

The interaction between marine and subaerial processes in the evolution of rocky coasts: The example of Castelejo (southwest Portugal)

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ABSTRACT

The rocky coast of Castelejo (the Southwest Alentejano and Costa Vicentina Natural Park) represents an excellent example of the complexity that is connected with the current evolution of this type of coasts. Fieldwork supported by cartographic analysis and by aerial and land photographs enabled us to produce a detailed geomorphological map (scale 1:5 000), where the landforms and processes of this area are indicated. At Castelejo we have a very active dynamic at present, with erosion and accumulation processes, either marine or subaerial, combined with changes in frequency and magnitude. The work carried out over the last three years, together with periodic surveys over the last 15 years, show that there is a cyclic sequence of processes that depends on the wave climate (which controls the presence or absence of sand on the beach) and on the climatic regime, mainly the wind and the intensity and concentration of rain.

Key words: Rocky coasts, geomorphological processes, Portugal.

RESUMEN

La interacción de los procesos marinos y subaéreos en la evolución de las costas rocosas. El ejemplo de Castelejo (suroeste de Portugal)

La costa rocosa de Castelejo (localizada en el parque natural del Sudoeste Alentejano y de la costa Vicentina) es un excelente ejemplo de la complejidad que puede revestir la actual evolución de este tipo de litoral. El trabajo de campo apoyado en análisis cartográfico y en fotografías aéreas y terrestres, permite ejecutar un mapa detallado (escala 1:5 000) donde se indican las formas y procesos de esta área. En Castelejo se tiene una dinámica actual muy activa, donde erosión y procesos de acumulación, marina o subaérea, se combinan con cambios de frecuencia y magnitud. El trabajo desarrollado en los últimos tres años, junto con observaciones ocasionales de los últimos quince, muestran la existencia de una secuencia cíclica de procesos que dependen del régimen de agitación marina (que controla la presencia o ausencia de arena en la playa) y del régimen climático, concretamente del viento y de la intensidad y concentración de la lluvia.

Palabras clave: Costas rocosas, procesos geomorfológicos, Portugal.

