillera and the Alps, respectively (Kuhlemann and Kempf, 2002; Braga et al., 2003; Roštínský and Roetzel, 2005; Rodríguez-Tovar et al., 2015; Nehyba and Roetzel, 2021).

The subsurface examples studied form part of an extensive Mesozoic rift-system developed in the North Sea during the opening of the North Atlantic (Fig. 2A) (Ziegler, 1992b). The main phase of crustal thinning occurred during Middle-Late Jurassic/Early Cretaceous times, resulting in the generation of large, rotated fault blocks, typically referred as basement or structural highs, due to their significant elevation respect to the surrounding areas (Faleide et al., 2010; Peacock and Banks, 2020). These were deeply eroded locally, exposing older sedimentary, metamorphic and crystalline bedrock, and shedding the erosional products into the adjacent basins. The sediments were mainly deposited in shallow-to-deep marine half-grabens on the footwall side of tilted fault-blocks and wider rift-margin platforms or terraces, characterised by the development of shallow marine shorefaces (Fig. 2B). The studied subsurface successions include the Late Oxfordian - Late Kimmeridgian, Fulmar Formation and younger Aptian-Albian Cromer Knoll Group deposits, studied in the West Margin of the Central North Sea Graben, which mainly overly Permian, Triassic and Middle Jurassic rocks of the Zechstein, Skagerrak and volcaniclastic Pentland formations, respectively (Donovan et al., 1993; Price et al., 1993; Patruno et al., 2022; Copestake and Partington, 2023), along with younger Hauterivian basalts in its southern margin, on the Auk Ridge (Trewin et al., 2003).

Data and methodology

Fieldwork was carried out during 2020 and 2021. Detailed sedimentary logs were collected from each of the onshore Miocene examples, 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 (Buckley et al. 2008) following the method outlined in Howell *et al.*, (2021). Images were first imported and georeferenced into Agisoft PhotoScan, a photogrammetry software used to reconstruct the geometry of the outcrops and create 3D models based on the identification of common points between images. The sedimentary logs were digitised in Inkscape, an opensource drawing software. Modern day conglomeratic rocky shorelines along the mediterranean coast of Spain, specifically, Ibiza and Catalonia, were also studied in order to complement the facies analysis and interpretation of the ancient examples described. Aerial and submarine photos of the backshore-to-shoreface transition were acquired using a water-proof GoPro camera attached to the chest. Images were automatically shot each 0.5 seconds. A 25 m long rope, with 10 cm white tape subdivisions, was extended along the beach transect to scale the objects in the images. The images were combined to create orthomosaics and photogrammetric models of the modern beaches, which were used to subdivide and study the different depositional zones, following the same methodology previously described for the UAV virtual outcrops. An open-source well core database from the British Geological Survey was used to locate candidates for subsurface rocky shore deposits along the western margin of the Central Graben in the North Sea. A total of 15 wells with cores through the basal portion of transgressive sequences over preexisting lithified substrates were logged. Sedimentary logging, recording the same information described for the Miocene examples, was performed remotely using high resolution images in a similar methodology described by Puig *et al.*, (2024) (Chapter Methods).

Results

Modern day gravelly rocky shoreline deposits.

Modern shallow marine gravels were studied in Sant Feliu de Guixols, Catalonia, and Ibiza, Balearic Islands (Fig. 3A and 3B). Both coasts are microtidal with a mean annual significant wave height of 0.5 - 0.8 m (Soukissian et al., 2017). The beach in the Sant Feliu coast overlies highly fractured Hercynian granitoids and is characterised by a steeply dipping (25º), reflective profile (cross section in Fig. 3C). The Ibiza example, overlies a Jurassic carbonate basement, showing a gentler (7º) dipping, dissipative beach profile (Fig. 3D). Both examples show common geomorphological features, including a landward dipping backshore zone, a seaward dipping beachface zone, a break in slope attributed to the beach step and a gently dipping, submerged, upper shoreface zone (Fig. 3C and 3D). The backshore zone is dominated by well-to-moderately sorted cobbles and boulders, (15-30 cm), whereas the Ibiza example is characterised by moderately-to-poorly sorted pebbles, 3-6 cm, and cobbles, 8-20 cm. In the Sant Feliu coast, a storm berm appears at the junction between the backshore and the beachface (Fig. 3C). The stoss side of the berm dips landwards, whereas the lee side dips seawards. The berm is a thin zone, representing 20% of the beach sediment volume, and is mainly characterised by well-to-very well sorted pebbles, 5-6 cm, and minor amounts of cobbles, 8-12 cm. Most of the beach sediment is accumulated in the beachface, comprising up to 60% of the total vertical thickness. This zone is subaerially exposed under normal wave energy conditions, and mainly characterised by cobble size particles. Clast size increase down the beachface, while sorting decreases, passing from moderately sorted pebbles, 5 cm, and cobbles, 10-20 cm, in the upper beachface, to moderately-to-poorly sorted cobbles, 15-25 cm, and boulders, 30-45 cm, in the lower beachface (Figs. 3C and 3D). Pebbles and cobbles are slightly imbricated along the upper and lower beachface zone, especially in the Sant Feliu beach. The base of the beachface is marked by a break of slope which marks the transition to the upper shoreface zone. The upper shoreface zone dips gently, reaching a maximum depth of 3 meters in Sant Feliu and 2 meters in Ibiza. It represents around 20% of the beach sediment volume, and is dominated by boulders characterised by moderate-to-poor sorting, which are angular-to-subrounded, blocky-to-discoidal, 30-40 cm up to 80 cm, with minor amounts of cobbles, 10-20 cm. No sand size particles where found along the Sant Feliu profile, indicating the existence of a bypass zone which prevents its deposition (Fig. 3C). A zone of sand deposition was present at the lower couple of meters of the Ibiza transect and extended further offshore. This was interpreted as the middle shoreface. The contact between the boulder covered and sand covered zones appears as an abrupt facies change, with no transitional sediments in between, placing coarse-to-medium grained sands directly in contact with upper shoreface boulders (Fig. 3D). A series of synthetic logs show that the described sedimentary sequence, in case of beach progradation, would be rather structureless, thin and characterised by a sharp based diastema at the upper to middle shoreface contact, overlain by a general fining upwards trend up to the backshore/berm level (Figs. 3C and 3D).

Outcropping Miocene conglomeratic rocky shoreline deposits

The studied Miocene successions unconformably overlie much older basement rocks (Figs. 4A, 5A and 6A). All three show a clear fining upwards trend and a threefold stratigraphic subdivision into i) a basal part consisting of moderate-to-poorly sorted, clast-supported, subangular-to-subrounded, pebble-to-boulder conglomerates, ii) a middle part consisting of basement derived moderate-to-well sorted, medium-to-very coarse grained sandstones and iii) an upper part characterised by fossil rich, well-to-very well sorted, medium-to-fine grained sandstones (Figs. 4B, 5B and 6B).

Sedimentary basement: The Jurassic carbonate cliffs of Tarragona, Spain.

