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Rockfall hazard mitigation in coastal environments using dune protection: A nature-based solution case on Barinatxe beach (Basque Coast, northern Spain)

Jon Ander Clemente[a,*], Jesus A. Uriarte[a], Daniele Spizzichino[b], Francesco Faccini[c], Tomás Morales[a]

[a] Department of Geology, Science and Technology Faculty, University of the Basque Country UPV/EHU, Leioa, Spain
[b] ISPRA, Geological Survey of Italy, Rome, Italy
[c] Department of Earth, Environmental and Life Sciences, University of Genoa, Corso Europa 26, Genoa, Italy

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ABSTRACT

Across the world, coastal environments of great landscape, recreational and environmental value are coming under increasing pressure. Within such environments, cliffs are particularly characteristic and unique elements, in which processes of instability develop. Their management requires a transdisciplinary approach ensuring protection of the natural condition of the environment, while at the same time allowing for their continued use and enjoyment. In the case of Barinatxe (Basque Coast), the beach has evolved into a system of foredunes, flanked by cliffs with frequent rockfall processes. This research analyzes the effect of coastal dunes as an element of natural protection. To this end, based on a Digital Terrain Model developed by Terrestrial Laser Scanning (TLS) and in situ geological characterization, 3D modeling has been used to analyze rockfall trajectories and evaluate their runout and energy. These models confirm the protective role of coastal dunes, which act as efficient natural barriers against rock blocks that become detached from cliffs. This is particularly important in areas where the use of tools based on Nature-Based Solutions (NBSs) guidelines is recommended.

1. Introduction

Rockfall is one of the most frequent and damaging types of mass movement (Rosser and Massey, 2022), common in areas of the world with steep rock slopes and cliffs, both in coastal areas and in inland rock formations (Geertsema and Highland, 2011). In many natural spaces around the world, cliffs have a great landscape and recreational value and attract ever greater numbers of visitors. There is, therefore, a growing need to manage these spaces from the perspective of visitor safety, but also with a view to preserving the environment (Morales et al., 2021). In such contexts, risk avoidance has classically been pursued through interventions such as appropriate land use planning regulations and structural measures such as dikes, mounds, dams and barriers, in order to increase the level of protection (Holub and Hübl, 2008; Accastello et al., 2019). The negative aspects of these measures, such as the high construction and maintenance costs involved and the environmental and aesthetic impact they entail (Godschalk et al., 1999; Touili et al., 2014; Gray et al., 2017), has increasingly led to a search for less invasive non-structural measures (Li and Eddleman, 2002; Cruz, 2007; Lacambra et al., 2008; Domínguez-Cuesta et al., 2022), combined with prevention, warning and education strategies based on detailed analyses of the terrain (Baum and Godt, 2010; Basher et al., 2015; Morales et al., 2021).

In recent times, there have also been increasing efforts to address environmental, social and economic challenges through what are known as nature-based solutions (NBSs). Although there is a wide range of definitions of NBSs (Sarabi et al., 2019; Solheim et al., 2021), the European Commission (Cecchi, 2015) identifies them as: “Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions”. A general review of the application of NBSs in urban settings is given in Sarabi et al. (2019), while Solheim et al. (2021) assess the value of implementing NBSs in rural landscapes, by managing vegetation cover

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* Corresponding author.
E-mail address: jonander.clemente@ehu.eus (J.A. Clemente).

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and surface waters to reduce impacts from small, frequent events. Specifically in relation to gravitational risks, Accastello et al. (2019) consider protective forests in mountainous areas as a mitigating measure to be integrated into Environmental Risk Management Strategies.

In this context, the aim of this paper is to analyze the role of coastal dunes as natural barriers for controlling rockfalls and their effectiveness as a nature-based solution for limiting risks in coastal environments. Dunes are found along most of the world's coasts (Martínez et al., 2004; Gao et al., 2020), and in Europe alone the total area of coastal dunes has been estimated at over 5300 km^2 (Delbaere, 1998; Heslenfeld et al., 2004). These environments often remain relatively stable over time, and in previous works, they have been considered as natural solutions against rising sea levels (Sterr, 2008; Pontee et al., 2016; Castelle et al., 2019; Van der Meulen et al., 2022).

The novelty of our study is that it considers dunes as barriers against gravitational processes. The methodological approach, based on detailed topography, assessment of rockfall dynamics and 3D rockfall modeling, seeks to evaluate the way in which dunes can naturally prevent possible damage caused by these events and the safety implications of dune removal. For this purpose, a real case study has been trialed. The characteristics of the study have been framed and its role discussed from a risk management perspective. The area selected for the study is the Barinatxe beach on the Basque Coast (northern Spain). This beach has a dune system developed at the base of the bordering cliff, which range from 35 to 70 m in height and regularly suffer falls of rock fragments. These processes represent a hazard to visitors and users and need to be managed in a way that respects the geological, environmental and landscape values of the surroundings, making this site particularly suitable for testing our approach.

2. Case study: Barinatxe beach

Barinatxe beach is 755 m long and has an area of about 200,000 square meters at low tide and 61,000 square meters at high tide. It is located on the Cantabrian coast of the Bay of Biscay (Fig. 1), between the municipalities of Getxo and Sopelana, in the Uribe Kosta region (Basque Country, northern Spain).

In geological terms (Fig. 2), the region is part of the so-called Basque-Cantabrian basin (Feuillée and Rat, 1971; Ramírez del Pozo, 1973). There, in a basin-bed marine environment, thick sedimentary series were deposited during the Lower Cretaceous - Eocene, characterized by a persistent and well-defined stratification, with major lateral continuity. During the Alpine Orogeny, these materials underwent considerable deformation, giving rise to a mountainous relief that constitutes the western continuation of the Pyrenean Mountain range (Baceta et al., 2012).

From a geomorphological perspective, the Basque Coast is generally *E*-W in orientation (Fig. 1) and is dominated by rocky cliffs with average heights ranging from 20 to 50 m. In enclaves protected from ocean currents and waves, sandy beaches of moderate extension have developed (Sanjaume et al., 2011; Flor and Flor-Blanco, 2014), generally <800 m in length. From some of these beaches, depending on the environmental conditions, dune fields have developed (Cowell and Thom, 1995; Bailey and Bristow, 2004; Provoost et al., 2009; Bateman et al., 2010). They include active dunes; systems degraded by anthropogenic action; and fossilized dunes (Gallego-Fernández et al., 2011) (Fig. 2).

Given the quality and continuity of the coastal outcrops, several recognized areas and protected sites have been created, among them the Basque Coast Geopark, with 2 golden spike marks (Schmitz et al., 2011), and the Bizkaia Flysch, with one golden spike (Payros et al., 2009), evidencing the area's major geological and geomorphological value.

