Geografia Fisica e Dinamica Quaternaria
GFDQ 48 (2025), 7-24

DOI 10.4454/bhk456vf

Piotr MIGOŃ[1], Vittoria VANDELLI[2*], Paola CORATZA[2],
Asier HILARIO[3], Mauro SOLDATI[2]

Rock-controlled coastal landforms in the flysch-dominated Basque Coast UNESCO Global Geopark

Abstract: Migoń P., Vandelli V., Coratza P., Hilario A., Soldati M., *Rock-controlled coastal landforms in the flysch-dominated Basque Coast UNESCO Global Geopark.* (IT ISSN 0391-9838, 2025). This paper aims to provide an inventory of coastal landforms present along the approximately 30-km-long coastline of the Bay of Biscay, within the boundaries of the Basque Coast UNESCO Global Geopark. The coast is primarily erosional, with vertical cliffs and steep slopes more than 100 m high abruptly giving way to shore platforms. Minor rock coast landforms include notches, marine caves, potholes and joint-aligned clefts within shore platforms, and boulder accumulations. The coastal morphology has developed in a thick flysch succession of Cretaceous to Eocene age. In the western section, the flysch is dominated by grey shales and greywackes and is known as the Black flysch of Lower Cretaceous age. In the eastern sector, separated from the western one by the Andutz Fault, the flysch is calcareous and dominated by rhythmic alternations of shales, marls and limestones. Moreover, the strike of the strata is roughly parallel to the coast in the Black flysch, whereas it is perpendicular or oblique in the Calcareous flysch. The dip is almost invariably towards the sea. These lithological and structural differences are reflected in the inventory of coastal landforms, with cliffs and shore platforms much better developed in the Calcareous flysch. Coastal landslides are ubiquitous in the Calcareous flysch, facilitated by the presence of steeply dipping bedding planes, so that sliding is mostly translational. Numerous outcrops provide evidence of distortion and brittle deformation of flysch strata due to landsliding.

Key words: Rocky coast, Geological control, Flysch, Coastal landslides, Basque Coast UNESCO Global Geopark, Basque Country, Spain.

Resumen: Migoń P., Vandelli V., Coratza P., Hilario A., Soldati M., *Formaciones costeras controladas por rocas flysch en el Geoparque Mundial de la UNESCO de la Costa Vasca.* (IT ISSN 0391-9838, 2025). Este artículo tiene como objetivo proporcionar un inventario de las formas del relieve costero presentes a lo largo de aproximadamente 30 km de litoral en el Golfo de Vizcaya, dentro de los límites del Geoparque Mundial UNESCO de la Costa Vasca. La costa es predominantemente erosiva, con acantilados verticales y laderas empinadas de más de 100 metros de altura que dan paso abruptamente a plataformas de abrasión. Las formas menores del relieve rocoso incluyen muescas (notches), cuevas marinas, potholes y fisuras alineadas con la fracturación en las plataformas costeras, así como acumulaciones de bloques. La morfología costera se ha desarrollado en una sucesión de tipo flysch de gran espesor, que data desde el Cretácico hasta el Eoceno. En la sección occidental, el flysch está dominado por lutitas grises y grauvacas, y es conocido como el flysch negro del Cretácico Inferior. En el sector oriental, separado del occidental por la Falla de Andutz, el flysch es calcáreo y está dominado por alternancias rítmicas de lutitas, margas y calizas. Además, el buzamiento de los estratos es aproximadamente paralelo a la costa en el flysch negro, mientras que en el flysch calcáreo es perpendicular u oblicuo. La inclinación de los estratos es casi invariable hacia el mar. Estas diferencias litológicas y estructurales se reflejan en el inventario de formas del relieve costero, con acantilados y plataformas de abrasión mucho más desarrollados en el flysch calcáreo. Los deslizamientos costeros son ubicuos en el flysch calcáreo, facilitados por la presencia de planos de estratificación con gran inclinación, lo que da lugar a deslizamientos predominantemente traslacionales. Numerosos afloramientos proporcionan evidencia de distorsión y deformación frágil de los estratos de flysch debida a los deslizamientos.

Palabras clave: Costa rocosa, Control geológico, Flysch, Deslizamientos costeros, Geoparque Mundial UNESCO de la Costa Vasca, País Vasco, España.

INTRODUCTION

UNESCO Global Geoparks are required to have geological heritage of international significance within their territories and, as far as possible, to show and interpret this heritage to the general public, fostering education and geotourism. The Basque Coast UNESCO Global Geopark (UGGp), located in the Basque Country (northern Spain) and established in 2010, is mainly renowned for its excep-

[1] *Institute of Geography and Regional Development, University of Wroclaw, Wroclaw, Poland.*
[2] *Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Modena, Italy.*
[3] *Basque Coast UNESCO Global Geopark, Provincial Council of Gipuzkoa, Spain.*
* *Corresponding author: Vittoria Vandelli (vittoria.vandelli@unimore.it)*

Paper published on the 25th anniversary of AIGeo, the Italian Association of Physical Geography and Geomorphology. GFDQ vol. 48, Guest Editors: Pappalardo M., Rotigliano E., Ferrando A.

tional geological record of the late Cretaceous and Palaeogene, including the K/T boundary (Martínez and Mariñoso, 2021; Pujalte *et al.*, 2022), spectacularly exposed in the coastal cliffs. Most of this geological succession is represented by flysch rocks and hence, "flysch" has become a geological term intimately associated with the Geopark and its core scientific values. Further inland, diverse karst landforms occur, including conical hills, fault-controlled poljes, sinkholes and caves, some hosting the prehistoric rock art (Aranburu *et al.*, 2015), and these are the main complementary values of the Geopark. In contrast, the coastal scenery that exposes the flysch succession in impressive cliffs and allows for its scientific examination, is apparently mostly appreciated for its aesthetic attributes and has remained under-researched in respect to its geomorphology and dynamics. This is particularly true regarding coastal landslides, which appear as key drivers of coastal evolution, at least along some sections. Specific coastal landforms such as cliffs, sea caves and shore platforms are presented as geosites within the Geopark (Hilario *et al.*, 2023) but have not been subject to systematic research.

This paper is intended as the first step to fill this gap and aims to show the diversity of erosional landforms present along the stretch of the Bay of Biscay within the boundaries of the Basque Coast UGGp. It is based on a systematic inventory of coastal landforms conducted all along the coast of the Geopark, accomplished through a combination of field survey, analysis of a digital terrain model, and examination of multi-temporal images available from different sources. The original part of the paper is composed of two main sections. We first present the inventory of landforms to provide a complete picture of geomorphic diversity, followed by a discussion section in which we explore geological controls explaining this diversity and use landforms and their spatial patterns to infer processes shaping the coast at both long- and short-term timescales. Since nearly the entire coast within the Basque Coast UGGp is cut in hard rock, this paper also represents a contribution to the rock coast geomorphology in general.

STUDY AREA

Physical setting

The coastal stretch of the Basque Coast UGGp lies between the estuary of the Urola River in Zumaia to the east and the mouth of the Artibai River in Ondarroa to the west (fig. 1). The end points are approximately 13.7 km apart in the straight line, whereas the actual length of the coastline is 30.7 km. Two estuaries, at Deba and Zumaia, along with the promontories of Mendatagaina and Algorri (fig. 1), allow one to subdivide the coastline into five sectors: (A) Ondarroa to Mutriku; (B) Mutriku to Deba; (C) Deba to Mendatagaina; (D) Mendatagaina to Algorri; (E) Algorri to the mouth of Urola River. This subdivision, based on the presence of characteristic landmarks (river mouths and headlands), reflects lithological variability. Sectors A to C are eroded in bedrock that is lithologically and stratigraphically different from that exposed in sectors D and E (see section "Geological setting").

The hinterland above the coastal cliffs is very rugged, even though altitudes in the near-coastal belt are generally less than 200 m a.s.l. It includes narrow rounded ridges separated by deeply incised valleys, with the inclination of valley sides locally exceeding 40°. This erosional relief is truncated on the seaward side by very steep slopes, including vertical sea cliffs, marked by the presence of a distinct break of slope.