The basal part is 2.5 m thick and consists of spherical and blocky-shaped, poorly sorted, angular-to-subrounded clast-supported boulders and cobbles (30-60 cm and 8-10 cm, respectively) (Fig. 4C). These grade upwards progressively into moderately sorted cobbles and moderately-to-well sorted, subrounded-to-rounded pebbles (1-4 cm) (Fig. 4C). Bed boundaries are diffuse and sedimentary structures absent, giving the package a rather massive and structureless aspect. *Gastrochaenolites* and *Entobia* bioerosional traces are found along the basal unconformity surface and in the conglomerate clasts (Figs. 4D and 4E). The conglomerates are barren of skeletal fossil remains, normally graded, and stacked forming a clear fining upwards trend. The middle part of the package is 0.75 m thick and denoted by an abrupt and poorly sorted pebble lag (1-2 cm in particle size) very rich in echinoderms of genus Clypeaster (Fig. 4F). This interval fines upwards into moderate-to-well sorted pebbles (6-7 mm) and granules. Fossils are scarce and include gastropods, bivalves and echinoderms. The upper part is 1 m thick and is characterised by fossil rich, well-to-very well sorted, medium-to-very coarse grained bioclastic sandstones and granules forming highly monospecific and vertically stacked levels of tightly packed coralline algae, bivalves and echinoderms. A very bioturbated level appears towards the top of the section, which is mainly affected by vertical burrows resembling *Ophiomorpha* (Fig. 4G).

Metamorphic basement: The Permian gneissic cliffs of Sorbas, Spain.

The basal part is 3 m thick and dominated by poorly-to-moderately sorted clast-supported conglomerates. The basal conglomeratic part is internally stratified and subdivided into three different intervals, each 1 m thick: i) a lowermost, normally graded and fining upwards boulder-to-cobble interval (40-60 cm particle size down to 15-30 cm), ii) an intermediate, structureless and relatively finer grained pebble and cobble interval (4-to-20 cm in particle size) and iii) an uppermost, reversely graded and coarsening upwards cobble-to-boulder interval (20 cm particle size up to 60 cm) (Figs. 5C and 5D). The three levels show local, faintly imbricated gravels. *Gastrochaenolites* bioerosional traces are found affecting outsized boulders particles, up to 60 cm long, at the top of the uppermost division (Fig. 5C). The sorting of the conglomerates is moderate-to-poor and relatively constant, in contrast, roundness and sphericity are more variable, with angular and subangular boulder-to-cobble sized blocks and subangular-to-subrounded spherical and discoidal clasts (Fig. 5D). Pebbles, from 3 to 6 cm, and cobbles, from 8 to 20 cm, are found filling the interparticle space of the previously described intervals. The middle part of the succession is also 1 m thick and characterised by greyish, well sorted, coarse-to-medium grained sandstones. The contact between the underlying conglomerates and the sandstone deposits is a sharp and gently dipping surface. Sandstones lack fossils and contain small amounts of floating granules and pebbles. The upper part is ochre in colour and more than 10 m thick, composed of reworked coralline algae forming tightly packed rholodithic rudstones. A lateral facies change is observed between the underlying deposits and the overlying rholodithic rudstones, which are indented towards the downdip portion of the outcrop. Rhodolith facies are well-to-very well sorted and massive (Fig. 5E), although thin veneers of pebbles and/or disarticulated oyster lags, along with isolated boulder clasts up to 15 cm long are commonly observed (Fig. 5F).

Igneous basement: The Precambrian granitic cliffs of Limberg, Austria

The basal part of the succession is 1 m thick, and characterised by poorly-to-moderately sorted matrix-to-clast supported conglomerates interbedded with well sorted coarse-to-very coarse grained sandstones (Fig. 6C). The conglomerates are dominated by subangular-to-subrounded discoidal pebbles (2 to 4 cm) and cobbles (7 to 10 cm), and minor amounts of blocky shaped clasts. Boulders (up to 60 cm) are also locally observed at the base (Fig. 6C). The matrix is composed of coarse-to-very coarse grained sandstone and granules. Fossilised marine barnacle colonies and serpulid tubes are encrusted on the conglomerates surface, especially on the larger clasts (Fig. 6D). Some of the angular clasts are imbricated and concentrated at specific levels. The conglomerate levels are structureless (Fig. 6E), except for the upper part of the package where thin, 10 cm thick, normally graded layers consisting of discoidal pebbles and ostreid shells displaying horizontal orientations occur (Fig. 6F). The middle part is 1 m thick and dominated by well-to-very well sorted, massive, coarse-to-medium grained sandstones. The upper part of the succession is dominated by 2.5 m of dune cross bedded and hummocky-swaley cross-stratified and massive well-to-very well sorted medium-to-fine grained sandstones. Thin gravelly and shell-rich laminae appear interbedded recurrently (Fig. 6G).

Interpretation

Outsized conglomerate clasts overlie the basement unconformities in all three successions. A clear compositional affinity is observed between the conglomerates and basement rocks, indicating that the underlying formations where the main sediment source. Disarticulated bivalve shells, encrusting fauna and bioerosional traces support a marine depositional environment. The overall fining upwards trends observed through the different successions indicate the development of a progressively deeper water depositional setting, although upwards fining trends within the conglomeratic intervals are interpreted as minor prograding beach sequences, in accordance with the modern examples studied (Figs. 3, 4B, 5B and 6B). The poorly-to-moderately sorted boulder dominated intervals at the lowermost positions of all three successions are interpreted as upper shoreface deposits, some of them possibly representing relict erosional products associated with the ravinement surface formed during the initial transgression of the area (Figs. 4B,5B and 6B). In the Tarragona and Sorbas outcrops, these grade upwards into finer grained, moderately sorted cobbles and pebbles interpreted as the lower and upper beachface deposits, respectively. The conglomeratic interval in Tarragona further fines upwards into a well sorted pebble dominated zone interpreted as the beach berm. The Limberg sedimentary sequence is interpreted to have been deposited in a more distal portion of the system, mainly recording the downlap termination of the beach on the basal upper shoreface deposits. A relative sea level rise and backstepping of the gravel beaches is interpreted from these levels upwards in all three successions (Figs. 4B, 5B and 6B). In the Tarragona outcrop this is marked by the appearance of a poorly sorted *Clypeaster* lag, interpreted as a flooding surface. In the Sorbas outcrop, this downlap is marked by a renewed coarsening upwards trend, where the upper beachface deposits pass vertically to poorly-to-moderately sorted cobbles and bioeroded boulders interpreted as lower beachface and upper shoreface deposits, respectively. In the Limberg outcrop upward increase in sandstone dominated interbeds is indicative of a progressively deeper environment. The overlying fossiliferous sand dominated strata in all three localities are interpreted as the middle shoreface deposits (Figs. 4B, 5B and 6B). Interbeds of gravel size particles and disarticulated corals, echinoderms or bivalves in the middle shoreface are interpreted as storm or high energy event deposits. These are ubiquitous features in all three successions and the only potential indicators of palaeoenvironmental conditions (see Discussion).

The West Margin of the Central North Sea Graben

Upper Jurassic and Lower Cretaceous deposits are found overlying unconformities along 250 km of the western margin of the Central Graben in the North Sea (Fig. 7). The dominant subcropping rocks are Triassic claystone and sandstone rich deposits of the Smith Bank and Skagerrak formations, respectively, and locally, Middle Jurassic rocks of the Ron Volcanic Member and Permian evaporitic deposits of the Zechstein Formation, respectively. The overlying Mesozoic deposits are mainly characterised by highly bioturbated fine-to-medium grained sandstones and are interpreted as shoreface deposits after recognition of *Ophiomorpha* traces, belemnites and disarticulated bivalve shells, in agreement with previous interpretations of the Fulmar Formation (Howell et al., 1996). The basal unconformity tends to be unbioturbated, except for some local *Gastrochaenolites* and unidentified firmground traces burrowing into Skagerrak sandstones and Smith Bank claystones, in wells 29/12-2 and 21/11-5, respectively (Fig. 7, 8A). Similarly, the unconformity boundary is generally depleted of conglomerate deposits, except for some locally thick, 3 m, pebble-to-cobble dominated intervals in wells 29/14b-1a and 30/16/3 (Fig. 8B, 8C), and much thinner pebble accumulations, 10-20 cm thick, in wells 21/11-7, 21/16-4, 21-30-3 and 31/26-4 (Fig. 7). The conglomerates composition in all wells matches the underlying basement or near subcropping formations. While no palaeoenvironmental indicators can be retrieved from the thinner pebble accumulations, except for a bioeroded basalt clast in well 21/30-3 (Fig. 7, 8D), the thicker conglomeratic intervals, composed of reworked basalt clasts, bear evidences of marine deposition in a rocky shoreface.