Specifically, the study area forms part of a coastline in which the geological record evolves from Maastrichtian (Upper Cretaceous) to the NE, at Atxabiribil-Arrietara beach (Batenburg et al., 2014; Clemente et al., 2021), to Lutetian (Eocene) to the SW, at Gorrondatxe beach. At Gorrondatxe, the golden spike of the Bizkaia Flysch marks the GSSP (Global Stratotype Section and Point) for the base of the Lutetian Stage (early/middle Eocene boundary; Molina et al., 2011), while at Atxabiribil-Arrietara beach the K/Pg (Cretaceous/Paleogene) boundary is also recognized (Lamolda et al., 1983). Barinatxe beach is located between these two, and the cliffs flanking it show an alternation of marly

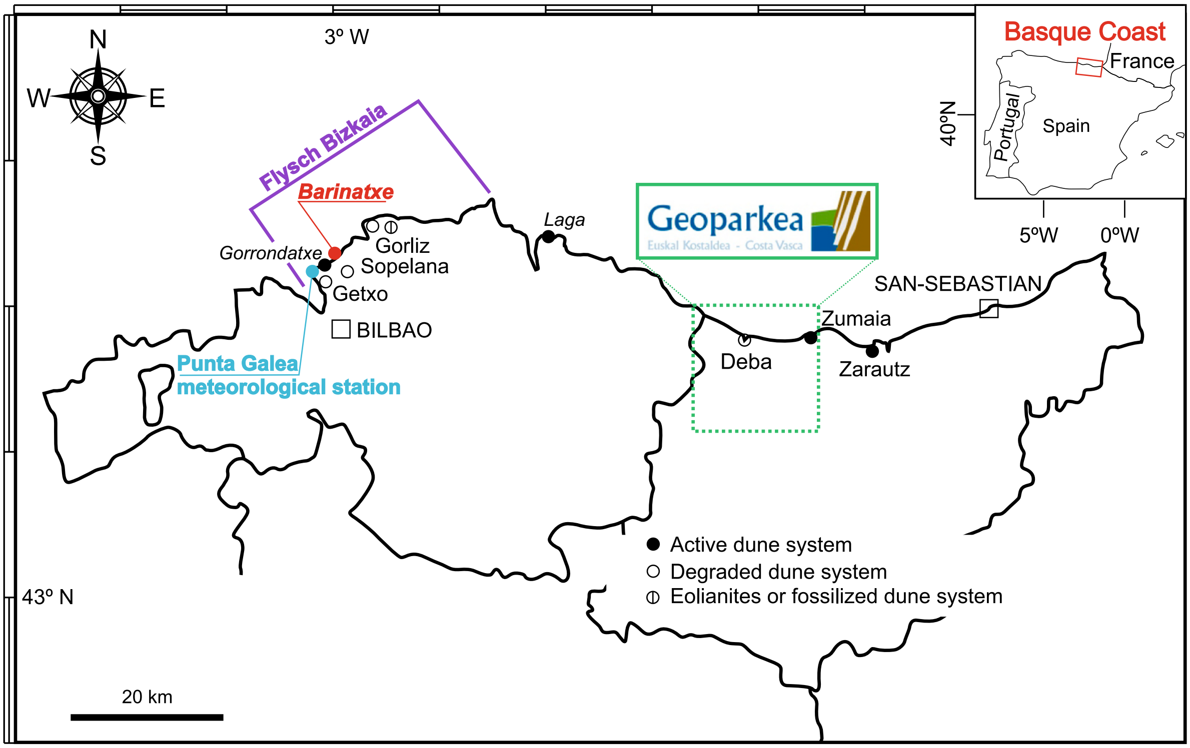

Fig. 1. Geographical location of the study area.

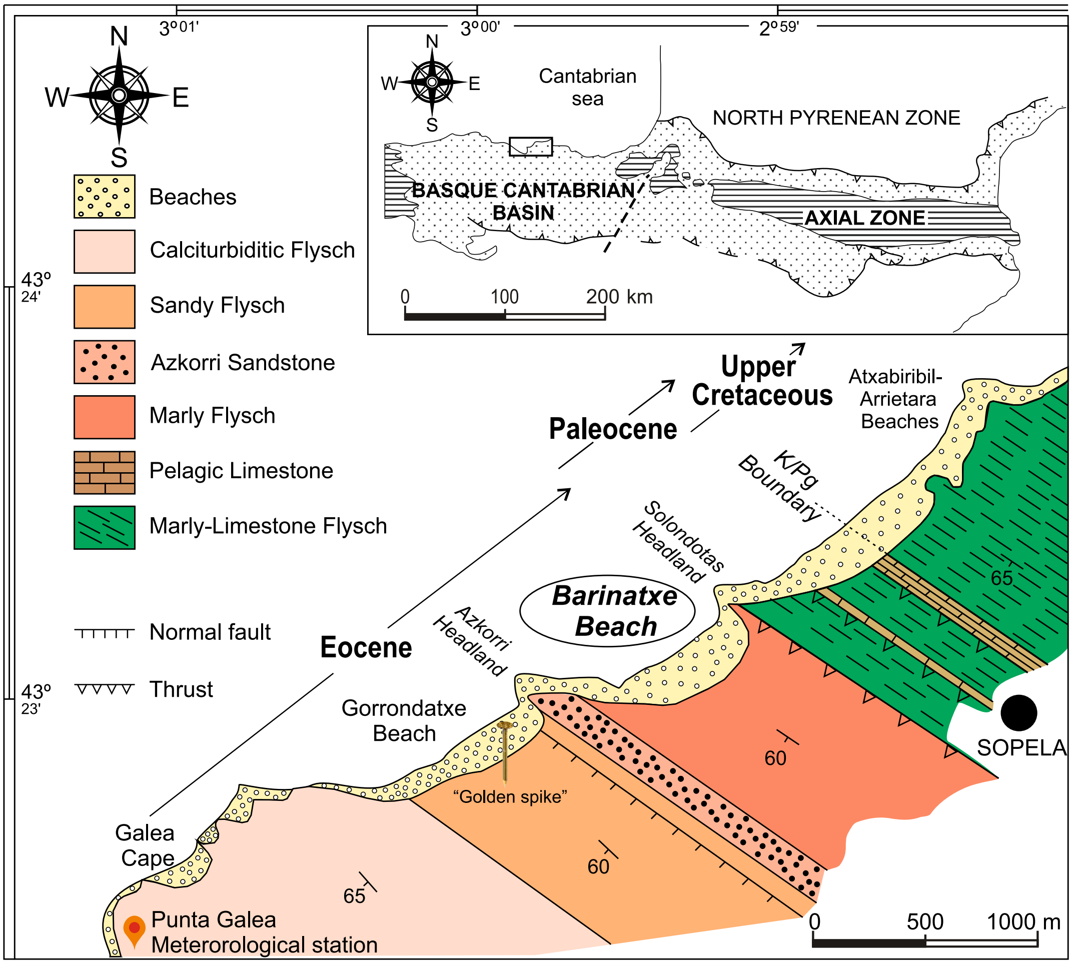

Fig. 2. Sketch map of the main structural features of the Pyrenean belt (modified from Boillot and Capdevila, 1977) and a simplified geological map of the Barinatxe beach in the Basque Coast (Bernaola et al., 2009).

materials of varying competence ("marly flysch"), from the Ypresian stage (early Eocene; Payros et al., 2007). The materials are arranged in steep dips, a characteristic feature of much of the Basque Coast (Payros et al., 2009). At the base of the cliffs there is a dune system. Since 2008, defensive measures have been taken to protect the dunes against the increasing influx of visitors, especially during the summer season, due to their geomorphological and environmental value.