The climate of the region is classified as temperate oceanic (humid temperate climate without a dry season), characterized by mild temperatures and rainfall distribut-

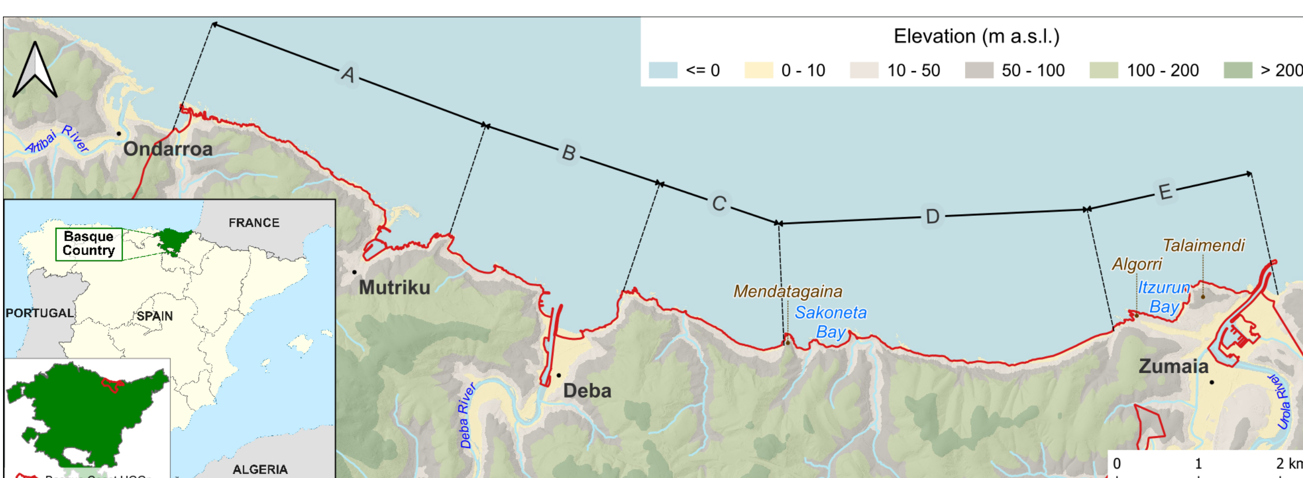

Figure 1 - Geographic setting of the investigated area. A to E are the different sectors of the coastline within the Basque Coast UGGp (boundaries of the Geopark are indicated by red line).

ed throughout the year (https://www.euskalmet.euskadi.eus/clima/euskadi/). Average winter temperatures in the Basque Coast Geopark area are slightly below 10°C, while summer temperatures average around 19°C. The mean annual precipitation is approximately 1,600 mm, with October, November, and December being the wettest months. Extreme daily rainfall may exceed 200 mm (Moncho and Caselles, 2011). The tidal range fluctuates between 1 to 5 m. The offshore wave regime of the region is characterized by a mean significant wave height of approximately 1.5 m, a peak period of 10 s, and a predominant wave direction from NNW (de Santiago *et al.*, 2021; Abalia *et al.*, 2024). Wave energy exhibits seasonal variability, with the most energetic conditions occurring in autumn and winter, and the least energetic in summer (González *et al.*, 2004; de Santiago *et al.*, 2021).

Geological setting

The coastal stretch of the Basque Coast UGGp is characterized by a deep marine sequence comprising alternations of hemipelagic marls and limestones, and intercalated turbidites from the Cretaceous to the Eocene in age. It should be noted that an early model of deep-water submarine fan formation was partly based on the Eocene sediments outcropping at Zumaia, confirming the remarkable geological value of the area (Kruit *et al.*, 1972). From a stratigraphic viewpoint, the two major events bracketing the Paleocene, i.e. the mass extinction at the Cretaceous/Paleogene (K/Pg) boundary and the global warming known as the Paleocene-Eocene Thermal Maximum (PETM), are exceptionally well recorded at Zumaia (Ward *et al.*, 1991). In this respect, a stratigraphic section outcropping in the coastal cliff at the Itzurun Beach, nearby the town of Zumaia, was selected to place the Global Stratotype Sections and Points (GSSPs) for the bases of the Selandian (Middle Paleocene) and Thanetian (Upper Paleocene) (Baceta *et al.*, 2010; Schmitz *et al.*, 2011; Martínez and Mariñoso, 2021; Gilabert *et al.*, 2022; Pujalte *et al.*, 2022).

Considering lithology and rock age, the coastal stretch of the Basque Coast UGGp can be divided into two sections of comparable length, corresponding to sectors A-C and D-E mentioned above (fig. 2). The western section between Ondarroa and the headland of Mendatagaina is eroded in Lower Cretaceous (Albian) flysch formations, mainly developed as grey shales, with intercalations of sandstones (greywackes) and, locally, the presence of conglomerates and breccia. They are subdivided into several formations, being

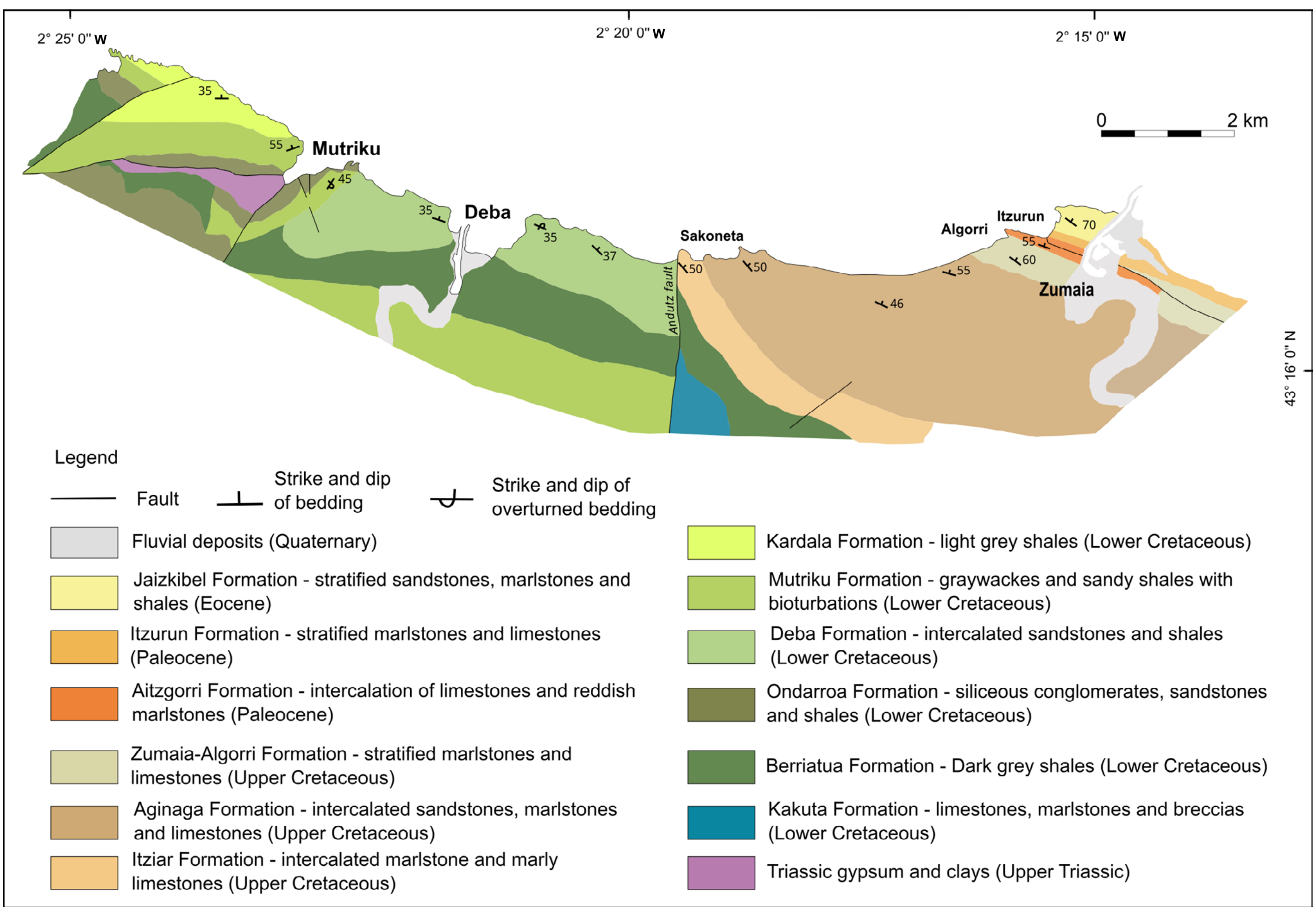

Figure 2 - Geological sketch map of the coastal area of the Basque Coast UGGp.

both in stratigraphic superposition and interfingering with one another. However, most of the coastline is eroded in the Deba, Mutriku and Kardala formations (Agirrezabala and Baceta, 2013). Collectively, they are known as “Black flysch” and represent a sedimentary response to the rifting process and opening of the Bay of Biscay.

The eastern section is eroded in younger flysch formations, spanning the long interval from the Cenomanian (Upper Cretaceous) to the beginning of the Eocene (Ypresian). Here the dominant lithologies are marls, shales and limestones, with variable turbidite intercalations that depend on the tectonic context and the relative sea level variation. Turbidite sandstones are more calcareous in the Cretaceous section and tend to become more siliciclastic in the Eocene section towards the east. Along more than 55% of the length of this sector flysch beds of the Aginaga Formation of Campanian age crop out, whereas more to the east the record becomes more condensed and subdivided into four formations, which are, from the oldest to the youngest, Zumaia-Algorri (Maastrichtian), Aitzgorri (Danian), Itzurun (Selandian-Thanetian), and Jaizkibel (Ypresian) (Agirrezabala and Baceta, 2013).

The boundary between these two coastal sections of dissimilar lithological composition is of tectonic origin and constituted by the Andutz Fault. The fault strikes N-S, intersects the coastline on the western side of Mendatagaina promontory and continues inland (fig. 2). Beside lithology, these two sections differ in terms of the structural grain and the dominant strike of the strata. In the western section the general strike is W-E and hence, broadly parallel to the coastline. In the eastern section it is more varied, from NNW-SSE close to the Andutz Fault to WNW-ESE in Zumaia. Thus, in different places along the coast the flysch strata are intersected by the shoreline at different angles, from almost perpendicular at Sakoneta and Algorri in the Calcareous flysch to almost parallel in the Black flysch.