Subsurface Upper Jurassic and Lower Cretaceous conglomerate rocky shore deposits

Thick clast-supported conglomerate deposits of basaltic composition occur around two volcanoclastic centres of Middle Jurassic and Lower Cretaceous age (Fig. 7). Late Jurassic conglomerates are found in well 29/14B-1A, overlying Middle Jurassic basalts and tuffs of the Ron Volcanic Member, whereas Lower Cretaceous conglomerates are found in well 30/16-3, overlying Permian deposits of the Zechstein Formation. The conglomerate clasts in Quad 29 are dominantly of pebble size (3-6 cm) and, locally, towards the base of the succession, up to cobble size (10 cm). Clasts are mainly sub-rounded, locally angular, and poorly-to-moderately sorted. The presence of embedded disarticulated bivalves, belemnites and platy coralline algae coatings surrounding the basalt clasts indicates a marine depositional environment (Fig. 8E). The conglomerate succession is vertically stacked forming a subtle fining upwards trend, interpreted as an upper shoreface to beachface transition, and reflecting a small phase of beach progradation, according to the modern examples studied. The majority of the clasts present alteration halos. A thin reddish horizon at the basal unconformity suggests that basement rocks might have been altered prior to the establishment of a marine depositional environment, either during subaerial weathering or by hydrothermal processes (Fig. 8F). Syn-sedimentary nodules, 2-5 cm in size, appear at the boundary between the conglomeratic interval and the overlying shoreface sandstones, indicating a period of sediment starvation (Fig. 8G). These nodules are interpreted as a transgressive lag deposit and the surface where they occur as a transgressive flooding surface. The Lower Cretaceous conglomerate deposits in Quad 30 are subdivided into two sedimentary packages, a basal and an upper one, both dominated by rounded-to-subangular clasts, and stacked forming a subtle coarsening upwards trend. The lower package is dominated by granules and pebble size clasts, 1-2 cm, and variable amounts of larger pebbles, 3-4 cm in size. The same grain fractions are present in the package above, however, cobble size clasts, 7-15 cm, are characteristic of this upper interval. A bioeroded basalt clast, along with embedded disarticulated bivalve shells and belemnite fragments are indicative of a marine depositional environment (Fig. 8H, 8I). The boundary between both sedimentary packages is interpreted as a flooding surface, separating underlying beachface deposits from upper shoreface deposits above. Continued deepening from this level upwards is observed by the accumulation and oxidation of iron minerals, which leads to a red coloration in the matrix and indicates a period of progressive sediment starvation, also supported by the appearance of syn-sedimentary nodules, belemnite accumulations and *Ophiomorpha* burrows (Fig. 8J, 8K).

Discussion

Facies, sedimentary architecture and depositional environment

Differentiating between continental and marine conglomerates overlying and unconformity in the absence of soils, subaerial indicators, ichnotraces or fossil remains challenging especially when they occur interrelated, as shown in the discussion of Nemec and Steel (1984). The type of sedimentary structures, the nature of the bed boundaries, the sediment maturity and its grading reflects the processes which acted during the deposition of the conglomerate deposits, which can be relatively similar in both settings. In our case, the presence of marine indicators, either bioerosional traces, encrusting fauna or embedded belemnites and disarticulated bivalve shells, has been essential to evoke a marine setting. Similarly, the unconformable relationship and compositional affinity between basement rocks and the overlying conglomerates, along with their stratigraphic position directly underlying transgressive shoreface sandstone deposits and, their distribution, especially those around small volcanic centres, favours the interpretation of rocky shores rather than fan deltas. The vertical stacking patterns, sorting, roundness and clast segregation of the Miocene and Mesozoic conglomerate sequences are very similar to the ones observed in the modern gravel beaches. While the fining upwards trends observed within the outcropping and subsurface conglomerates are interpreted as minor progradational beach pulses in an overall retrogradational and deepening upwards sequence, the sedimentological criteria used to recognize and subdivide its depositional zones diverges from other ancient and modern gravel beach sequences studied by Bluck (1999, 2011), Massari and Parea (1988) and Postma and Nemec (1990). These authors commonly report selection pavements and well developed clast shape segregations in their examples of the beachface zone, which presents a wide range of clast sizes, starting at 1-2 cm, and shapes, including discs and blades. In contrast, these features, the sandier interbeds and the disc/blade shaped particles, are very uncommon in the Miocene and Mesozoic examples in the current study. While these features form as a consequence of the different hydrodynamic behaviour between disc-shaped and spherical-shaped particles during swash and backswash processes at the beachface (Massari and Parea, 1988), the limited clast shape variability in our examples is interpreted to be mainly responsible for the absence of selection pavements and clasts segregation, promoting a rather structureless aspect. The absence of disc shaped particles might be related to the nature of the source areas which do not supply this type of particles, or with the maturity of the beach, being rather immature and dominated by equant shaped spherical particles (Bluck, 2011). While it is not possible to infer the detailed palaeoenvironmental conditions in which the studied conglomerate successions formed, due to the lack of sedimentary structures, the recurrent accumulation of disarticulated bivalve lags and beachface or upper shoreface gravels within the distal and sandier shoreface deposits indicates deposition under storm influence. Ledesma-Vázquez et al., (2006) suggest that the signature of storms is common in coastal conglomerate successions in the rock record, as fair weather conditions are usually obliterated by subsequent storms. This is in line with previous work, that interpreted storms and other high energy events as evidenced from the accumulation of echinoderms and other mollusc lags in the Tarragona sections (Belaustegui et al., 2012), the presence of gravelly shell layers in the Burgschleinitz Formation (Pervesler and Roetzel, 2011), and the bioclastic accumulations of admixed shells, gravels and rhodoliths in the Sorbas basin (Puga-Bernabeu et al., 2007). Storm influenced conditions are also reported from the subsurface deposits of the Fulmar Formation in the UK sector, and its time equivalent in the Norwegian North Sea, the Ula Formation (Gowland, 1996; Howell et al., 1996; Baniak et al., 2014).