3. Methods

In this context, the effect of the dunes in relation to the hazard posed by continuous rockfalls from the sea cliffs bordering the beach and the dunes' capacity as a protective natural barrier has been analyzed in the following stages.

3.1. Topographic data

First, a detailed 3D point cloud (3DPC) of the study area was generated (Fig. 3). Although the environment would in principle be an ideal site for use of an Unmanned Aerial Vehicle (UAV), the limitations resulting from the proximity of Bilbao Airport made it more advisable to employ a Terrestrial Laser Scanner (TLS). The equipment used was a FARO Focus 3D X330, which enables objects to be scanned from a distance of up to 330 m, with an interval error of ±2 mm. Our survey was conducted on March 28, 2021, in the beach area, at 16 points positioned between 150 and 200 m from the target, allowing us to generate an overall point cloud of the area, comprising 74,459,375 points with an accuracy range of up to 976 kpts/s.

This equipment includes GPS for data georeferencing. In our case, all data was georeferenced in accordance with the European Terrestrial Reference System (ETRS89) of the EUREF (Regional Reference Frame Sub-Commission for Europe) (Adam et al., 2002; Bruyninx et al., 2019).

Using the free Cloud Compare v.2.11 software, we were able to modify the point cloud and create the corresponding DTM, for analysis in raster format, by projecting the point cloud perpendicularly onto a flat raster surface, with a cell size of 0.5 m. The software also enabled us to export the original point cloud in other formats, such as ASCII and TXT, which are required for the modeling phase of the research.

The raster was then combined with georeferenced orthophotos in ECW format, obtained from the Geoeuskadi Spatial Data Infrastructure of the Basque Country (www.geoeuskadi.com). These 2021 orthophotos can be modified and adapted to the above information, using the Geographic Information System QGIS 3.6 NOOSA.

3.2. Fieldwork data collection

3.2.1. Rock mass and dunes characterization

In relation to the rock mass, special attention was paid to the network of discontinuities affecting the massif and the nature of its materials. In this regard, the persistence of discontinuities is one of the factors that most limit the extent of fragmentation (Cai et al., 2004; Kim et al., 2007; Morelli, 2016). Likewise, the main characteristics of the discontinuity families were assessed, including dip and orientation, spacing, persistence, roughness, opening and filling (ISRM, 1978; Bieniawski, 1989;

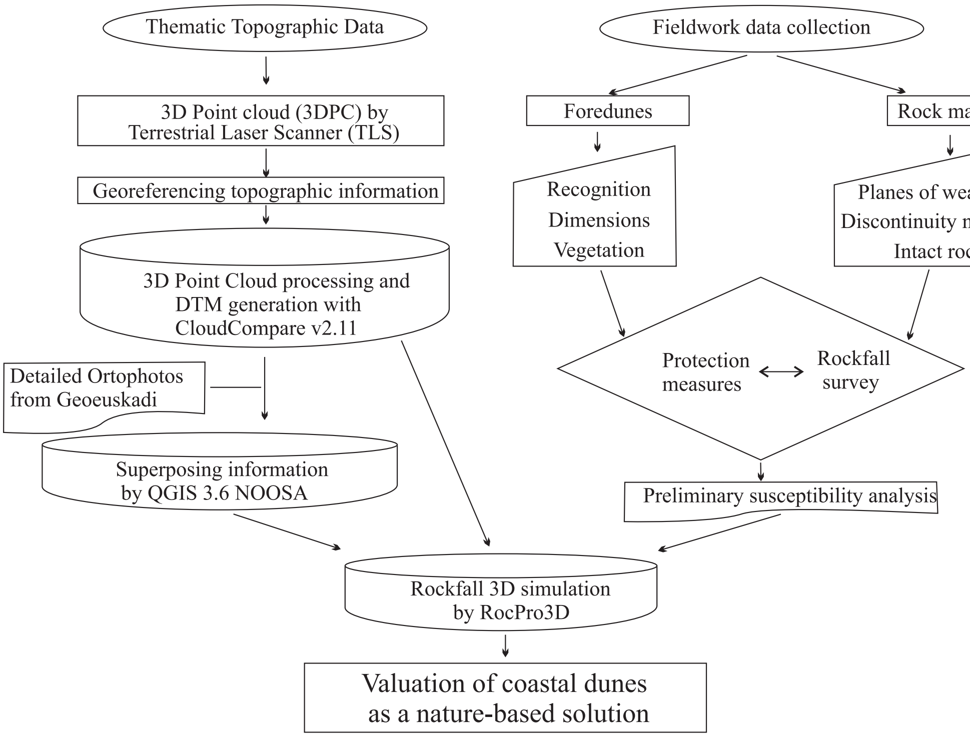

Fig. 3. Methodological flow chart.

Palmstrom, 2001).

As well as identifying the lithology of the intact rock, we also estimated its strength in situ using a Schmidt Hammer (Ulusay, 2015).

Characterization of the rock massif was completed with a determination of the Rock Mass Rating (RMR) as per Bieniawski (1989) and the Geological Strength Index for flyschoid materials as per Marinos and Hoek (2001).

With respect to the dune system, the assessment included identification of materials, origin, degree of development, morphology and typology, relation to external dynamic agents, fundamentally the prevailing winds at the Punta Galea meteorological station (Figs. 1 and 2), and vegetation coverage.

3.2.2. *Rockfall survey (typology and falling rock fragments characterization)*

Bimonthly visits were made for 3 years to record and identify the origin of falls (source areas), typology of failure and trajectory and runout of detached blocks. In this regard, whereas the network of discontinuities gives rise to the structure of planes of weakness that determine the shape and size of the unstable elements, their orientation with respect to the cliffs determines the dynamics of failure (Corominas et al., 2017; Morales et al., 2021). In our work, an analysis of instabilities in stereographic projection was performed using RocScience's Dips.v.6.0 software.

These field surveys established the weight and dimensions of the blocks. In areas in which access was not limited by dune conservation, direct measurements were taken at the foot of the cliffs (weight and volume of fallen blocks) and from scars on the cliff wall (Palmstrom, 2005; Corominas et al., 2017).

These observations were checked against the availability of natural and anthropogenic protective elements as part of the preliminary susceptibility analysis.