MATERIALS AND METHODS

The geomorphological investigations carried out on the coastal stretch of the Geopark were supported in a preliminary phase by the examination of available materials such as scientific papers, inventories of geosites within the Geopark, thematic and topographic maps, popular science materials produced by the Geopark, and multi-temporal imagery from different sources. This desk work activity allowed us to define localities of potentially highest relevance and plan the schedule of field work campaign. During the latter we surveyed most sections of the coast between the Saturraran Beach in the west to Zumaia in the east, and analysed in detail the beach-rock platform/cliff transition between Sakoneta and Zumaia, being the most significant from a geomorphological viewpoint. Additional observations were conducted from offshore, utilizing a coastal vessel survey to gain a broader perspective of the study area. Qualitative landform recognition was supplemented by simple measurements using laser rangefinder to estimate distances from key geomorphic features and their dimensions. Both ground photographs and drone imageries were collected. The latter consisted of oblique photographs, acquired using a drone DJI mini 2 SE flown at varying elevations (ranging from a few meters up to 60 m above ground level) and from multiple angles, with the aim of qualitative interpretation and documentation rather than orthophoto generation. Additionally, remote sensing data were acquired to provide further evidence of the temporal evolution of the investigated coastal stretch and support the geomorphological interpretation. These included orthophotographs from 1945 to 2022, Google Earth imagery from 1991 to 2024, and Digital Terrain Models (DTMs) from 2008, 2012 and 2016 derived from LiDAR data. Updated DTMs, produced by integrating LiDAR with orthophotogrammetric data from 2013 and 2017, were also used, all with a spatial resolution of 1 m. The DTMs and the orthophotographs were downloaded from the Spatial Data Infrastructure of the Basque Country geoportal (http://www.geo.euskadi.eus). Google Earth imagery was examined directly within the Google Earth platform, while orthophotographs and DTMs were analysed using QGIS Desktop version 3.34.8 (QGIS Development Team, 2024). The comprehensive list of the remote sensing datasets considered in this study is provided in the Supplementary Material.

The analysis of a high-resolution DTM was employed to extract key morphometric parameters relevant to the characterization of coastal cliffs and the shoreline. These parameters included slope angle, elevation of cliff edges, horizontal distance of cliff edges from the shoreline and its sinuosity. Slope and elevation data were derived from the DTM using standard terrain analysis tools in QGIS. The positions of cliff edges were delineated by identifying abrupt changes in slope (topographic breaks). The mapped cliff lines were then used to calculate their horizontal distance from the current shoreline, the latter was derived from the 2017 DTM (the most recent available).

Shoreline sinuosity was calculated as the ratio between the actual length of a given coastal segment and the linear distance between its two endpoints. This parameter provides insight into the degree of irregularity or meandering of the shoreline, which may be indicative of underlying geological controls or erosional processes (cf. Swirad and Rees, 2015).

Climatic information was obtained by extracting values for the Basque Coast UGGp area from daily precipitation and temperature raster datasets averaged for the period 1971-2016, downloaded from the database of the public environmental management company of the Basque Government (https://www.euskalmet.euskadi.eus/clima/euskadi/; spatial resolution <1 km).

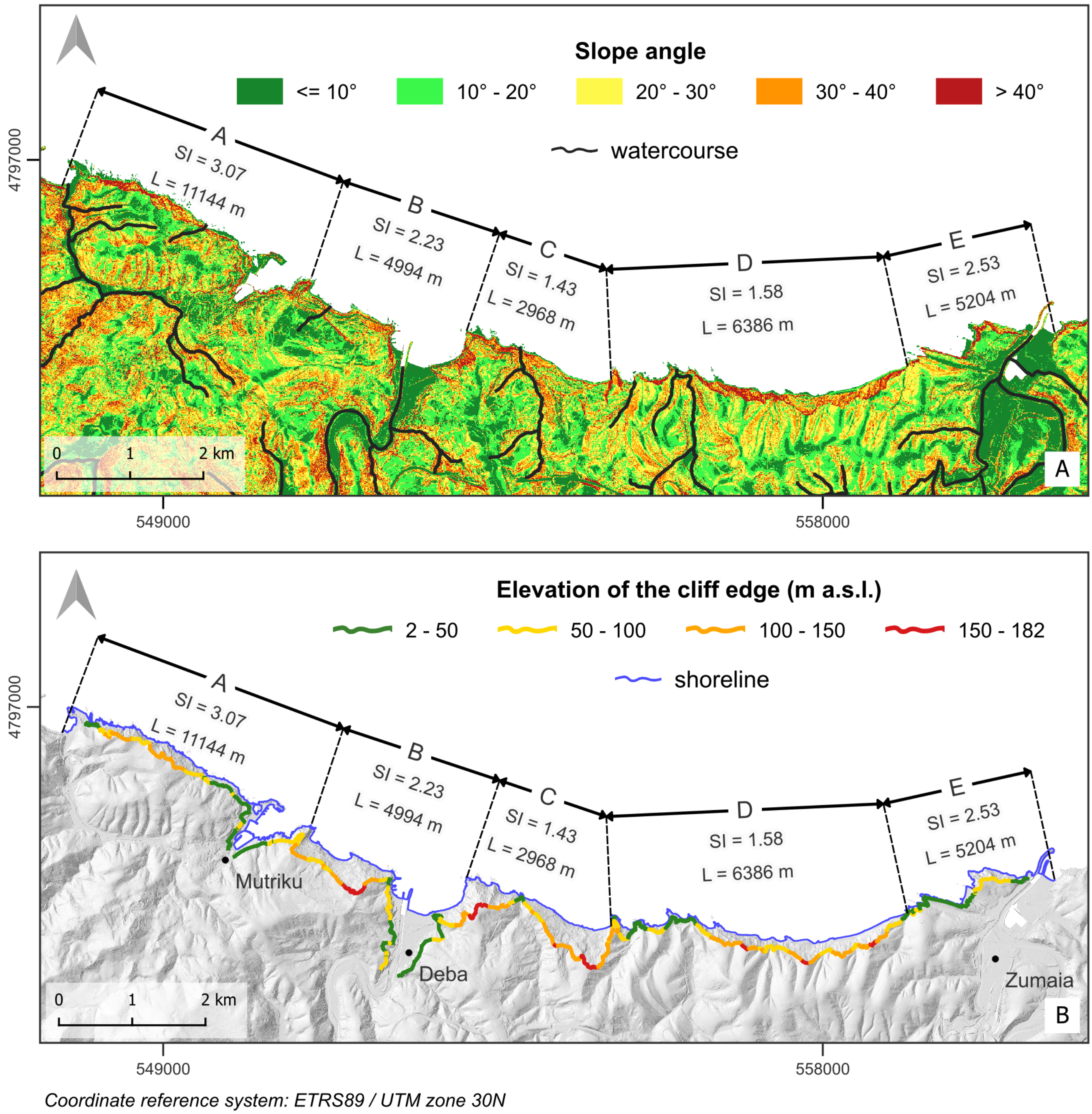

Figure 3 - Morphometric parameters of the analysed coastal stretch. Segments A to E correspond to the five coastal sectors described in the text. Abbreviations: SI - Sinuosity Index; L - Actual Length.

LANDFORM INVENTORY

General morphometric characteristics

The entire coastal stretch is 30.7 km long, which gives the overall sinuosity of 2.2. However, there are evident differences in sinuosities calculated for shorter, distinctive coastal sectors A to E (fig. 3). These are 3.07; 2.23; 1.43; 1.58; and 2.53 for the consecutive sectors. The estuaries rather than lithology have decisive influence on the sinuosity value. Two sectors in the central part of the coast (C, D), even though they are developed in contrasting bedrock (Black flysch and Calcareous flysch, respectively), have the lowest sinuosity values, around 1.5. The presence of coastal landslides (see next sub-sections) does not increase shoreline sinuosity.

The slope map (fig. 3A) shows the predominance of very steep coastal slopes, inclined more than 40°. These precipitous slopes are either sea cliffs *sensu stricto* or head scarps of coastal landslides. In the latter case, they are located up to some 500 m inland from the actual shoreline. The longest reaches of very steep coastal slopes are located in the western part of sector A and throughout sector D, where the steep belt is also the widest. The slope map also captures some shore platforms (narrow green bands along the shoreline). Undercutting of gently sloping (<20°) inland terrains by coastal cliffs is evident too and the distinctiveness of the morphological edge above the cliffs allowed us to define an active cliff zone. Its width varies along the investigated coast from less than 50 m to some 500 m in the eastern part of sector C (fig. 3B). Likewise, the height of the edge varies, from less than 10 m at the mouths of minor valleys in Sakoneta and Zumaia to more than 170 m to the east and west of Deba, and west of the Mendatagaina promontory (fig. 3B). The mean cliff-edge elevation for sectors A to E is as follows: 64 m (A), 81 m (B), 119 m (C), 85 m (D), and 43 m (E). The percentage of the cliff edge exceeding 100 m above sea level (a.s.l.) in each sector is: 24% in sector A, 34% in sector B, 78% in sector C, 41% in sector D, and 0% in sector E. The fundamental lithological bipartition of the coast, with the boundary at Mendatagaina is poorly reflected in the morphometric characteristics of the coastal belt.

East section - Calcareous flysch

Coastline configuration

The eastern section of the coast is 11.6 km long and was divided into two sectors (fig. 1; see section "Physical setting"). Sector D as a whole, from the Mendatagaina headland to Algorri, is approximated by a gently curved arc, although in its westernmost part, at Sakoneta, two minor embayments are present. The bounding headlands have N-S or NNW-SSE extension consistent with the strike of flysch strata. The dip is steep (around 50°) towards E/ENE. Thus, all three promontories are homoclinal ridges, less steep on the eastern side, and truncated by the sea in the north. Mendatagaina is higher than the other two, reaching an altitude of 110 m a.s.l. The other headlands are approximately 50 m high, although the highest cliff is present inside the embayment between the two, reaching 70 m in height.