Controls on the occurrence of subsurface Mesozoic rocky shoreline deposits

Only two wells along the west margin of the Central North Sea Graben contain marine conglomerate deposits formed in or at the proximities of former rocky shorelines. These span a variety of ages and are spatially offset (i.e. Jurassic at the North and Cretaceous at the South). This is in line with previous palaeogeographic reconstructions from Copestake et al., (2003) and Milton-Worsell et al., (2006), which show the Late Jurassic and Early Cretaceous transgression in the study area advanced towards the Auk Ridge, where the Cretaceous conglomerates deposits are found (Fig. 7) (Trewin et al., 2003). This suggests that the interpreted rocky shore deposits are recording a progressive marine onlap onto the higher portions of the basin margin and that the basal bedrock unconformity above which they develop represents a heterochronous transgressive surface (Howell et al., 1996). However, this unconformity surface typically lacks a basal conglomerate deposit, despite the presence of a lithified pre-Upper Jurassic substrate (Fig. 7). Similarly, this contrasts with observations made from modern day shorelines, where lithified coastline portions, made of older basement rocks, are typically occupied by conglomeratic rocky shores. In these sections it is suggested that not all of the subcropping and lithified rock formations were capable of sourcing gravel size products or in case they did, to preserve them during subsequent wave erosion. In modern day rocky coastlines, competence of the bedrock, which is a function of the lithology, weathering degree and structural complexity, determines the type of coastal cliffs, which can be either classified as hard or soft (Trenhaile, 2011). The affinity between Miocene and Mesozoic conglomerate intervals and subcropping granites, gneisses, limestones and basaltic rocks suggests that these deposits only form and preserve where competent hard coastal cliffs existed (Fig. 9). In contrast, it is interpreted that most of the West Margin of the Central North Sea Graben, composed of subcropping claystones, evaporites and fine grained sandstones, was dominated by soft coastal cliffs which precluded the formation or preservation of gravel size conglomerate deposits (Fig. 9). Due to its weak resistance, mass failed gravel products at the cliff base were disgregated during wave erosion, promoting the formation of shoreface sandstones or finer grained sediments which were transported further offshore (Fig. 9). Yet this process is known from short term observation of modern coastal cliffs (Bray and Hooke, 1997; Le Cossec et al., 2011; Swirad and Young, 2021), the different stratigraphic signature of hard and soft cliffs in the geological record is largely unknown. Based on the distribution of Mesozoic deposits along the West Margin of the UK Central Graben, we indicate that conglomerate facies models can only be applied to the study of ancient rocky coastlines associated with hard coastal cliffs, since the long term sedimentary record of soft cliffs does not preserve gravel size particles.

Conclusions

Rocky shoreline conglomeratic deposits might be difficult to interpret in the geological record and can misidentified with fluvial or alluvial deposits. To avoid these, special emphasis should be placed on the ichnological and palaeontological aspects of the deposits, identifying marine bioerosional traces and skeletal faunal remains. Despite the structureless aspect of modern and ancient rocky shoreline conglomerates, we demonstrate that it is possible to interpret these successions based on its sedimentological aspects. According to the observed vertical stacking patterns and sorting variability, prograding conglomerate beach deposits fine upwards and can be subdivided into: i) a boulder or cobble dominated, poorly-to-moderately sorted upper shoreface zone, ii) a slightly imbricated, fining upwards, moderately sorted beachface zone, iii) a well-to-very sorted berm zone and iv) a well-to-moderately sorted backshore zone. The lack of sedimentary structures precludes a confident interpretation about the detailed paleoenvironmental conditions in which the conglomerates formed, although the recurrent presence of gravel and shell-rich interbeds in the overlying shoreface sandstones, indicates deposition under storm influence. The affinity between the occurrences of Miocene and Mesozoic rocky shoreline conglomerates and resistant basement rocks (granites, gneisses, limestones and basalts), along with their absence when underlaid by soft basement lithologies (claystone, evaporites and fine sandstones), indicates they only form and preserve where hard coastal cliffs existed. So “why are ancient rocky shores so uncommon in the subsurface of the North Sea?”. The Jurassic and Cretaceous palaeoshorelines at the West Margin of the Central North Sea Graben, characterised by weak basement lithologies, were dominated by soft coastal cliffs, unable to supply or preserve mass failed gravel size products from wave erosion. While gravel deposits do occur in modern rocky shores along soft cliffs, they are non-preserved in the long term, therefore conglomerate facies models cannot be used to the study soft coastal cliffs in the geological record. Despite that, part of the answer is also related with misidentification or overlooking issues, given that previously unrecognised rocky shore conglomerate deposits were formed locally around volcanic centres, where hard basaltic coastal cliffs existed. While the successions studied show slight variations in terms of sedimentary structures, sediment maturity and sorting compared with previous works, they add new information to the existing models and expand our knowledge on the nature of shallow marine conglomerates and the expression of rocky shores in the geological record, demonstrating that subcropping basement lithology along the shoreline margin is a key factor controlling the formation and preservation of conglomerate rocky shore deposits.

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Figure captions

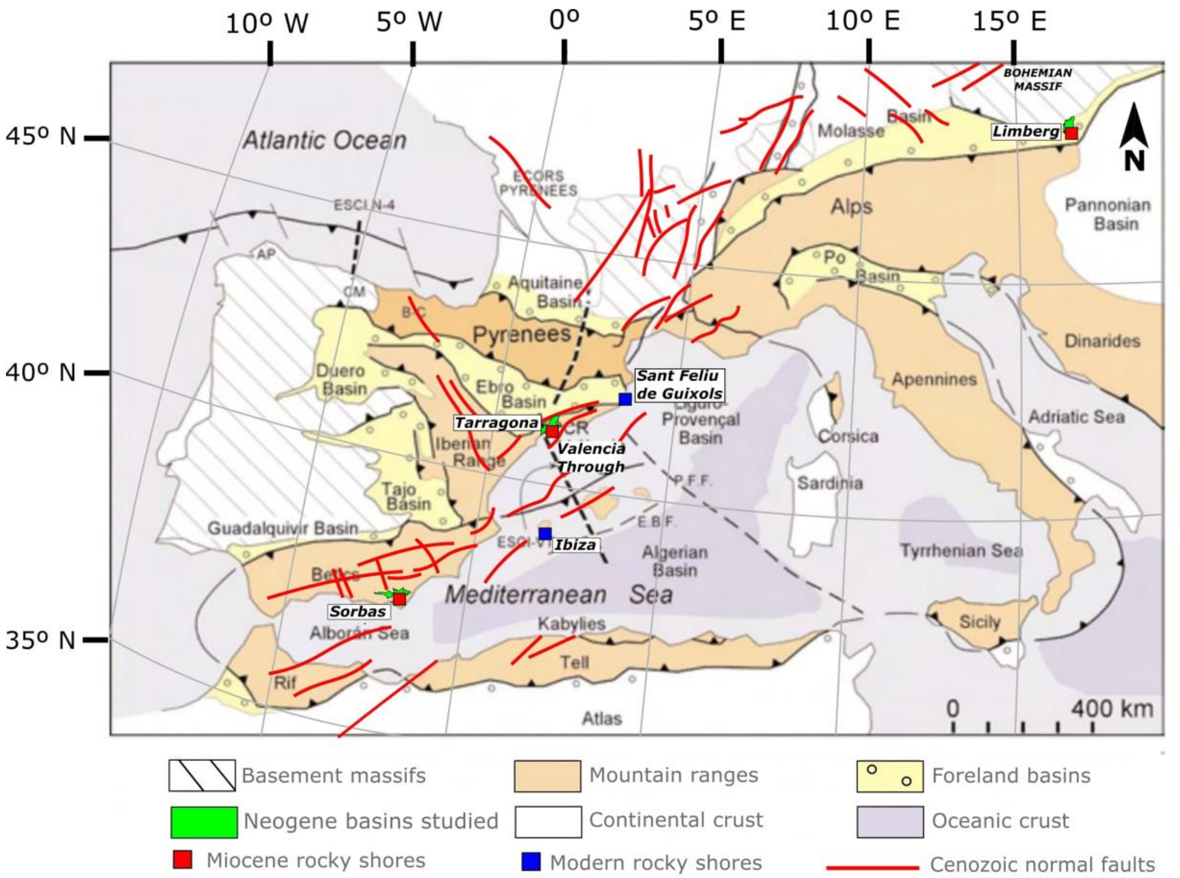

Figure 1: (A) Structural map of the European Cenozoic Rift System and the Alpine Orogeny highlighting the main foreland and extensional basins studied (green). Note that the location of the Miocene and modern day rocky shores studied is annotated with red and blue polygons, respectively. Modified from Vergés and Sàbat (1999) and Martí and Bolos (2019).