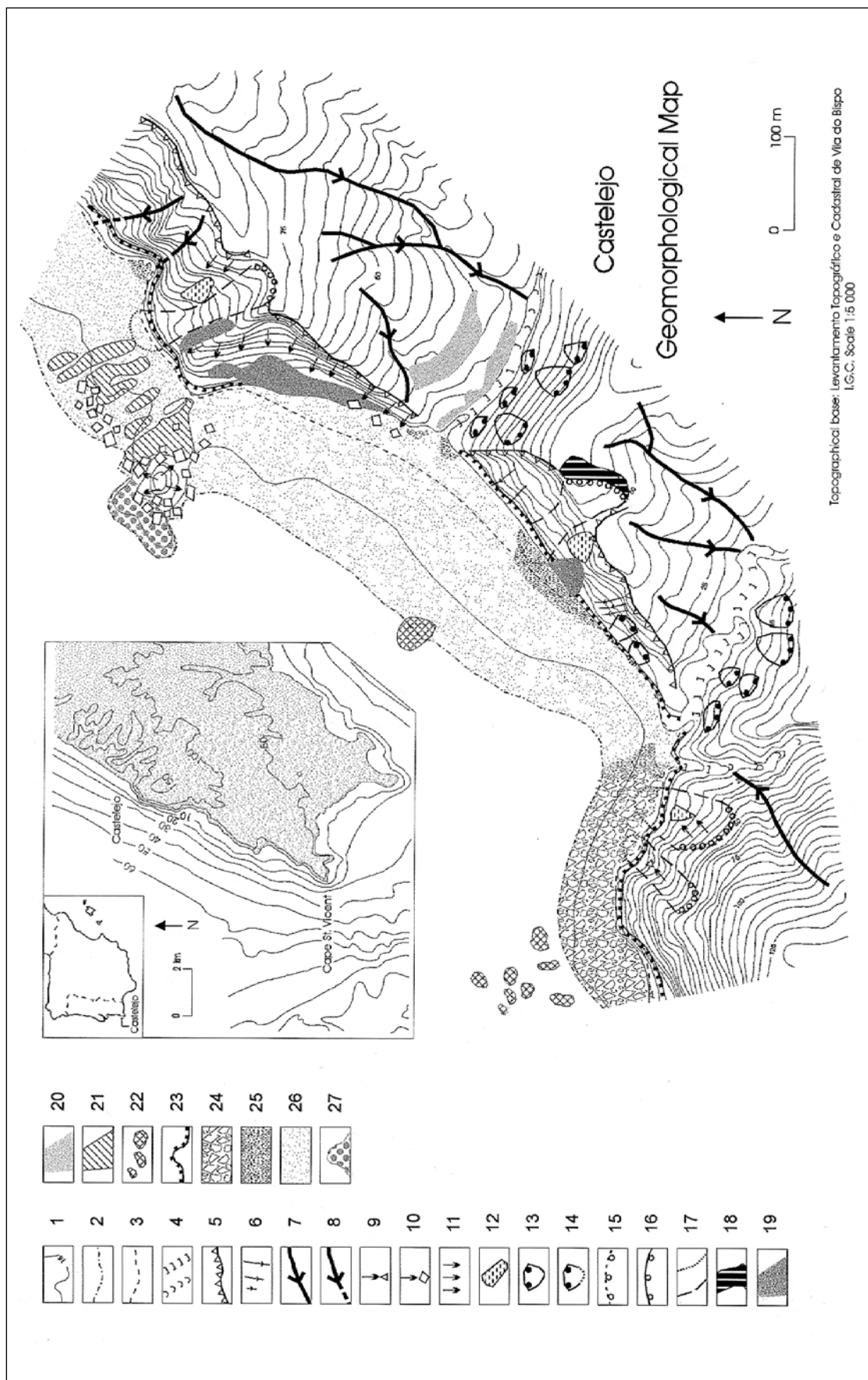


Figure 1. Geomorphological map of Castelejo. (1): contour line (in metres); (2): mean level of low tide; (3): mean level of high tide; (4): small valleys with the bottom in U and flat; (5): top and base of the coastal slope; (6): rill erosion; (7): gully; (8): suspended gully; (9): high-magnitude rockfalls in the turbidites; (10): high-magnitude rockfalls in the aeolianites; (11): low-magnitude rockfalls in the turbidites; (12): talus slope; (13): superficial landslide; (14): lobe of superficial landslide cut by marine erosion; (15): old translational landslide scarp; (16): recent translational landslide scarp; (17): slide limit (certain; probable); (18): very unstable sector (with cracks); (19): climbing dune on the coastal slope (with a coluvio-aeolic deposit); (20): climbing dune in the margins of the valley (with a coluvio-aeolic deposit); (21): shore platform; (22): skerries; (23): cliff; (24): blocks and boulders; (25): cobbles; (26): sand; (27): *plateforme à vasques* in the eolianites

INTRODUCTION

Over the last several decades, a large amount of money has been spent on protection works whenever a sea storm or heavy rainfall cause damages in urban coastal areas. These works rarely solve the problem, because they are often designed in ignorance of the causes that are provoking the coast's local retreat. In the particular case of rocky coasts, the causes are generally multiple and they change spatially and temporally. Therefore, the determination of all the factors and processes that control the present-day dynamic of the rocky coasts is a fundamental step, not only for understanding how these coasts are evolving now, but also to predict their future evolution.

In the southwest of Portugal there are several examples of rocky coasts with a particular present-day dynamic (Neves, 1995; Neves, 1996). In this case, we chose Castelejo, because of the complexity and richness of the present-day evolution of this area, in the Southwest Alentejano and Costa Vicentina Natural Park.

MATERIALS AND METHODS

Our research on the rocky coast of Castelejo was based mainly on fieldwork, supported by cartographic and aerial photograph analysis. Complementary land photographs taken in different years at the same places provided useful information on coastal dynamics. Once all these elements had been collected, it was possible to draw up a detailed geomorphological map, at the scale 1:5 000, afterwards reduced (figure 1). We decided to include

on the map some of the processes that occur on the margins of two small valleys in the area, because the landforms created by these processes and their evolution could affect the future coastal slope morphology. We also divided the coastal slope (CS) into four sectors (A, B, C, D), for the sake of clarification (figure 2). The rates of retreat presented were calculated comparing aerial photographs from different years (1982 and 1989), and using pegs placed near the top of the coastal slope in 1994. We must also point out that in the present article, we consider the coastal slope as the part of the slope facing the sea that was cut mainly by subaerial processes, while the cliff is the base of that slope that was shaped mainly by marine processes.