From Sakoneta to Algorri the coastline does not show any variability in ground plan, following the gentle arc, even though the height of the active cliff zone varies from approximately 30 m to 150 m. Although the active cliff zone represents a continuous belt of landslides (see section "Landslide-shaped coastal slopes"), the depositional parts of these landslides are all trimmed along the shoreline.

Sector E near Zumaia has a more varied configuration, reflected in its higher sinuosity of 2.53. It begins with three minor bedrock headlands, partly submerged during high tide, followed by a larger embayment and then the promontory of Algorri. They are all extended WNE-ESE, reflecting the strike of the flysch strata, but differ in terms of geology. The minor headlands are within the Zumaia-Algorri Formation, made of alternating mudstones and limestones. The latter are more resistant and having locally higher thickness (1-2 m) and being separated by mudstone beds less than 0.5 m thick, form the rock ribs. The embayment is excavated in the uppermost part of the Zumaia-Algorri Formation (and exposes the K/T boundary), whereas the Algorri headland is built mainly of limestones belonging to the younger Aitzgorri Formation. Reflecting the dip of strata to the NNE, it takes the form of a homoclinal ridge approximately 30 m high. However, except the tip of the headland, only the northern slope faces the sea and it does so over a distance of 600 m, whereas in the south it is bound by a dry valley parallel to the extension of the ridge and sloping to the east. Thus, the valley is clearly beheaded and had its upper part in the area where the marine embayment now exists.

The Algorri headland is followed by the asymmetric Itzurun Bay, bounded on the northern side by a short headland of Marianton, parallel to the Algorri one. It is excavated in the marlstones and sandstones of the Itzurun Formation. The width of the bay between these two headlands is 450 m. The final section of the coast is a north-facing cliffed slope of Talaimendi headland, extended parallel to the strike of the youngest Jaizkibel Formation of early Eocene age.

Rock cliffs

Nearly the entire eastern section of the Basque Coast UGGp coastline consists of steep coastal slopes which can be divided into two main varieties: (a) marine cliffs *sensu stricto*, where a bedrock slope, vertical or considerably inclined (>35°), is in direct contact with the sea, at least during storm events; (b) landslide-shaped slopes, where the distal parts in contact with the sea are not made of in situ bedrock but of colluvial packages in different stages of disintegration. The latter will be presented separately in section "Landslide-shaped coastal slopes". These two varieties account for approximately 45% and 55% of the coastal length, respectively.

The wave-undercut cliffs show variable morphology in detail, primarily depending on the orientation of the strike of flysch strata with respect to the outline of the coastline, hence the intersection angle between the two. If the strike is perpendicular, cliffs have jagged faces composed of alternating ribs and recesses in more and less resistant layers, respectively (fig. 4A). Sakoneta Bay is the best example of this subtype of cliff, where the flysch beds dip steeply (40-50°) to the NE and the curvilinear cliff base faces NW. A similar situation occurs in the northern part of the Itzurun Bay, where the flysch beds are almost standing upright (fig. 4B). In contrast, if the strike is locally parallel to the coastline, the cliff face coincides with an exposed bedding plane (or

Figure 4 - Rock cliffs in the Calcareous flysch. A) jagged cliffs formed by steeply dipping flysch beds (40-50° NE) at Sakoneta Bay, the best example of this cliff subtype; B) similar near-vertical beds in northern Itzurun Bay; C) smooth bedding planes where strike aligns with the coast, at Algorri promontory (~20 m high); D) similar structure but higher (~50 m) at Mendatagaina; E) large boulders at the base of Talaimendi, likely from a submerged offshore ridge, as they differ lithologically from the overlying cliff.

a few closely spaced planes) and is remarkably smooth over tens of metres long. Cliffs of this type may have different heights. Those of the Algorri promontory (fig. 4C) are relatively low (up to 20 m), whereas those on the eastern side of Mendatagaina promontory are up to 50 m (fig. 4D).

Exposed rock slopes of cliffs are affected by gradual block-by-block disintegration, facilitated by a dense network of joints and cracks in the flysch beds, as well as by occasional rock fall, but rockfall-derived talus is scarce, probably limited to places where rock-slope failures occurred very recently. Exceptional are large boulders at the base of the cliffs of Talaimendi promontory, but their connection with the cliff above is uncertain as lithologically they do not match each other and the source of boulders may be related to thick turbidites located about 100 m to the north in a higher stratigraphic position, perhaps as a now submerged ridge further offshore (fig. 4E). Otherwise, storms appear capable of removing big boulders and re-exposed the cliff base. All wave-undercut cliffs are juxtaposed with shore platforms (see section "Shore platforms"), locally covered by gravel, and in no place plunging cliffs occur.

Landslide-shaped coastal slopes

In addition to the above-mentioned cliffs, the east section of the investigated coastal stretch is characterized by slopes affected by numerous landslides of different types and size, the onset of which is controlled by the setting and lithology of the flysch strata. Two examples are taken to describe the most significant landslides in the Calcareous flysch.

The Pikote landslide is located along the coastal stretch between Elorriaga and Zumaia, in the locality of Andikaerreka. Its length along the coastline is some 360 m, while the width varies from approximately 200 m in the central part to 150 m at its flanks. The edge of the landslide scarp has an approximate length of 400 m and the landslide deposit covers some 45,000 m^2. The absence of vegetation along the slope, visible on a sequence of historical orthophotos dating back to 1945, suggests that the area has been unstable at least since that time. One major landslide event occurred in 1997, as documented in historical records, and resulted in the loss of livestock and agricultural land. The landslide deposit comprises different morphological units which reflect the dynamics and evolution of the gravity-induced processes involved (fig. 5). Deformation and folding of the rock layers were recognized within the landslide as well as a back-tilted block at its front.

The second landslide, located at Baratzazarrak, has a length along the coastline of some 380 m, while the width varies from approximately 280 m in the central part to 130 m at its western flank (fig. 6). The edge of the landslide scarp has an approximate length of 550 m and the landslide deposits cover an area of 60,000 m^2, characterized by displaced blocks with stepped and hummocky topography (fig. 6, features A, B).

The Baratzazarrak mass movement can be classified as a complex landslide. Field observations of landforms indicate a complex style of activity, including both a main rotational movement and secondary translational sliding testified by planar shear surfaces within the landslide body (fig. 6, features C, D). Additionally, debris slides have been observed along the cliffs bordering the landslide flanks, highlighting active geomorphic processes on the slope (fig. 6, feature E).

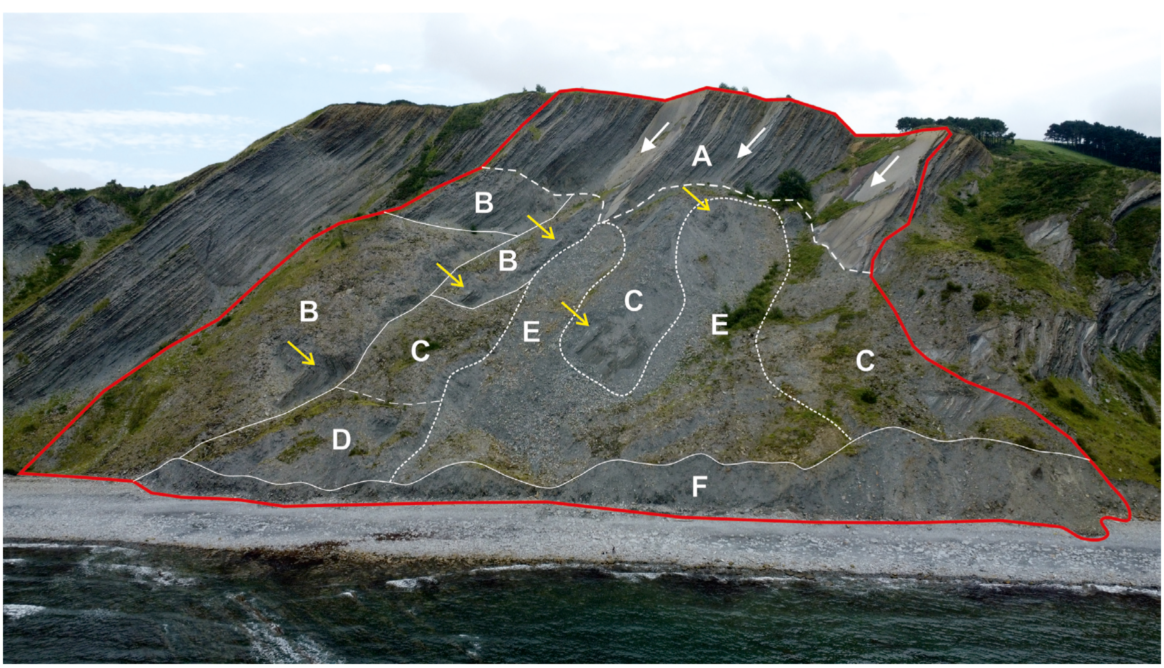

Figure 5 - Annotated drone photograph of the Pikote landslide showing its main units. Red line shows the extent of the entire landslide area as of July 2024. A) head scarp, with three main slip planes indicated by arrows; B) slid blocks with the internal structure largely preserved, only locally deformed; C) slid blocks which experienced higher internal deformation and breakdown of flysch strata; D) subsequent rotational slide in the frontal part of the slid block, with a back-tilted upper surface (grass-covered area in the top); E) subsequent debris slides and flows within the most disintegrated parts of the landslide colluvium; F) landslide toe subject to marine undercutting and trimming. Yellow arrows show places where intact original bedding of flysch is preserved.