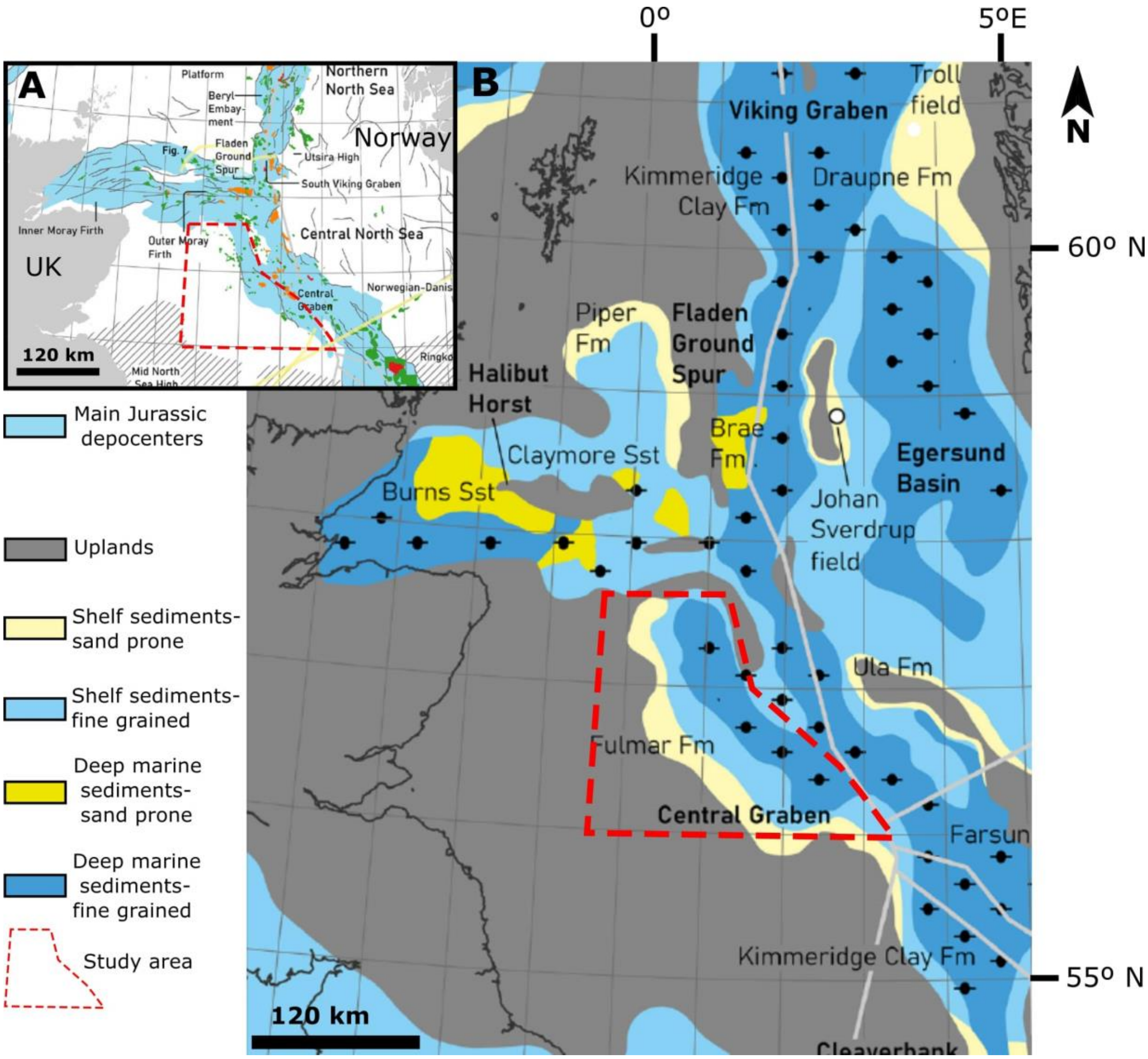

Figure 2: (A) Structural map of Mesozoic North Sea Rift extent highlighting the main Jurassic depocenters (blue). (B) Palaeogeographical reconstruction of the latest Jurassic and its different shallow to deep marine depositional environments. Note the location of the Jurassic paleoshoreline within the study area. The shallow marine deposits of the Fulmar Formation are onlapping onto the exposed uplands made of preexisting rock formations. Modified from Patruno *et al.*, (2022).