Geomorphological analysis of Castelejo

The rocky coast of Castelejo is located 10 km northeast from the Cape St. Vicent on the western coast of the Algarve (figure 1). The entire southwest Portuguese coast presents a dynamic that clearly differentiates it from the rest of the Portuguese littoral: the sedimentary balance is negative, both on the coastal platform and on the continental shelf (Pereira, 1990), mostly due to a weak supply from the watercourses (in this region they have small importance), and to a lack of sediments on the continental shelf, which is also relatively narrow (width less than 40 km, sometimes not more than 10 km) and with a very strong slope angle –higher than 10 m/km (Pereira, 1993). Therefore, it is a coast with scarce and narrow beaches, where cliffs are predominant (Pereira, 1996).

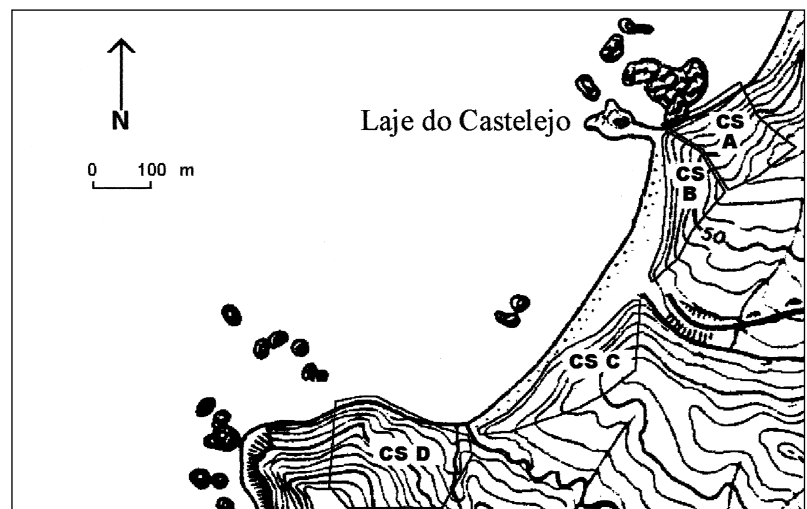


Figure 2. Division of the coastal slope of Castelejo into four sectors (CS A, B, C, D)

The waves that reach the southwest coast are generated in the North Atlantic and they come from the northwest 80 % of the time (Pires, 1989). Rarer, but also important, are the waves coming from the southwest, which correspond frequently to storm events.

Near Castelejo, the coastal platform reaches heights of 100-130 m and is deeply cut by some small valleys. The area studied, which includes some 1 000 m of coastline (with a northeast-southwest orientation), presents a shore platform-cliff-coastal slope system, with the shore platform mostly covered by a sand beach 600 m long, with a 150 m maximum width (spring low tide). The entire system is cut into the Flysch Group of Baixo Alentejo (carboniferous turbidites composed of an alternation of grauwacke and schists with a variation in thickness, usually less than 200 mm, but in some sectors with layers more than 600 mm thick). This material is very folded and intensely faulted by the countless tectonic events to which the all region has been subjected during its long geological history. There is also, in some sectors of this area (Laje do Castelejo -figure 2- and the northeast margins of the small valleys), a group of aeolianites, with a medium degree of consolidation (Pereira, 1987).

The slopes facing the sea at Castelejo present some morphological characteristics that enable us to consider how the action of continental processes have prevailed in their evolution, particularly

mass movements, e.g. slides and rockfalls (Neves, 1995). In spite of the intense fragmentation in this area, which introduces modifications in the resistance and permeability of the materials, and of the constant changes of stratification characteristics from one sector to another, it is possible to establish some distribution patterns of the different slope erosion processes (table I). Thus, in the places where schists and grauwacke are not very thick (< 200 mm) and stratification is opposite to the sea, the slope evolves by rockfalls of low magnitude but high frequency. This process particularly affects the CS C (figure 1). In a mere three years of measurements, the retreat of the coastal slope top due to this process was estimated at 50-150 mm/year. In sectors not reached by the sea, these rockfalls can produce talus (figure 1) composed by heterometric and angular material with a 34°-35° slope equilibrium angle, which is confined between the limits indicated by Selby (1982), who found that most talus slopes have angles between 30° and 38°. In the sectors where the outcrops, particularly grauwacke, reach a thickness of more than 600 mm, and stratification is also opposite to the sea, there is a tendency towards the occurrence of high-magnitude, low-frequency rockfalls. This type of rockfalls occurs particularly in CS D (figure 1). On the other hand, the retreat of the coastal slope cut in grauwacke and schists leaves the aeolianites overhanging in some sectors. The cornices thus formed evolve through rockfalls (figure 1), usually

Table I. Main erosion processes acting on the Castelejo coastal slopes

	Type of erosion	Lithology and structure		Evolution processes
Base of the coastal slope	Marine erosion	Turbidites Aeolianites		Abrasion (cliff formation)
Rest of the coastal slope	Sub-aerial erosion (mass movements)	Turbidites of small thickness (< 200 mm)	Stratification opposite to the sea	Rockfalls Low magnitude and high frequency
		Turbidites of high thickness (> 600 mm)		High magnitude and low frequency
		Aeolianite cornices		
		Turbidites with stratification towards the sea		Rockslides High magnitude and low frequency

of large blocks, which is also a high-magnitude, low-frequency process.