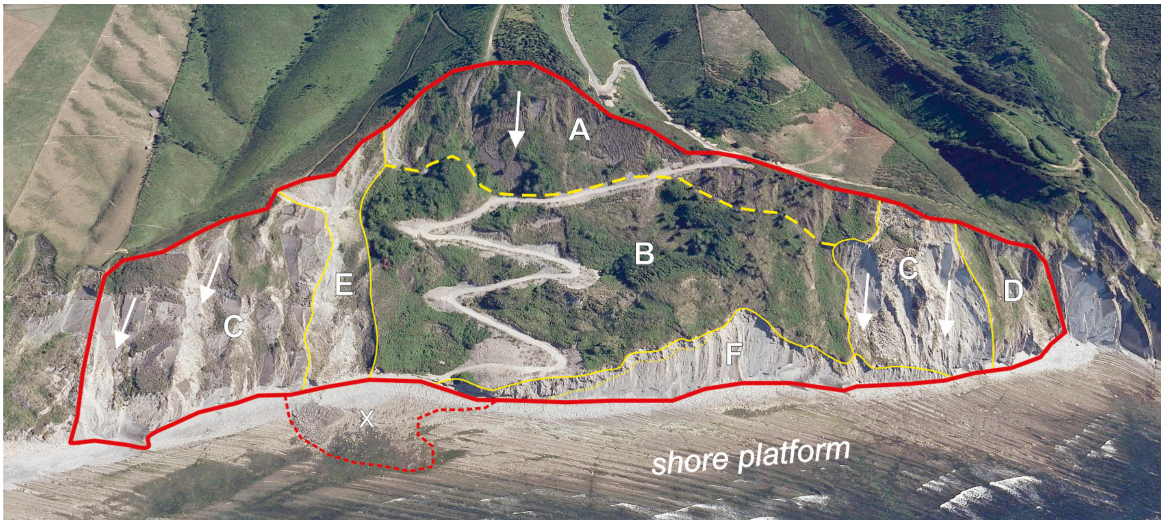

Figure 6 - Annotated Google Earth imagery (image dated 2011) of the complex Baratzazarrak landslide showing its main units. Red line shows the extent of the entire landward part of the landslide area. A) head scarp; B) displaced blocks with stepped and hummocky topography; C) exposed slip planes of translational slides (sense of movement indicated by arrows) and minor perched patches of disintegrated bedrock; D) marginal part of the landslide, with slip planes largely overgrown; E) subsequent debris slides; F) landslide toe subject to marine undercutting and trimming. The dotted line separates landslide deposits (above) from intact bedrock (below). The area marked by 'X' within the shore platform shows considerable distortion and disintegration of flysch strata, interpreted as an effect of overload caused by landslide body, which extended father into the sea but was subsequently eroded.

Aerial photographs confirm that the landslide pre-dates 1945-46, as they show the landslide deposit already in place and covered by vegetation. Since that time, the landslide has experienced periodic localized reactivations. In particular, orthophotos from 1977-78 and 2012 reveal fresh shear surfaces characterized by exposed, vegetation-free rock planes. Notably, the orthophotos from 1977-78 also indicate a potential debris slide along the eastern flank, further illustrating the highly dynamic nature of the slope. The landslide toe is actively subjected to marine undercutting and trimming (fig. 6, feature F).

At the landslide flanks, features possibly attributable to visco-plastic deformation, resulting in folding of the flysch strata, are present. The evidence of deformation of flysch beds was also observed at the level of shore platform immediately in front of an eroded toe of the landslide (fig. 6, feature X). Normally, flysch layers follow WNW-ESE strike and dip towards the north at an angle of 20-30°, but in the platform section adjacent to the trimmed toe of Baratzazarrak landslide the arrangement of strata is different. In plan, they follow a semi-circular pattern, pointing towards the sea, whereas in cross-section their dip is much steeper, locally up to vertical and even overturned (i.e., dipping to the south). Inland, these anomalously dipping strata hide under the landslide deposits. In addition, the strata are heavily broken along densely spaced fractures. Remarkable is the sharp boundary between the deformed and undeformed flysch. These distortion zones are only developed just below the largest landslides, thus the causal connection between both seems clear enough.

Shore platforms

Sloping shore platforms belong to the landmarks of the Basque Coast UGGp and are particularly well-developed along the eastern coastal sector (fig. 7). The most renowned locality is Sakoneta (Hilario *et al.*, 2023), but in fact the platforms coexist with cliffs along most of the coastal stretch between Mendatagaina and Zumaia, except some rocky promontories. However, although they may appear planar from a distance, they are highly corrugated reflecting multiple lithological changes within the flysch succession.

The Calcareous flysch consists of repetitive alternations of thin strata of more resistant limestone and sandstone and less resistant mudstone and marl, which are hardly more than 1 m thick and not uncommonly only 20-30 cm thick. More resistant layers stand out, forming sharp ridges: "teeth" (narrow) or "ribs" (wider), depending on the width of the bed, whereas less resistant layers coincide with linear depressions. The height of upstanding elements varies, also depending on the thickness and resistance of strata, from only a few tens of centimetres (fig. 7A) up to 3-4 m near Algorri (fig. 7B). The continuity of upstanding elements is locally interrupted by joint-aligned troughs (fig. 7C).

The dip of strata is another factor controlling the microrelief of the platforms. If the dip is not far from horizontal (up to 20° or so), the ridges resemble cuestas, with smooth, gently sloping ramps on one side, and steep faces on the opposite one, with overhangs above the less resistant underlying beds. With an increasing dip the ridges become more and more steep and symmetrical, whereas at very steep dip almost vertical fins form (fig. 7D). At the

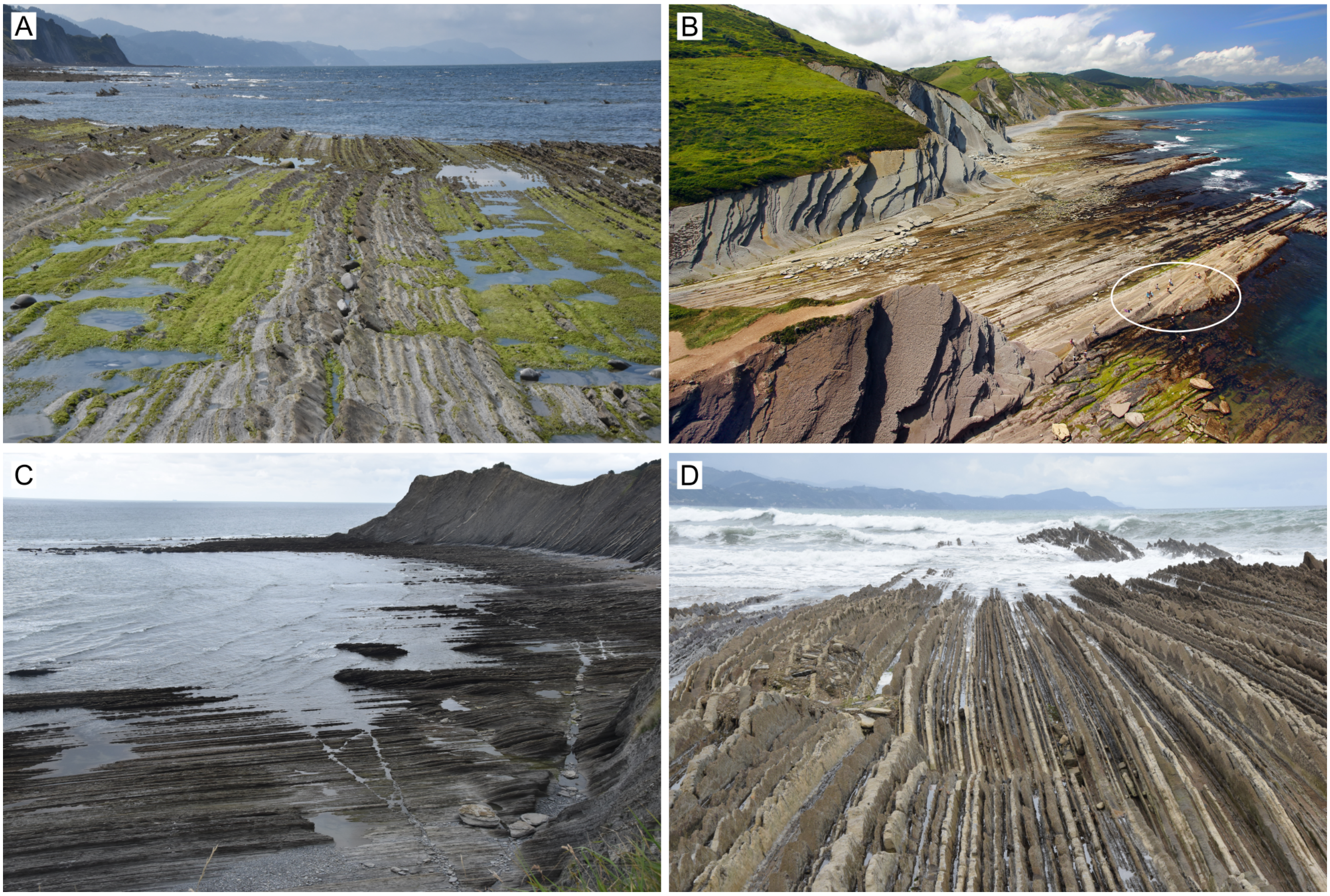

Figure 7 - Examples of shore platforms in the Calcareous flysch. A) low relief of a shore platform beneath Elorriaga, B) high relief of a shore platform at Algorri (note people on a few metres high ridge for scale), C) shore platform dissected by joint-aligned troughs at Sakoneta; D) near-vertical fins are associated with very steep dips (Itzurun Bay).

most local scale, facetted microrelief of the ridges reflects orthogonal jointing of the flysch beds, with individual facets following joint surfaces.