3.3. *Modeling and rockfall simulation*

Using the above information, individualized rockfall simulations were performed with RocPro3D software (RocPro3D, 2018). This software allows a 3D mesh of the study area to be generated from the point cloud created with the Terrestrial Laser Scanner (TLS) with triangulation using the Delaunay method. By means of this hybrid model, rockfall simulations can be addressed from a lumped mass approach, as a single material point, or a rigid body approach, accounting for the fragment shape. In our study, we used the rigid body approach, which considers the block impact on the soil surface as a quasi-instantaneous phenomenon during which movement is nil. The main advantage of this software is that it enables 3D simulation of rockfall trajectories, using a probabilistic approximation that takes into account variations in block shapes, soil characteristics of soils, and irregularities in the terrain. The impact is characterized by energy dissipation, taking into account the two restitution coefficients R_n (normal restitution) and R_t (tangential restitution), which are the parameters most commonly used in rockfall studies (Pfeiffer and Bowen, 1989; Chau et al., 2002; Paronuzzi, 2009; Bourrier et al., 2012; Buzzi et al., 2012; Wang et al., 2014; Giokari et al., 2015; Asteriou and Tsiambaos, 2018; Li et al., 2020; Tang et al., 2021).

This processing results in the generation of detailed three-dimensional rockfall simulations, including rockfall trajectories and energies; the superimposition of orthophotos provides more realistic three-dimensional models.

3.4. *Valuation of dunes as an element of natural protection*

Once the fall trajectories had been defined, changes in the topography, in relation to the disappearance of the dunes, were entered into the original point cloud. With this aim, the Cloud Compare software was used to modify the relief and create a new DTM without the dune system.

The three-dimensional model created was also introduced into the RocPro3D program, allowing determining the runout of the detached rock blocks, their impact energy and height in this new scenario. This software also allows recognizing the protection needs at the base of the cliff, in order to avoid the passage of rocky blocks.

Comparison of results in both scenarios enabled to assess the effect of coastal dunes as a natural retention barrier against detached rock fragments and their role in limiting the negative impact of the instability processes.

4. Results

4.1. Core information on dune system

The Barinatxe dunes are located on a steeply sloping beach with a NE-SW orientation. They consist of fine to medium-sized quartzite sands with fragments of organic origin removed by the wind from the beach foreshore. The wind in the area has a clear NW prevalence, mainly perpendicular to the beach and dunes (Fig. 4a), with an average speed of 18.6 km/h (5.16 m/s), exceeding the threshold speed of 5 m/s for the development and preservation of coastal dunes (Sloss et al., 2012). The climate is humid temperate, with an average temperature of 14.8 °C and annual rainfall of between 700 and 1200 mm/year (based on data from the Punta Galea weather station for 2001–2019).

Morphologically the dunes are asymmetrical in shape, characterized by a lower slope on the windward side and a steep ramp on the leeward side (Figs. 4a, b and c). On the inland side, the coastal cliff acts as an obstacle to the wind, favoring the development of eddies that create a marked depression between the crest of the dunes and the cliff, giving them the character of echo dunes (Tsoar, 1983, 2001). This depression, about 130 m in length and 5 m in width, is maintained over time. Overall, the dune system covers an area of 6100 m^2, acting as a natural barrier against rockfall from the cliff.

One additional aspect of note is the relatively abundant vegetation growing on the dunes (Fig. 4), especially in the summer periods (Fig. 4b), when incipient vegetation develops. This vegetation cover is subsequently destroyed in the erosive phases of winter (Fig. 4c). The flora includes a small population of tree mallow (*Lavatera arborea*). This species is listed in the Catalogue of Threatened Species of the Basque Country, and as a result, in 2008 a protective perimeter was staked out around the dunes.

4.2. Characterization of instability processes: Rockfalls

The outcrops of flysch sequences in the cliffs show an alternation of marl and marly limestone layers, ranging from a few centimeters to several decimeters in thickness (Fig. 5a), with varying levels of resistance to erosion. The result is an uneven surface with protrusions and indentations at different scales. A Schmidt hammer was used to characterize the strength of both types of material (360 determinations), giving rebound values (R) of 30–40 for the more resistant marly limestones and <12 for the marls (Table 1), equivalent to simple compressive strength values of 60 to 80 MPa, in the first case, and <20 MPa in the second, according to Miller's (1965) graphical chart. These findings coincide with the results of previous studies (Morales et al., 2004).

The massif is affected by three principal well-defined joint sets, one running parallel to the bedding planes and the others intersecting it, mainly at right angles. The bedding is the most evident plane of weakness and has the greatest persistence (>10 m); it runs perpendicular to the main cliff throughout the environment of the beach, with steep dips to the southwest (S_0: 60/220). The two main joint families, J_1 (45/330) and J_2 (30/100), complete the joint system of the rock mass. These have a much lower persistence and are mainly limited to the thickness of the strata (<1 m). Indeed, these joints appear well developed in the more brittle layers of the interbedded sequence (marly limestones) and tend to terminate at the adjoining marly layers (Fig. 5a), since the distributed deformation within the ductile layer dissipates the stresses at the fracture tip and promotes fracture termination (Cooke et al., 2006; McGinnis et al., 2017). The orientation of the bedding and joints is maintained along the length of the beach.