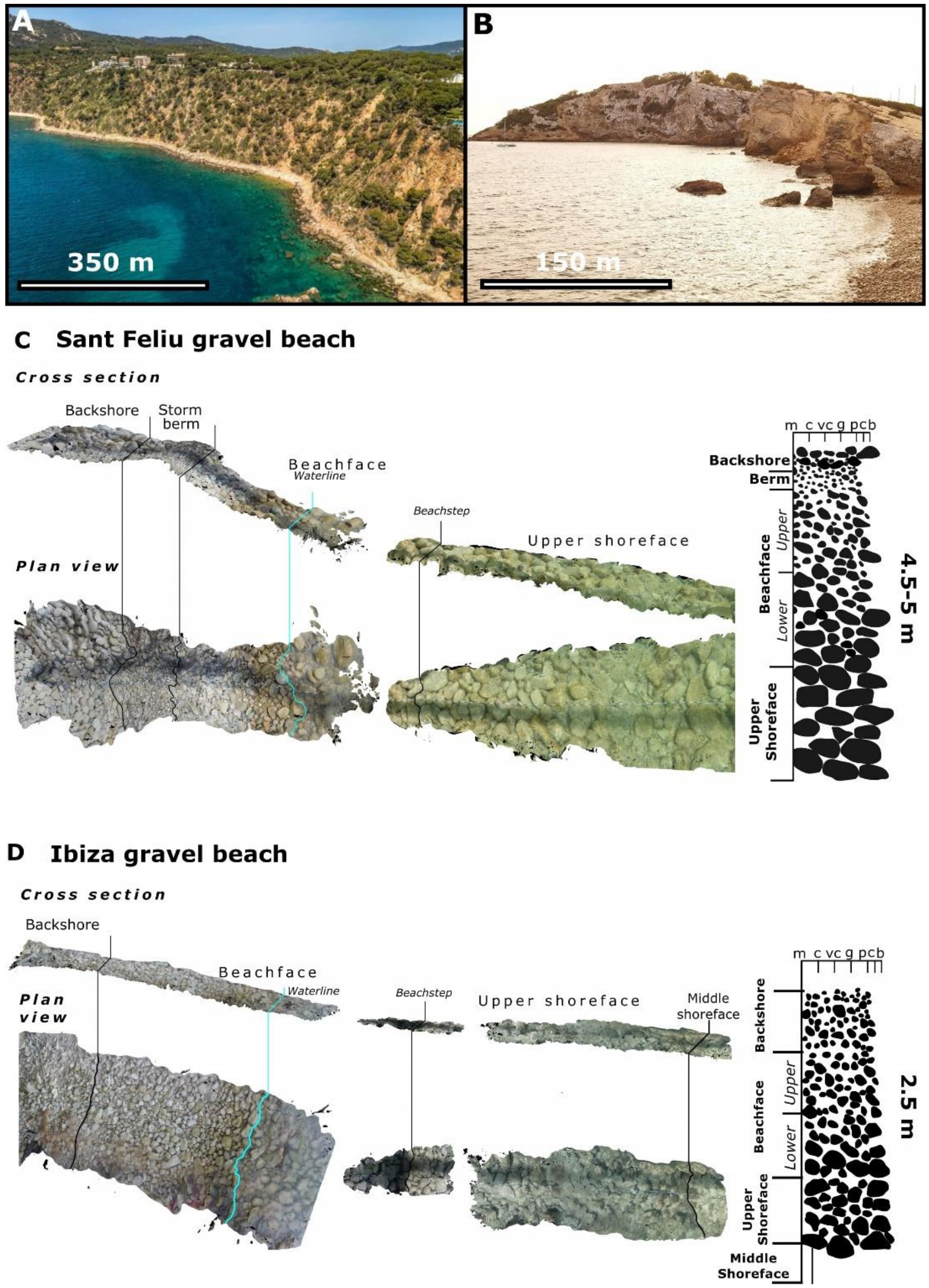

Figure 3: (A, B) Modern day gravel rocky shorelines studied in Catalonia (A) and Ibiza (B). The horizontal scale applies to the shoreline extending along the background landscape. (C) Depositional zones and sediment type of the granitic gravel beach in Sant Feliu, Catalonia. Note the steeply dipping beachface slope and the grain size variations from the backshore down to the upper shoreface. (D) Depositional zones and sediment type of the carbonate gravel beach in Ibiza. Note the gentler dipping beachface slope, and the similar grainsize distribution compared with the Sant Feliu beach. The cross sections and plan view profiles are all 25 m long. Synthetic logs for both gravel beaches show that in case of beach progradation, the sedimentary successions would stack forming an overall fining upwards trend.

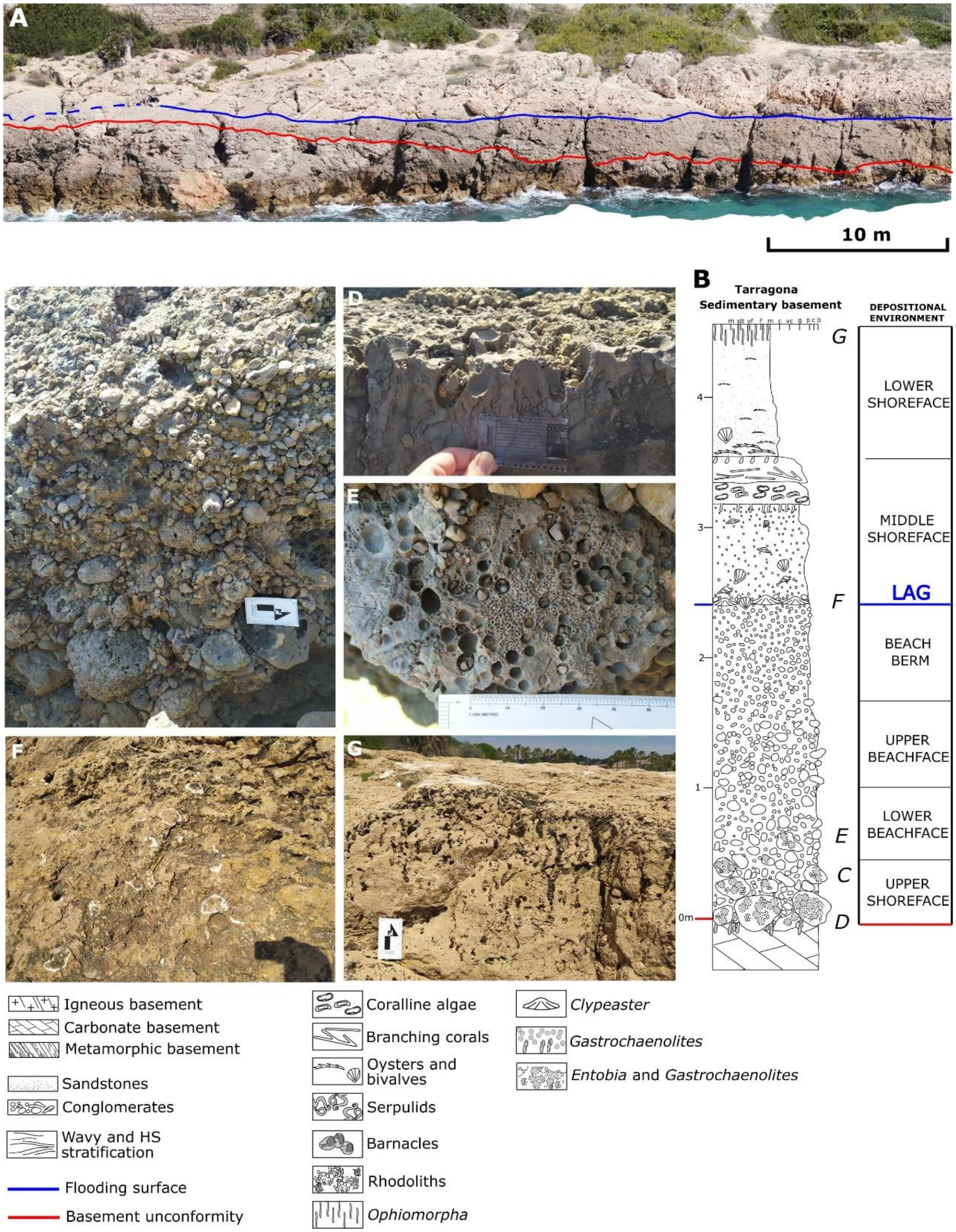

Figure 4: (A) Miocene rocky shore deposits of the Tarragona Sequence unconformably overlying carbonate basement rocks. (B) Logged section. Note the overall fining upwards trend. (C) Structureless and bioeroded clast-supported cobbles and pebbles. Note the upwards transition from poorly to moderately sorted deposits. (D) *Gastrochaenolites* bioerosional traces affecting the basal unconformity surface. (E) Cobble size clast affected by *Gastrochaenolites* and *Entobia* bioerosional traces. (F) Clypeaster lag. (G) Highly bioturbated shoreface sandstones affected by *Ophiomorpha* burrows.