Platforms are repeatedly exposed and submerged according to the diurnal rhythm of the tides. At maximum emergence, the width of exposed parts reaches 100-120 m, with the farthest extent at the Sakoneta headland, up to 180 m into the sea. In contrast, at high tide the platforms are almost entirely submerged.

Notches and sea caves

Sea caves occur in various places along the coastal sector cut in the Calcareous flysch, particularly at Playa de Itzurun in Zumaia and at Mendatagaina promontory. They are evident rock-controlled features and develop through preferential erosion focused on various lines of weakness. These may be bedding planes, fractures, or the combination of both (fig. 8A). Bedding-controlled caves require initial breaching of a more resistant layer facing the sea, whereas their subsequent enlargement takes place in weaker strata inside the cliff. The cave shown on fig. 8B, located at Playa de Itzurun, is the largest example of this type, being 30 m long and up to 8 m wide. The height to the ceiling is up to 8 m at the opening. The cave gallery in cross-section is slanted inland, in perfect accordance with the inclination of the strata. In contrast, the cave presented on fig. 8C, only a few metres away from the former one, has enlarged along a fracture which is perpendicular to the bedding and intersects the cliff at a right angle. It is 11 m wide at the opening and continues for 13 m into the cliff, getting more and more narrow. Both these caves are within the range of high tide. The sea caves at the tip of Mendatagina promontory have been facilitated by fractures related to the Andutz Fault and have developed along bedding planes, which here are striking perpendicular to the coastline (fig. 8D).

Coastal notches are neither very common nor particularly distinctive along the Basque Coast UGGp coastline. Reasons likely reside in the properties of flysch strata exposed at the base of the cliffs. Notches are typically associated with more massive lithologies, with fewer discontinuities, or exploit horizontal lines of structural/lithological weakness. In addition, the rock above the notch should be strong enough to withstand tensile stress and not to col-

Figure 8 - Marine caves developed in flysch in the Basque Coast UGGp. A) general view of bedding-controlled cliff at Playa de Itzurun, with arrows indicating the location of individual caves. The entrance to the first cave on the left is hidden behind the cliff face; B) bedding-controlled cave at Playa de Itzurun; C) fracture-controlled cave at Playa de Itzurun; D) bedding and fracture-controlled caves at Mendatagaina promontory.

lapse into the void created by wave undercutting. None of these conditions seems to be fulfilled at the coastline of the Basque Coast UGGp, where frequent alteration of flysch strata of contrasting resistance and their steep dip do not favour uniform undercutting of cliff base. However, in a few places rounded basal recesses have been found and these show resemblance to coastal notches (fig. 9).

West section - Black flysch

Coastline configuration

The western section of the coast is 19.1 km long and divided into three sectors separated by the small bay of Mutriku and the estuary of Deba. In terms of general coastline configuration they are similar, with low sinuosity between the estuaries and the absence of significant headlands, but they show more varied ground plan in detail.

The westernmost sector (A; fig. 1) begins with the Saturraran Bay, with a sandy beach inside, excavated in shales of the Mutriku Formation and delimited in the north by a rocky headland and a stack built of greywackes belonging to the same formation. These erosional features extend for 230 m into the sea, following the NW-SE strike of the strata. The dip is close to vertical and the stacks are correspondingly symmetrical in a cross-section. Further to the east the coastline is approximately straight, cut in shales of the Kardala Formation, until it reaches the bay of Mutriku, which is approximately 750 m long and 550 m wide in the most distal part, where it joins the open sea. The inner part of the bay hosts the harbour of Mutriku and has been completely modified by constructional activities.

The next sector (B) starts with a minor promontory of Alkolea, which closes the Mutriku bay on the eastern side and reflects complicated tectonics along a local fault (fig. 2) (Agirrezabala *et al*., 2022). The promontory is 270 m long and 150 m wide at the landward head, and is built of greywackes which here strike SW-NE Further to the east the coastline is composed of alternating broad bays and straight cliff lines, broadly parallel to the WNW-ESE strike of the Black flysch strata, here belonging to the Deba Formation. The estuary at Deba is approximately 650 m long and 850 m wide in the most distal part. Inside there is a wide sandy beach, whereas the most inland part made by coastal dunes in the past has been heavily transformed anthropogenically and is occupied by reclaimed land.

The promontory of Aitzandi marks the eastern boundary of the Deba estuary and the beginning of sector C, which then extends to the Mendatagaina headland. The coastline is nearly straight and closely parallel to the WNW-ESE strike of the Deba Formation. Most of this section is occupied by a large Mendatagaina landslide (see section "Landslide-shaped coastal slopes").

Cliffs and coastal slopes

Coastal slopes along most of the western sector are not precipitous cliffs but steeply inclined (30-50°) ramps, with flysch bedrock exposed in the lower slope sections, whereas the upper slopes are covered by regolith and vegetated. However, the upper limit of bare rock belt does not retain constant elevation but shifts up and down, apparently reflecting the state of stability and time elapsed from the last episode of mass movement (fig. 10A, B). Slope morphology in detail reflects bedrock properties, particularly the clarity of bedding. In the Deba Formation, to the east of Deba, bedding surfaces are well-developed and exposed as large slabs measuring tens by tens of metres (fig. 10A). Further to the west, beyond Mutriku, cliffs are cut in the more homogeneous Kardala Formation and show less regular morphology, with evidence of remodelling by both minor rock slides and larger landslides. Localized taluses of large angular boulders provide evidence of most recent rock falls and planar rock slides, whose presence is also tes-

Figure 9 - A notch in the coastal section beneath Elorriaga. The ruler is 1 m high.

Figure 10 - Coastal slopes in the Black flysch. A) well-developed bedding surfaces east of Deba, exposed as large slabs measuring tens by tens of metres; B) minor bays, some with pocket gravel beaches, and steep but not cliffed coastal slopes; C) localized taluses of large angular boulders as evidence of rock falls and planar rock slides, whose presence is also testified by scars within the rock slopes.

tified by scars within the rock slopes (fig. 10C). In addition, between Deba and Mutriku the cliff base was altered by seawall constructions, to provide protection to the coastal road that goes immediately above.

Landslide-shaped coastal slopes

The largest landslide complex in the Black flysch section occurs to the west of the Mendatagaina promontory. Its length along the coastline is more than 1.2 km, whereas the width varies from approximately 100 m in the westernmost part to 500 m in the eastern part, indicating the widest section of the active cliff zone. The landslide area is morphologically complex and likely consists of several contiguous landslide bodies, which may have been active at different times (fig. 11). Unit (A) is a complex landslide which has most expanded inland by retrogressive development and is currently approximately 500 m long. The most elevated part of the landslide crown is at 150 m a.s.l. The upper part of the landslide represents irregular hummocky terrain, now largely overgrown by forest, whereas the lower part seems to consist of more coherent blocks. The toe part is trimmed by the sea and subject to secondary displacements (fig. 12).

The landslide unit (B) did not advance inland as much as unit (A) and probably consists of several displaced blocks, whose internal deformation during movement gave rise to the rough, heavily vegetated terrain (fig. 11). It is approximately 450 m long and up to 250 m wide, with the elevation difference of 120 m. Minor secondary slides affect the frontal part, apparently triggered by wave undercutting of colluvial complexes. Even further to the west extends the landslide unit (C), which represents a complex translational slide. Coast-parallel bedding surfaces, inclined to the north, act as slip planes. Some displaced slabs retain their soil and vegetation cover, whereas others have largely disintegrated into platy boulders which cover the slope/shore platform junction.

Another large landslide is present in the western sector, to the west of Mutriku. It is approximately 400 m in length along the coastline and up to 200 m wide, with an arcuate head scarp suggesting rotational component of movement.