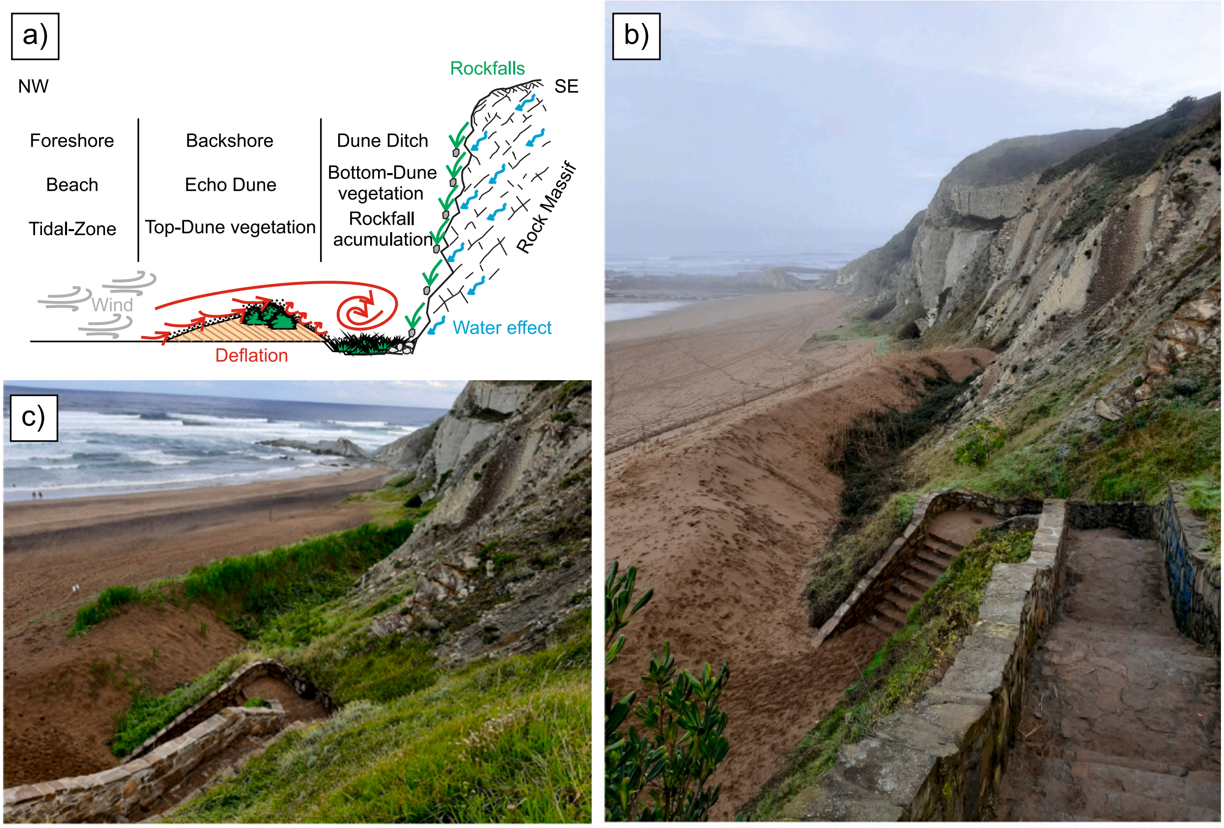

Fig. 4. Dunes on Barinatxe beach: a) conceptual sketch, showing the different beach sectors and the main dynamic processes; b) in winter; c) in summer.

Fig. 5. Characterization of instability processes. a) Flyschoid sequence; b) planar instabilities on the main slope on J_1; c) block toppling on the secondary slope on J_2; d) maximum runouts at the northern end of the area of protected dunes.

Table 1
Rock mass characteristics.

Materials	Schmidt rebound number		Uniaxial compressive strength (σ_{ci})
Marls	6–12		10–20 MPa
Marly limestones	30–40		60–80 MPa
Discontinuities	S_0	J_1	J_2
Dip/Dip direction	60/220	45/330	30/100
Spacing	2–65 cm	20–90 cm	10–55 cm
Persistence	> 10 m	< 1 m	< 1 m
Aperture	< 0.1 mm	< 0.1 mm	< 0.1 mm
Roughness (JRC)	Slightly rough (6–8)	Smooth (4–6)	Smooth (4–6)
Infilling	None	Calcite filling <5 mm	Calcite filling <5 mm
Weathering	Slightly weathered	Slightly weathered	Slightly weathered
Rock mass index RMR 45–50 GSI 35–40			

This arrangement results in the detachment of rock blocks of moderate size. The larger blocks come from the thicker calcareous levels (with a maximum thickness of up to 62 cm) and are bounded by the aforementioned joint families which, with usual spacing of 20 to 40 cm for J_1 and 10 to 30 cm for J_2, and maximums of up to 90 and 54 cm respectively, limit and determine their size.

With regard to the instability process, as a result of the favorable perpendicular orientation of the bedding, on the main slope the detached blocks progress along the J_1 plane (planar failure, Fig. 5b). In addition, greater erosion of the less resistant marly strata than of the more competent strata creates marked indentations that leave the competent strata unsupported, allowing the detached blocks to rotate on their base before falling (toppling failure, Fig. 5c) down the secondary slopes perpendicular to the main one.

Fig. 6 shows the kinematic analyses by stereographic projection for the main and secondary slopes, evidencing the potential development of planar failure and toppling, respectively (Fig. 6). The same figure also shows the main rockfall source areas, trajectories and runout determined in the field surveys (Figs. 5d and 6). The maximum sizes of detached blocks recorded in the accessible areas of the beach are of the order of 0.3 m^3 (7200 N), which is consistent with the scar volumes observed on the cliff and the maximum spacing of the discontinuities.

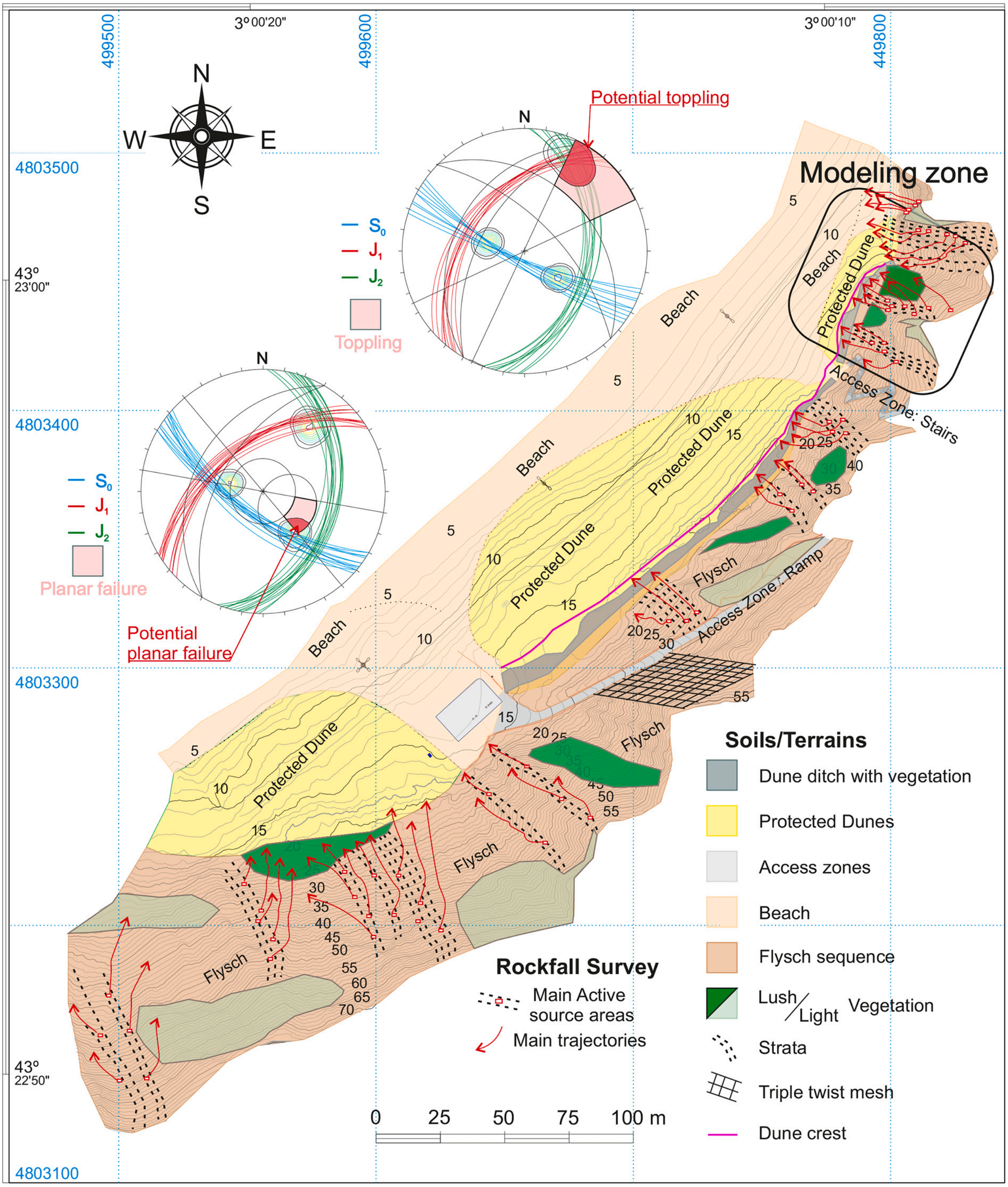

Fig. 6. Differentiation of materials at Barinatxe beach, showing main active source areas and rockfall trajectories. Includes kinematic analysis of the planes of weakness (bedding S_0, joints J_1 and J_2) in stereographic projection (Dips.v.6.0 software, RocScience, 2013).