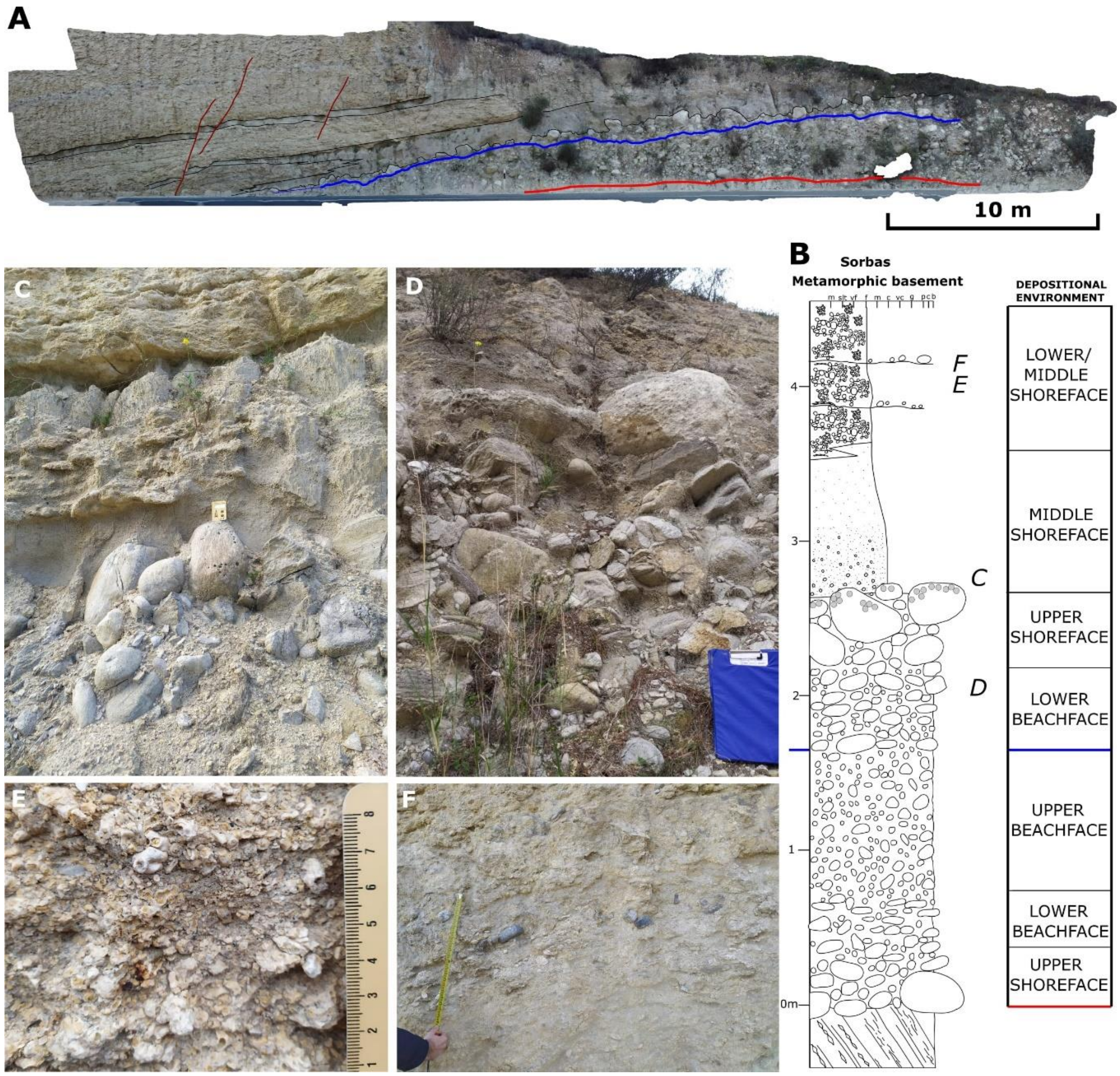

Figure 5: (A) Miocene rocky shore deposits of the Azagador Member unconformably overlying metamorphic basement rocks. (B) Logged section. Note the three fold subdivisions within the conglomerate interval and the fining-to-coarsening upwards trends. (C) Bioeroded boulder size clasts at the uppermost part of the conglomerate package. (D) Structureless, moderately-to-poorly sorted cobbles and boulders at the lower beachface to upper shoreface transition. Note the coarsening upwards trend. (E) Rhodolith beds. (F) Pebble and cobble interbeds within the rhodolith rich lower/middle shoreface deposits.

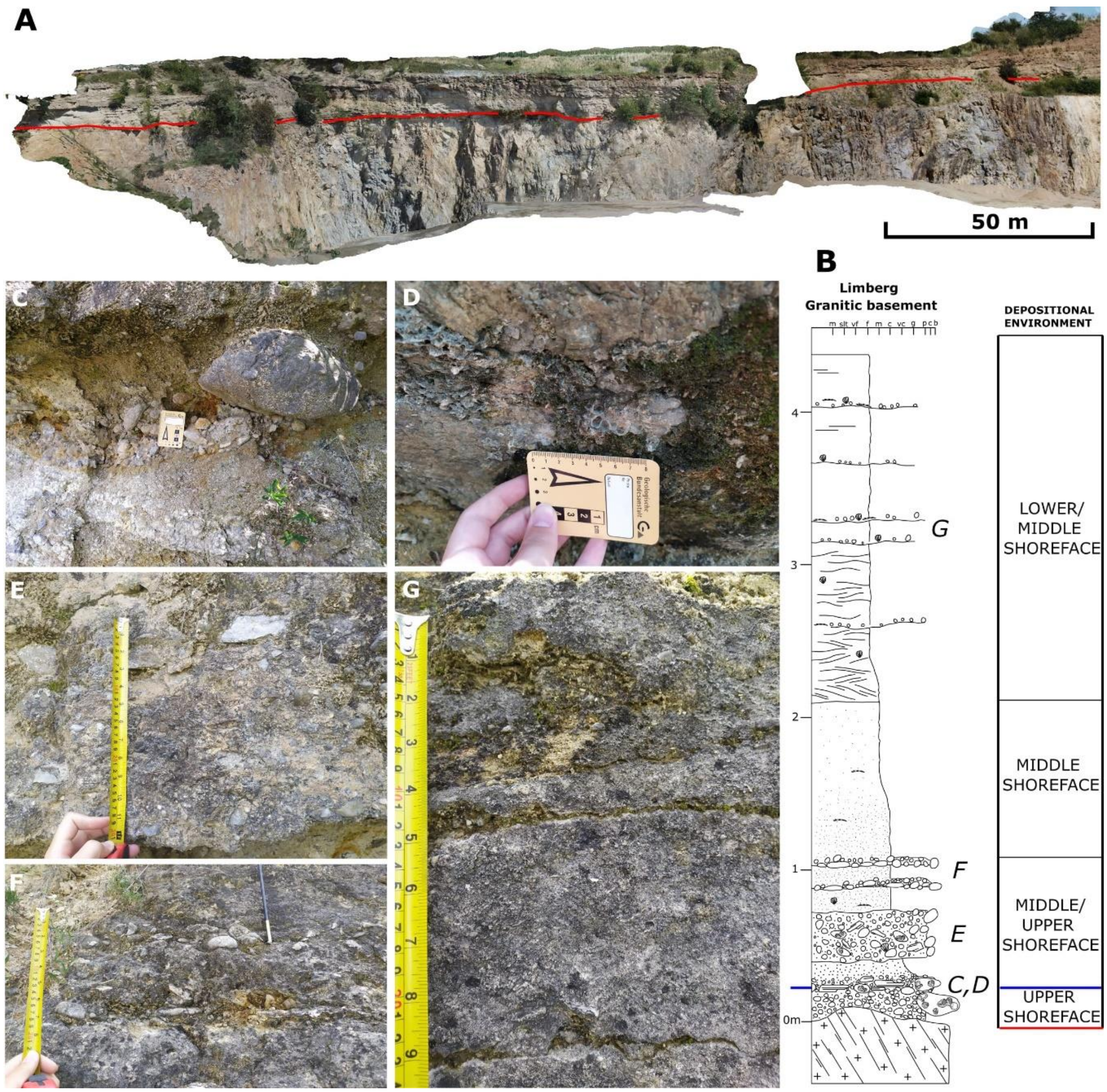

Figure 6: (A) Miocene rocky shore deposits of the Burgschleinitz Formation unconformably overlying granitic basement rocks. (B) Logged section. Note the overall fining upwards trend and the reduced thickness of the conglomerate interval. Dune cross bedding and hummocky-swaley cross stratification is developed in the lower/middle shoreface sandstone deposits (C) Poorly-to-moderately sorted outsized clasts overlying the basal unconformity. (B) Barnacle colony encrusted on a boulder size clast. (E) Structureless and poorly sorted conglomerate bed. (F) Coarse sandstones and interbeds of discoidal pebbles displaying horizontal orientation. (G) Thin granule and shell-rich interbeds within the lower/middle fine grained shoreface sandstone deposits