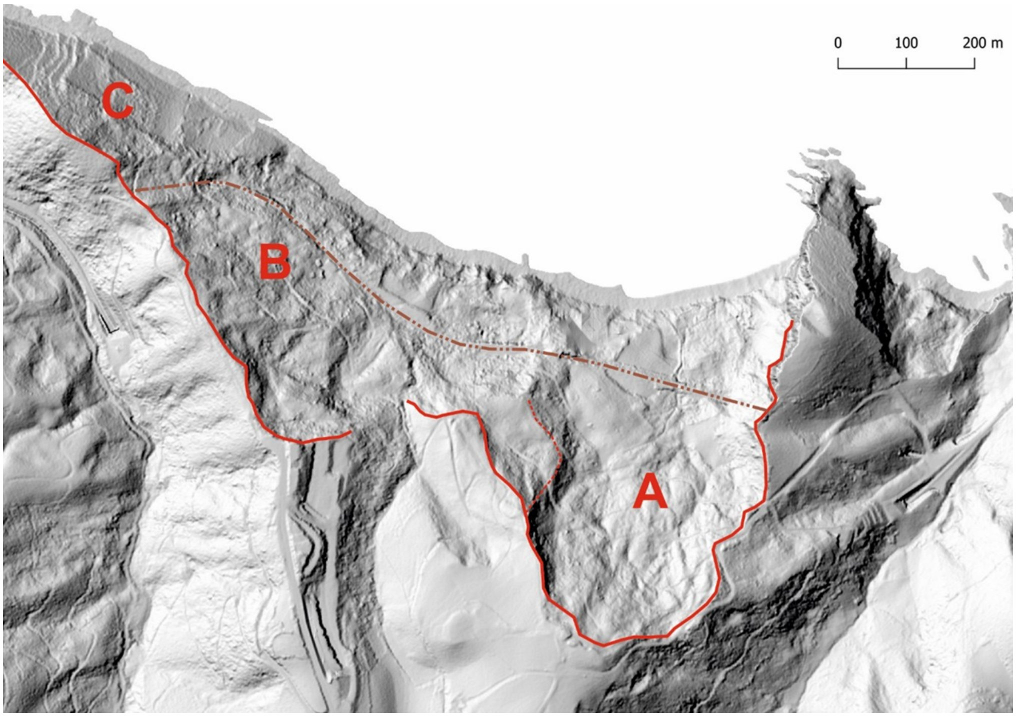

Figure 11 - Landslide area to the west of Mendatagaina promontory on high-resolution DTM. Solid red line indicates an approximate course of the landslide crown, broken brown line shows the course of an abandoned railway track. Letters indicate the diverse landslide units: A, B: Complex landslide with retrogressive development; C: Complex translational slide.

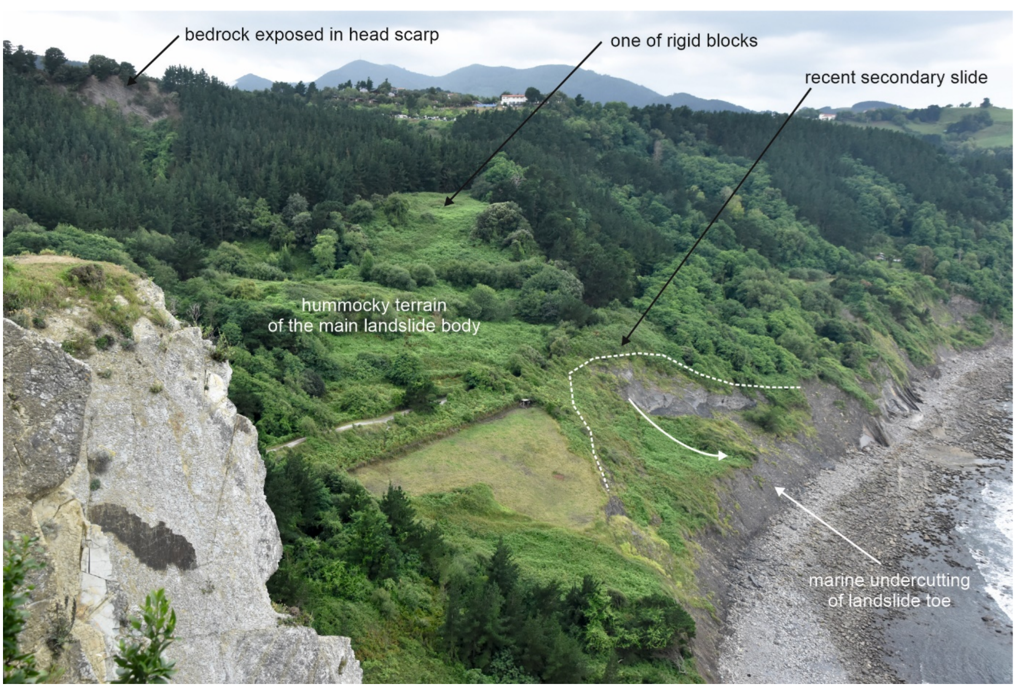

Figure 12 - Morphological details of the Mendatagaina landslide unit A (see fig. 11) which is extensively covered by vegetation. Secondary slides can be clearly seen in the toe part.

Shore platforms

The shore platforms in the western sector of the coast are different from those in the east. Except specific localities such as next to Saturraran beach, they lack regular repetition of strata of contrasting resistance to abrasion and hence, jagged microtopography is absent or poorly developed. Moreover, even where such alternations exist, the strike is generally parallel to the coastline, in contrast to the Calcareous flysch, where it is at an angle or close to perpendicular to the coastline. Therefore, platforms consist of multiple ramps gently sloping towards the sea, of increasing height in the landward direction (fig. 13A). Elsewhere, they show wavy topography with no regular pattern of minor landforms.

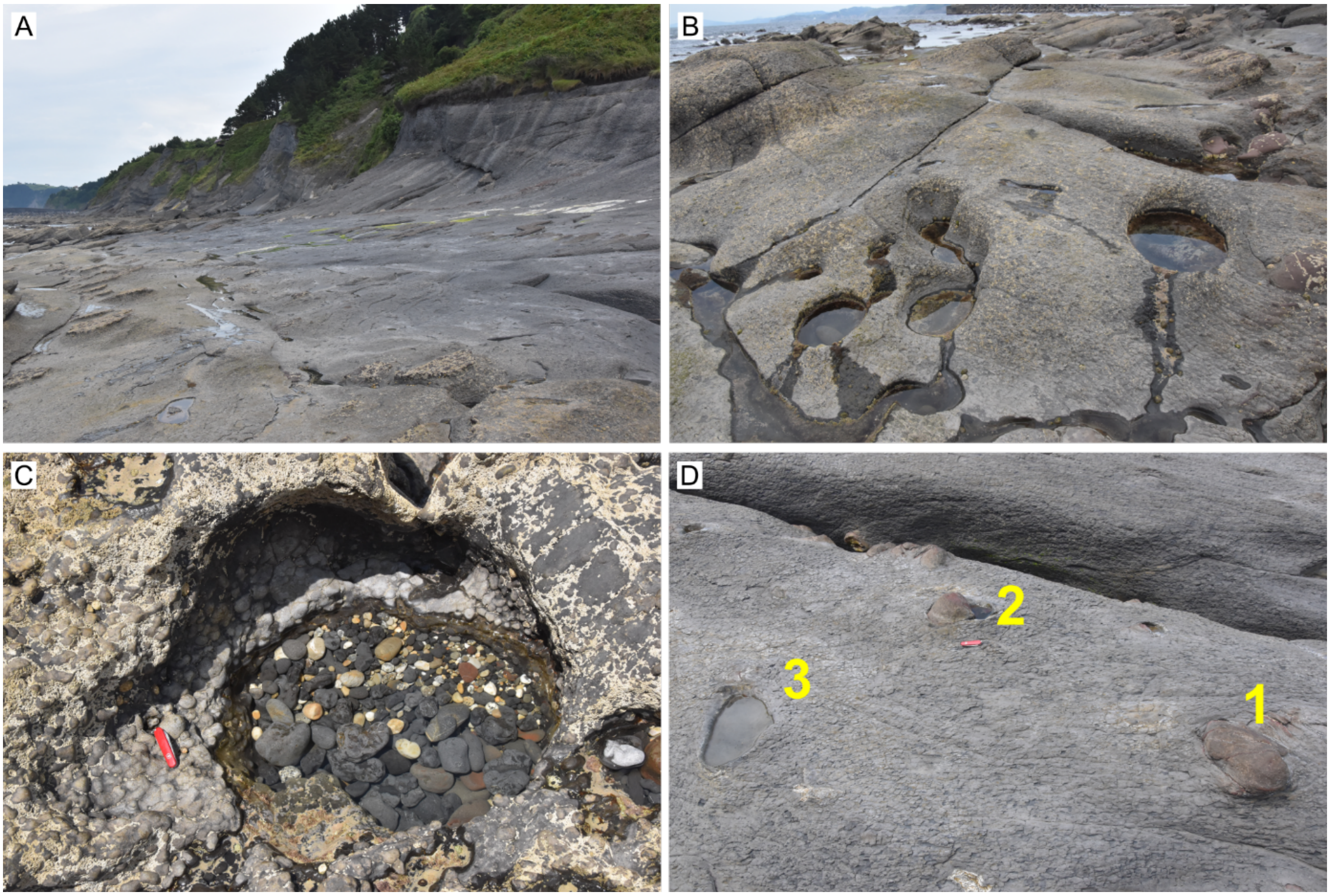

Figure 13 - Shore platforms in the Black flysch and related microtopography. A) undulated surface of a ramp-like shore platform next to Mutriku; B) group of potholes and connecting channels; C) large circular pothole in Mutriku, filled with pebbles; D) evolution from a protruding siliceous concretion (1) to the small pothole (3). (2) shows an intermediate stage, where the concretion is partly broken along a crack, one part has been removed and a small basin originated in this place. Wave removal of the remaining part of the concretion will produce a hollow similar to that of (3). A knife (red) indicates scale.