4.3. 3D modeling of rockfalls

For the purpose of evaluating the action of the dunes in the rockfall process, the northern part of the beach was selected (Fig. 6), since it includes a sector of protected dunes to the south and a marginal sector to the north, where the dune is poorly developed, in a similar dynamic environment. The lack of construction interventions in this area also facilitates observations of the rock cliff, which in other sectors is limited, e.g., by the existence of a mesh in a large stretch of the access ramp and restricted access in the central area of protected dunes.

For modeling purposes, the materials were first differentiated, and 7 separate terrain types identified according to their nature and properties (Fig. 6): sandy beach, sandy dune system; dune ditch, (corresponding to the leeward depression of the dune, which retains continuous vegetation); the flysch sequences; lush cliff grass cover; light cliff grass cover; and anthropized access areas. Using this differentiation, rebound values were calibrated via 3D back analysis to achieve the best agreement between observations and modeling estimates (Sarro et al., 2018; Fanos and Pradhan, 2019). The values obtained (Table 2) are within the ranges given in the literature for similar materials, from nearly nil to about 0.7

Table 2

Terrain adjusted parameters and random deviations considering Gaussian distributions.

Material properties		Flysch	Light vegetation	Lush vegetation	Sand beach	Sand dune	Dune ditch	Access zone
Restitution coefficients (R)	*Units*							
Mean normal value μ_Rn		0.55	0.45	0.4	0.32	0.35	0.3	0.5
Mean tangential value μ_Rt		0.9	0.85	0.7	0.72	0.65	0.5	0.90
Std.-Dev. σ_R		0.011	0.012	0.012	0.0048	0.016	0.0125	0.011
Limit velocity V_R (lim)	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_R (lim)		0.0055	0.006	0.006	0.0016	0.012	0.0075	0.0055
Lateral deviation (θh)								
Std.-Dev. σ_θh	(°)	10	5	5	6.25	7.5	8.75	10
Limit velocity V_θh	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_θh (lim)	(°)	5	2.5	2.5	3.125	3.75	4.355	5
Vertical deviation (θv)								
Std.-Dev. σ_θv	(°)	1	1	1	1	1	1	1
Limit velocity V_θv	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_θv (lim)	(°)	2	2	2	2	2	2	2
Friction coefficient (k)								
Mean value μ_k		0.45	0.6	0.6	0.6	0.55	0.5	0.45
Std.-Dev. σ_k		0.036	0.045	0.045	0.036	0.045	0.045	0.036
Limit velocity V_k (lim)	(*m/s*)	10	10	10	10	10	10	10
Limit Std.-Dev. σ_k (lim)		0.03	0.03	0.03	0.03	0.03	0.03	0.03

for the normal rebound coefficient and 0.7 to 1 for the tangential coefficient (Bourrier et al., 2012; Sarro et al., 2018; Fanos and Pradhan, 2019). With respect to the lateral and vertical deviations of the rebound angle, are computed and used to modify the reflected velocity orientation. This approach results in lateral dispersion values consistent with those obtained in previous works for similar materials in steep areas (Asteriou and Tsiambaos, 2016; Sarro et al., 2018; Akin et al., 2021; Zheng et al., 2021).

With regard to the results of the modeling, the simulations shown in Fig. 7 show the trajectories corresponding to the largest volumes given in the previous section, since the largest detached blocks constitute the worst-case scenario in terms of safety when they remain intact while traveling (Pfeiffer and Bowen, 1989), attaining the highest energy (Sarro et al., 2018; Akin et al., 2021; Morales et al., 2021). For this purpose, 12 source areas were considered in the study area, from which 270 rockfalls were simulated. The trajectories of the detached blocks on the cliff follow the lines of maximum energy. Their progress is limited by two elements: the lush vegetation at the bottom of the depression; and the dune, including the dune ditch. In the first case, the retention is partial, and some blocks reach the base of the cliff. In the second case, the retention is total; none of the blocks get past the dune to reach the beach, unlike in the northern sector, where the dune system is poorly developed (Fig. 5d).

In addition, Fig. 8 shows the position of the stopping points recorded in the field (Fig. 8a) and those obtained by modeling (Fig. 8b). In both cases, it can be seen that in the southern sector of the modeled area no block progressed beyond the crest of the dune to reach the beach. In contrast, in the northern sector, where the dune is poorly developed, the blocks reach the beach and even surpass the delimited protection line. The figure is completed with the information corresponding to the number of trajectories per cell (Fig. 8c), and minimum traveling times (Fig. 8d).

4.4. *Assessment of the protective role of the dune*

Two approaches were used to assess the protective action of the dune: we first considered the impact of removing it and then, evaluated the basic parameters for sizing a protective barrier with the same retention capacity. In addition to the runout, another essential parameter to be considered is the energy of the rock blocks throughout their entire trajectory. In our study, it was especially critical to assess the energy of the blocks reaching the dune.

The effect of dune removal was considered by modifying the original point cloud (Fig. 9a) using Cloud Compare v.2.11 software and creating the corresponding DTM (Fig. 9b and d). As can be seen, degradation of the dunes would enable some detached blocks reaching the beach, up to distances of 20 m from the base of the cliffs (Fig. 9b), in a situation similar to that which currently exists at the northern sector of the modeled area (Fig. 8), with the consequent risk for visitors.

In order to prevent the negative effects of the removal of the dune, therefore, we considered incorporation of a protective artificial barrier in the 3D model (Fig. 9c and d). In this case, the barrier tool of the RocPro3D software allows analyzing the passage of the detached rocks in the desired vertical profile. The graph in Fig. 9c shows the energies of passage through a profile in the line of the dunes, with a maximum value of 163.4 kJ, and passage heights remaining below 3 m (blue line) above the ground (brown line). These are the basic parameters for designing a barrier that would replace the protective role offered naturally by the dune, favoring not only to safety, but also conservation and resilience in an environment of high anthropic pressure. In this regard, it should be noted that in the area with protected dunes there is no record, even in historical accounts, of blocks falling from the cliffs onto the publicly accessible beach.

Protection and conservation of the dune is thus shown to be an efficient Nature-Based solution (NBS) in an area of compromised management.