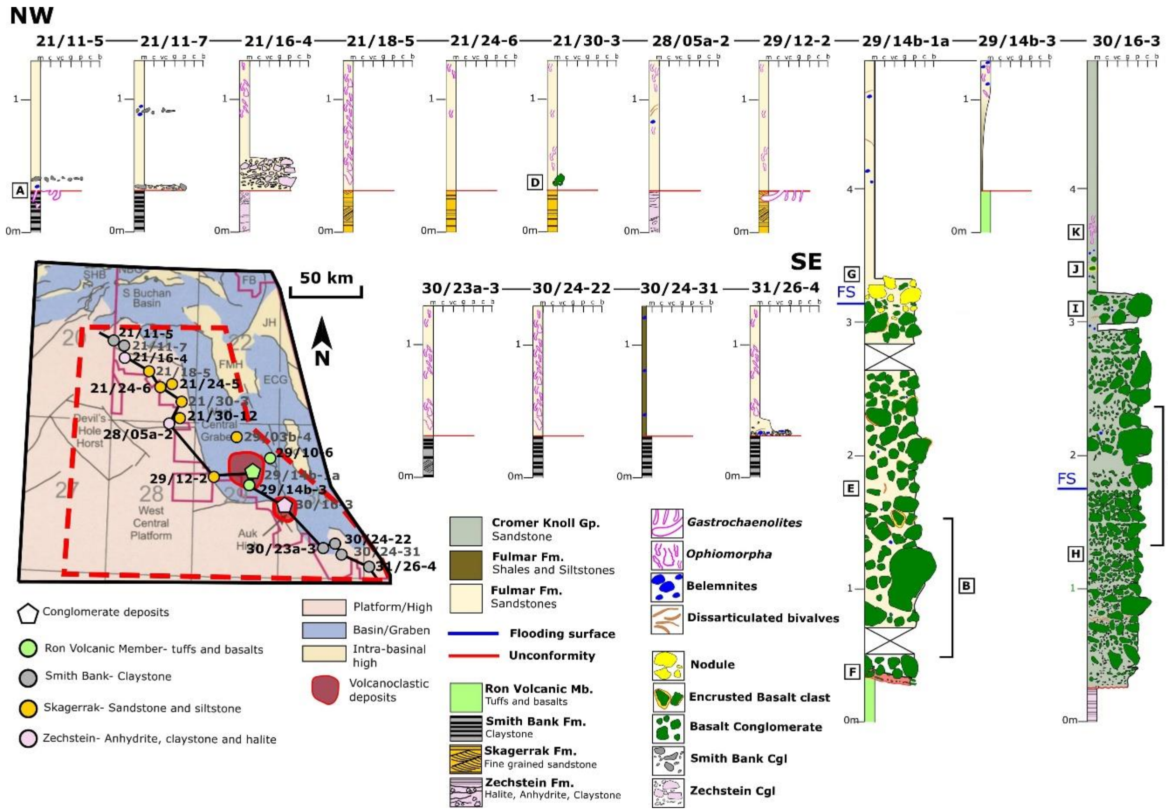

Figure 1: Well cores and stratigraphic logs of Late Jurassic and Early Cretaceous deposits studied along the West Margin of the Central North Sea Graben. The panel is not at scale, and there is no correlation implied. The studied rift margin is dominated by subcropping claystones and fine grained sandstones of the Smith Bank and Skagerrak formations, respectively. The basal unconformity surface is locally bioturbated by Gastrochaenolites and mostly depleted of basal conglomerate deposits, being directly overlayed by shoreface sandstones of the Fulmar Formation and Cromer Knoll Group. Upper Jurassic and Lower Cretaceous marine conglomerates are scarce and occur locally, associated with two volcanic centres of Middle Jurassic and Lower Cretaceous age

Figure 8: (A) Gastrochaenolites and unidentified firmground traces affecting subcropping claystones of the Smith Bank Formation. (B,C) Clast supported Late Jurassic and Lower Cretaceous marine conglomerate deposits of basaltic composition. (D) Pebble size basalt clast bioeroded by Gastrochaenolites. (E) Disarticulated bivalve shell embedded within pebbles and cobble size clasts. (F) Red horizon developed between subcropping deposits of the Ron Volcanic Member and the overlying conglomerates of the Fulmar Formation. (G) Syn-sedimentary nodules at the transgressive surface developed between the conglomerates and overlying shoreface sandstone deposits of the Fulmar Formation. (H) Pebble size basalt clast bioeroded by Gastrochaenolites. (I) Disarticulated bivalve shell embedded within pebbles and cobble size clasts. (J) Transgressive lag deposit showing belemnites and syn-sedimentary nodules embedded in a red coloured sandstone matrix. The red coloration is formed due to the prolonged oxidation of iron minerals during conditions of sediment starvation. (K) Ophiomorpha burrows affecting Lower Cretaceous sandstone deposits of the Cromer Knoll Group.

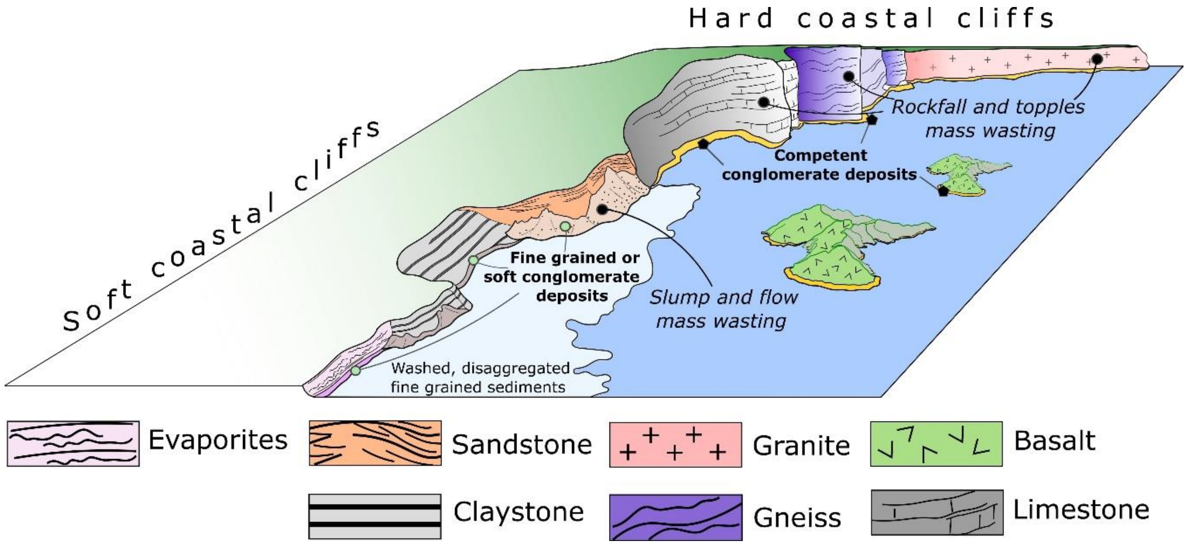

Figure 9: Block diagram illustrating the interplay between basement lithologies, hard vs soft coastal cliffs and the occurrence of rocky shore conglomerate deposits. Rockfall and topples mass wasting processes, which favour the supply of gravel size particles, dominate on hard cliffs, whereas slumping and other mass wasting flow types are characteristic of soft cliffs. The majority of disaggregated sediments accumulated at the base of soft cliffs are washed and transported further offshore, while dense and competent conglomerate deposits from hard cliffs tend to accumulate forming coarse grained beaches. Whereas conglomerate deposits are characteristic of hard cliffs, they can also form along soft coasts, however, their soft character and low resistance to wave erosion would ultimately disaggregate them as fine grained sediments.