However, this type of relief allowed for the development of potholes which are almost absent in the Calcareous flysch. They are particularly abundant to the west of Mutriku in the marly and lithologically homogeneous Kardala formation, where their dimensions vary from 10-15 cm in diameter and less than 10 cm in depth, to much larger features, approximately 1 m across and up to 50 cm deep (fig. 13B, C). They typically have gravel and pebbles inside, which are abrasive tools set in motion by waves during high tide. Some potholes, especially the oval ones, have developed along fracture lines, locally occurring in strings, one after another. Other potholes seem to be initiated by preferential erosion of siliceous concretions inside the flysch. These concretions, being more resistant, are upstanding elements and protect the flysch below, causing minor undulations of the platform. However, they are also easy to detach from their base by strong waves and if this happens, a hollow emerges on top of such an undulation (fig. 13D). These can then develop into potholes.

DISCUSSION

Diversity of geological controls

The coastline in the Basque Coast UGGp is primarily erosional and subject to retreat in the long term. Hence, the majority of landforms along the coast is erosional, with hard rock cliffs and sloping shore platforms being dominant. However, depositional landforms occur too, especially within more sheltered settings such as minor bays and estuaries.

The coastal morphodynamics is strongly influenced by the lithological contrasts and structural orientations of the flysch successions, namely the Black flysch and the Calcareous flysch, which exhibit markedly different geomorphic expressions (cf. table 1). In particular, the intersection of flysch strata with the shoreline at different angles in different places along the coast is of fundamental importance for the initiation, mechanisms, and evolution of coastal landslides. The latter are strictly controlled by the dipping of the strata. When the dip of the strata is

Table 1 - Comparison of geological and geomorphological features between the Black flysch and Calcareous flysch sections in the Basque Coast UGGp.

	Black flysch	Calcareous flysch
	Geology	
Lithology	Greywackes (more resistant) Shales (less resistant)	Limestones, sandstones (more resistant) Marls, mudstones (less resistant)
Structure	Strike mostly parallel to the coast Moderate dip (~20-40°) in seaward direction	Strike of variable orientation in respect to the coast, from parallel to perpendicular Variable dip, from moderate (~20-30°) to vertical
	Landforms	
Cliffs	Sloping Smooth, planar microtopography due to structural accordance	Vertical Jagged microtopography reflecting local lithological change in flysch
Mass movements	Minor rock slides and angular talus Two larger landslide complexes (rotational/translational)	Abundant multiple translational landslides along bedding planes Secondary debris flows and slides within colluvium Trimmed colluvial packages Localized rock falls
Platforms	Less developed platforms Wavy topography Potholes abundant	Larger platforms Jagged microtopography – ribs and troughs Landslide-induced structural deformation
Stacks and rocky promontories	Few	More common
Caves	None	Present, mostly bedding and fracture-controlled
Hanging valleys	Few and indistinct	Common

perpendicular to the coastline and the bedding planes are inclined towards the sea, rock sliding prevails, with failure surfaces along the bedding planes. When the direction of dip is oblique to the coastline, landslide mechanisms tend to be more complex, also in relation to the mechanical behaviour, thickness and related resistance to erosion of individual strata.

The coastal section developed in the Black flysch, characterized by alternating layers of turbiditic greywackes (resistant) and shales (less resistant), typically exhibits a seaward-dipping stratigraphy (20-40°), with the strike mostly parallel to the shoreline. This configuration produces sloping cliffs with smooth, planar faces that follow the dip. The latter also plays an influence of the erosional landforms which in this section tend to have gentler and less rugged shapes, with shore platforms featuring undulating surfaces and abundant potholes. Slope instability processes are generally limited to minor rock slides and isolated talus accumulations, although larger landslide complexes, such as rotational/translational features, can locally occur.

The coastal section developed in the Calcareous flysch comprises more lithologically diverse sequences – resistant limestones and sandstones interbedded with weaker marls and mudstones – and exhibits a broader range of structural orientations, with bedding aligned both parallel and perpendicular to the coastline (fig. 2). This results in highly variable cliff landforms. Where bedding dips steeply or is near-vertical, cliffs tend to be vertical and jagged, reflecting differential weathering along lithological contacts. These cliffs are more prone to multiple translational slides, rock falls, and remobilization of surficial deposits. Likewise, shore platforms have highly irregular relief reflecting alternation of more and less resistant strata, as well as variable strike of the strata in respect to the shoreline. Therefore, within a limited area they represent most variants described by Trenhaile (1987). However, a possible correlation of platform width with structural background has not yet been attempted. In addition, notable even though localized features on shore platforms are strongly distorted and broken strata evidencing structural deformation from mass-wasting processes. The presence of caves, largely bedding-controlled, and hanging valleys enhances the diversity of landforms in this coastal section.

This litho-structural interplay explains the observed spatial heterogeneity in cliff types and morphological features of platforms across the investigated coastal stretch. Areas where the bedding strikes parallel to the shoreline tend to develop smoother and more continuous cliff faces, whereas sections with bedding oriented perpendicular to the coast typically exhibit more irregular, serrated cliff profiles due to the prominent exposure of bedding planes in cross-section.

Active geomorphological processes on cliffs

The ongoing geomorphological processes in the Basque Coast UGGp are primarily driven by the interaction between geological structures and coastal dynamics. Hence, the evolution of the coastline is influenced by geological controls and long- and short-term processes, among which the gravity-induced ones play a major role.

The Pikote landslide, located between Elorriaga and Zumaia, is a significant example of the complex interplay between geological structures and coastal processes. The landslide area has been unstable since at least 1945, with a major event occurring in 1997. The landslide deposit comprises different morphological units, reflecting the its dynamics and evolution. The gradual, visco-plastic response of the rocks suggests they responded to sustained low-strain rates, enhancing ductility in otherwise brittle sedimentary layers. Creep deformation in these layers is associated with prolonged subsurface confinement and periodic loading, such as seasonal variations in moisture content, which can further soften weaker layers and support slow plastic flow. This aligns well with landslide-induced deformations in flysch, where lateral compression and shear result in complex folding and bending patterns (cf. Chigira, 1992).

The Baratzazarrak landslide, located west of the Pikote landslide, is another example of the dynamic nature of the coastal slopes. Field observations indicate a complex style of activity, including secondary debris slides along the cliffs bordering the landslide flanks. The presence of deformed flysch beds is tentatively interpreted as resulting from an overload imposed by the displaced landslide masses. The colluvium and part of the flysch bedrock have been eroded by waves, exposing bedrock previously concealed beneath it. The slow displacement is compatible with visco-plastic deformations occurring at the landslide flanks, with the resultant folding of the flysch strata.

The geomorphological evolution of the landslide-shaped slopes reflects a dynamic interplay between mass movement processes and coastal erosion. The toe of the landslides is currently subject to active marine undercutting and wave-induced trimming, which contribute to the progressive removal of landslide debris deposited on the shore platform. In some cases, landslide deposits may temporarily extend across the platform surface, altering local topography and sediment distribution; however, wave action and tidal processes often erode and redistribute these materials. The prolonged undercutting at the base of steep slopes reduces toe support, increasing and leading to slope instability. As a result, the coastal landscape evolves through episodic landslide activity followed by marine erosion, contributing to the retreat and reshaping of the shoreline over both short and long timescales.

Coastal erosion processes in the Basque Coast UGGp are also influenced by the interaction between wave action and geological structures. The shore platforms and cliffs are subject to continuous erosion, leading to the retreat of the coastline. The variability in lithology and structural orientation of the flysch strata results in differential erosion rates, contributing to the diverse coastal landforms observed in the region. Increased extreme weather events are likely to exacerbate coastal erosion and cliff instability, further shaping the geomorphological evolution of the coastline.

CONCLUSIONS

The research carried out involved an integrated application of remote sensing and field survey techniques which allowed us to build-up a landform inventory and to outline the geomorphological processes affecting the coastal cliffs, although the actual rates of these processes were not the focus in this study. Special attention was given to the geological control on landform development since in the investigated area two types of flysch formations crop out, the Black flysch and the Calcareous flysch, characterized by different lithological and structural properties. The different mechanical behaviour of rock strata and their diverse orientation with respect to the coastline result in spectacular landforms which are highly dynamic due to the interplay of coastal and gravity-induced processes.

The research provided an advance in the knowledge of rocky coasts (cf. Trenhaile, 1987) and offered further insights contributing to a better understanding of the geomorphological evolution of a highly sensitive area. The latter is, in fact, characterized by widespread landslide activity that can be dramatically enhanced by intense rainfall or storm surges which tend to be more and more frequent in relation to climate change (cf. Sarkar *et al.*, 2022; Micu *et al.*, 2022).

The outputs of this research can be beneficial for local institutions, including the Geopark management, in terms of environmental enhancement of the valuable geoheritage of the Geopark and for understanding potential hazards (cf. Bollati *et al.*, 2023). These are topical issues in the frame of sustainable development, as far as the safety of people and infrastructures, and the socioeconomic conditions of communities are concerned.

Further investigation of the long- and short-term geomorphic changes of the whole coast of the Geopark and, particularly, in specific sites will provide insights on the possible effects of climate change providing clues for mitigation and adaptation actions.

SUPPLEMENTARY MATERIAL

A list of the remote sensing datasets considered in this study is provided in Supplementary Material at https://doi.org/10.4454/bhk456vf

ACKNOWLEDGEMENTS

This paper is part of the Project 'Coastal Landforms of the Basque Coast UNESCO Global Geopark – From Inventory to Geomorphological Map' funded by the Basque Coast UNESCO Global Geopark (Scientific responsible: Mauro Soldati). The research was also carried out in the framework of the FAR 2024 project of the University of Modena and Reggio Emilia (Scientific responsible: Paola Coratza).

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(Ms. received 22 May 2025, accepted 10 July 2025)