5. Discussion

Current land management requires the development of approaches that guarantee the conservation of natural spaces and benefit society, mitigating risks and increasing resilience, within the framework of what are known as Nature-Based Solutions (NBSs) (Villegas-Palacio et al., 2020; Kumar et al., 2021; Vojinovic et al., 2021; Wu et al., 2021). In this regard, the results obtained in this paper allow verify the effectiveness of dunes as natural protection barriers against coastal cliff rockfalls.

In the pilot case of Barinatxe beach, the retention capacity of the dunes has been proven, through both a field survey and three-dimensional modeling of trajectories. In contrast, the model shows that in the case of dune removal, the detached rocky blocks show trajectories that reach the beach at the base of the cliffs, covering distances of up to 20 m. This scenario would pose an additional risk to users and visitors, similar to that registered in beach areas without dunes, and would require structural measures with a significant landscape, environmental and ecological impact, and a negative public perception (Touili et al., 2014; Gray et al., 2017).

In both scenarios, the trajectory simulations were ground-truthed with field observations. In this regard, the use of three-dimensional

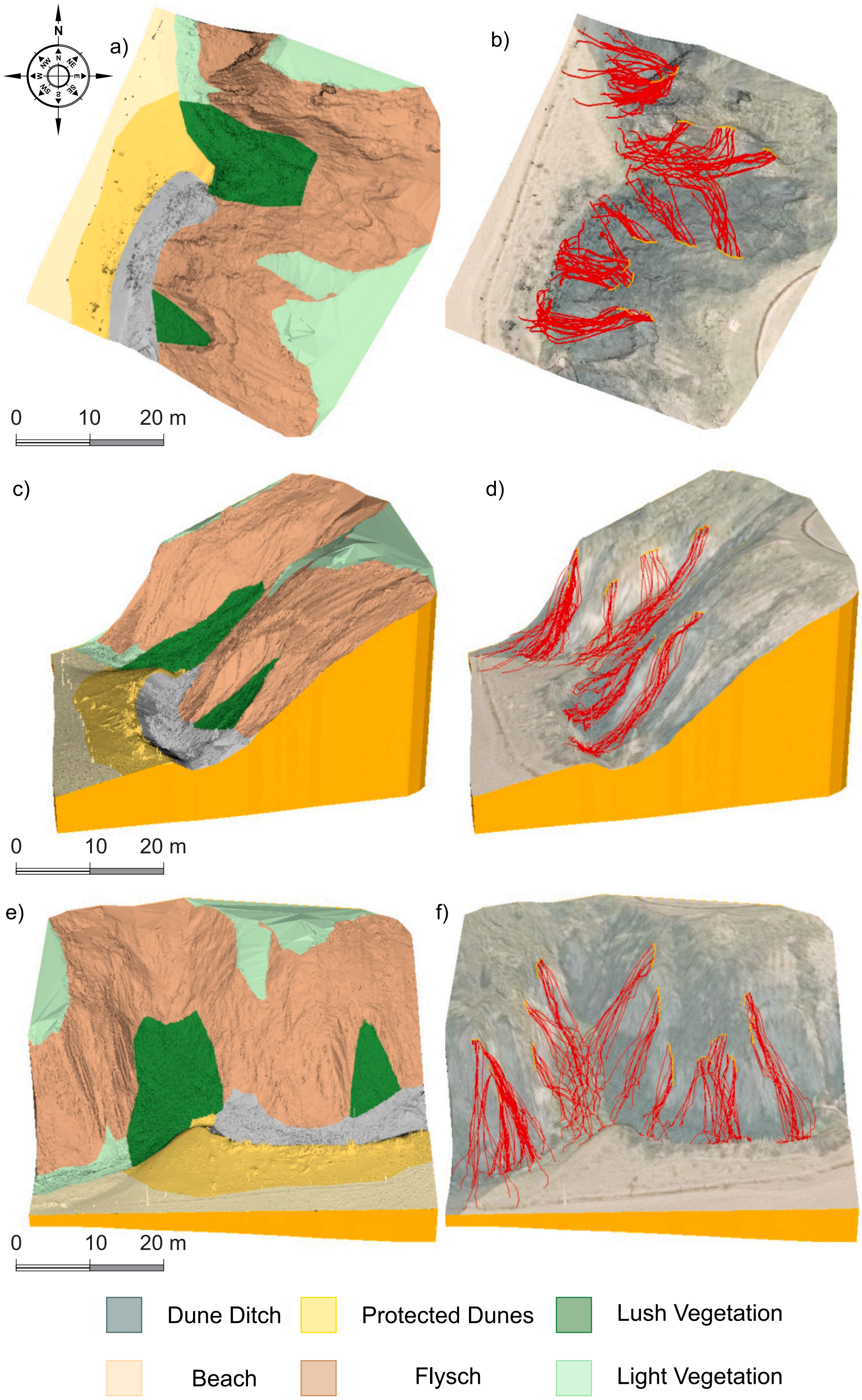

Fig. 7. 3D model showing differentiated terrains and trajectories (red lines) from: zenithal (a and b); profile (c and d) and frontal (e and f) views. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

models provides more realistic images than those derived from 2D models (Volkwein et al., 2011; Li and Lan, 2015). This approach requires detailed topography by terrestrial laser scanner (in our work + − 2 mm), and an increase in the relevant parameters in the trajectory-computing process, including characteristic parameters of rebound of materials (Bourrier et al., 2012; Asteriou and Tsiambaos, 2018; Ji et al., 2020) and lateral and vertical deviations of rebound angles (Asteriou and Tsiambaos, 2016; Akin et al., 2021; Zheng et al., 2021). In our work these parameters were calibrated via back analysis, giving values in the range of those reported by other authors in comparable steep terrains (Sarro et al., 2018; Fanos and Pradhan, 2019; Morales et al., 2021). At this point, additional laboratory and, more specifically, field determinations (Bourrier et al., 2012; Asteriou and Tsiambaos, 2018; Ji et al., 2020) will enable verification and improvement of the results and an improvement in the knowledge on the influence of geology and macro- and micro-topography throughout the rockfall process, limiting uncertainties in

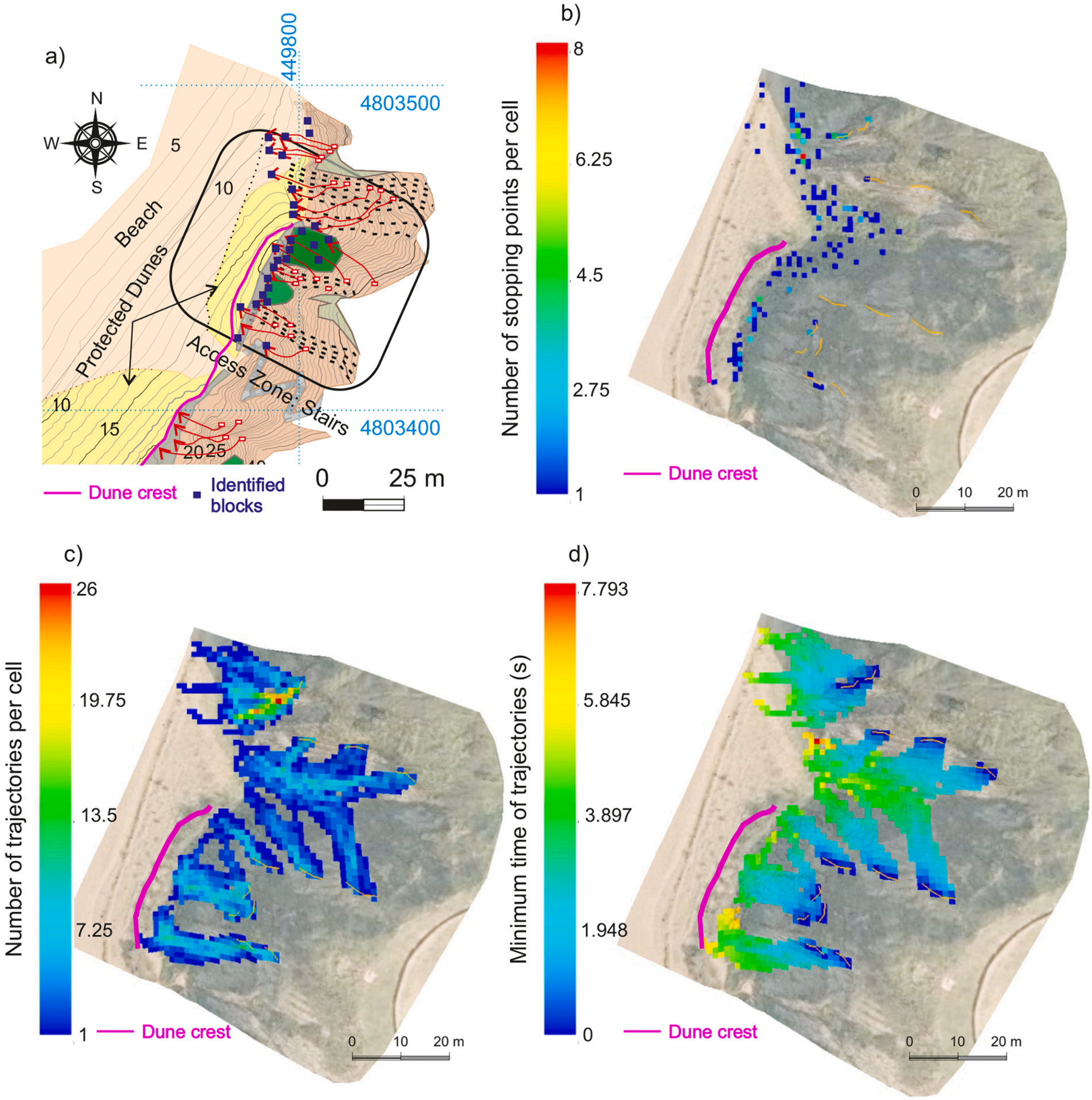

Fig. 8. Analysis of rockfalls; a) fieldwork identification of detached blocks; model results: b) stopping points; c) number of trajectories per cell; and d) minimum time of trajectories.

the evolution of trajectories at a real-scale (Crosta and Agliardi, 2004; Wang et al., 2014; Asteriou and Tsiambaos, 2016).

A comparison of results allows us to add a capacity to limit the risk of rockfall to the benefits of dune conservation and recovery. Previous works have recognized the capacity of coastal dunes as a protective element against storm surges (Elsayed and Oumeraci, 2016) and coastal flood risk (Houser et al., 2008), in addition to their recognized high ecological and landscape value (Wootton et al., 2016; Sigren et al., 2014, 2018). This study increases the scope of the consideration of dunes in coastal risk reduction strategies (Figlus, 2022), incorporating their efficiency as natural barriers against rockfalls.

6. Conclusions

This work verifies the protective role of coastal dunes as natural barriers against the risk of rockfall from coastal cliffs. In this sense, the dunes have proven to be an effective natural solution to prevent rockfalls reaching the beach area open to the public.

The methodology, based on a Digital Terrain Model developed by Terrestrial Laser Scanning (TLS), in situ geological characterization and 3D modeling, has been tested at Barinatxe beach, and has proved to be suitable for evaluating the trajectory, energy and runout of rockfalls. From this, detailed 3D models allow the effect of the dunes on rockfall evolution to be analyzed and the impact of their disappearance on beach safety to be assessed.

Overall, the payback on protection and conservation of dunes and the commitment to protect these natural elements of high geomorphological, ecological and environmental value is an increase in safety and resilience, proving to be an effective NBS strategy.

CRediT authorship contribution statement

Jon Ander Clemente: Conceptualization, Data curation, Investigation. **Jesus A. Uriarte:** Data curation, Investigation, Supervision. **Daniele Spizzichino:** Methodology, Supervision, Writing – review & editing. **Francesco Faccini:** Methodology, Supervision, Writing –

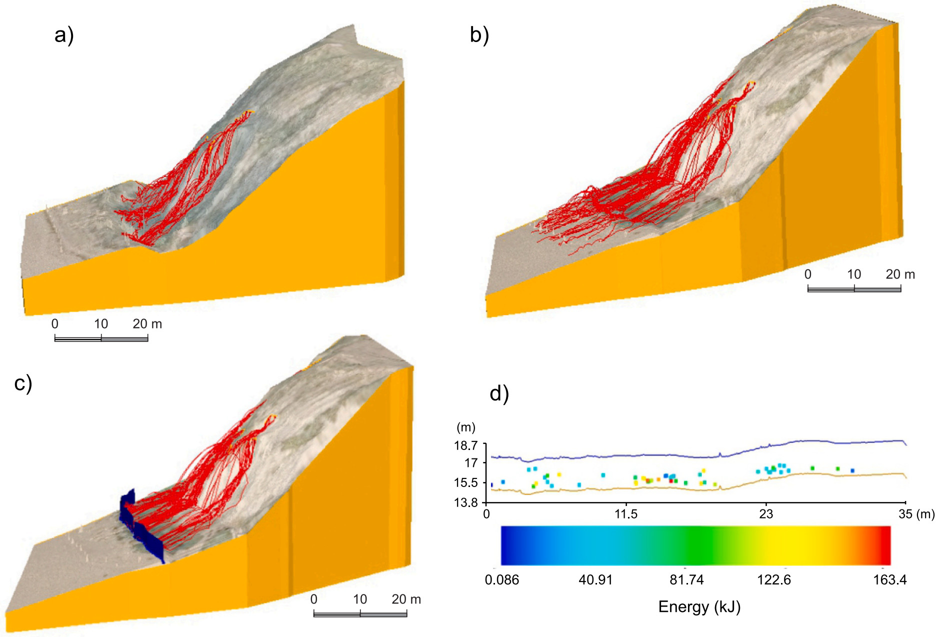

Fig. 9. Evolution of rockfall trajectories: a) in the current situation; b) following removal of the dunes; c) following installation of a protective barrier; d) basic parameters for barrier design.

review & editing. **Tomás Morales:** Conceptualization, Formal analysis, Methodology.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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