Another kind of mass movement –slides– also occurs in Castelejo, with a significant impact on area’s evolution, since there is only one coastal slope (VC B) where such mass movements do not occur. Despite an annual average precipitation of less than 500 mm, sometimes heavy and concentrated rainfalls do occur in this region, which can cause a slide event. In these situations, the daily precipitation exceeds, in many cases, the monthly average values (for instance, in Sagres, near Cape St. Vicent, 185.4 mm was recorded on 24 November 1988 alone, although the November average precipitation value for that station is less than 70 mm). On the margins of the area’s two small valleys, several superficial slides were registered, affecting only the deposits that cover those slopes. Contrariwise, on the coastal slopes only two superficial slides were found, because here most of the slope is cut into the substratum. Thus, all the rest of the recorded slides, following the classification proposed by Varnes (1984), belong to the translational rock-slide type, hitting the substratum in places where the stratification tends towards the sea, and affecting large volumes of material. They all occurred before 1982, but almost all show evidence of subsequent reactivation. Particular attention must be given to CS C where, between 1982 and 1989, several reactivations of the translational slide located there caused the top of the slope to retreat 7-9 m; in addition, the area above the main scarp is deeply unstable, with several cracks parallel to the slope top, separating compartments that had already suffered some displacements. This points to a strong probability of the occurrence of new mass movements in this sector in the near future.

There are not many landforms on the coastal slopes of Castelejo connected with the action of hydric erosion. We found two small sectors in CS C af-

ected by rill erosion, and two gullies in the northern sector of CS A (figure 1). The channels formed by rill erosion in CS C have depths and widths that usually do not surpass 250 mm, and they occur in sectors where the slope is covered by deposits, composed mostly by millimetric schist clasts that give an increased impermeability to the slope; the slope angle is steep in the southern sector (30°) and very steep in the northern sector (56°). Here, the rill erosion evenly affects the cliff. This indicates that, although waves are responsible for the general cut-

Table II. Retreat of the rockslide lobes between 1982 and 1989 at Castelejo

Coastal slope	Retreat
A	6 m
C	4-6 m
D	3-4 m

ting of this part of the slope, the wave climate has lately not been so active that it has surpassed the erosion caused by the few rainfall episodes registered in the area. The two gullies indicated in CS A (figure 1), which were not measured because their access is dangerous, present the particular characteristic of being suspended. This feature could suggest that the rate of retreat of the coastal slope base has exceeded the cutting capacity of the rainfall runoff.

The base of the coastal slope morphology, in some sectors, presents evidence that it was cut by the action of the sea, thus forming a cliff. This action of the sea can also regulate the evolution of the entire slope, directly or indirectly. Directly, the cutting of the slope base increases its angle here, contributing to the destabilisation of the rest of the slope through loss of its base support and, as Sunamura (1992) also concluded, this may provoke the occurrence of mass movements (figure 3).

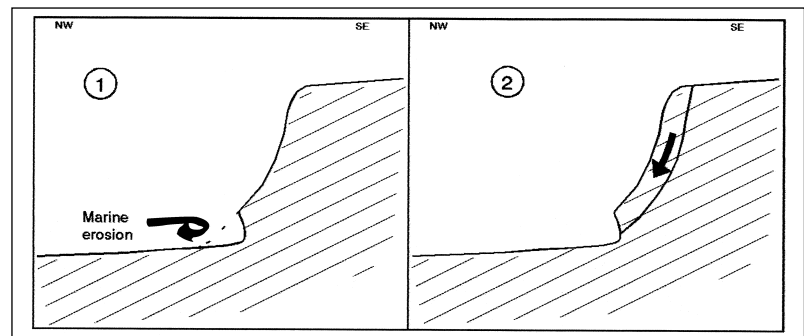


Figure 3. Direct action of the sea in the destabilisation of the coastal slope

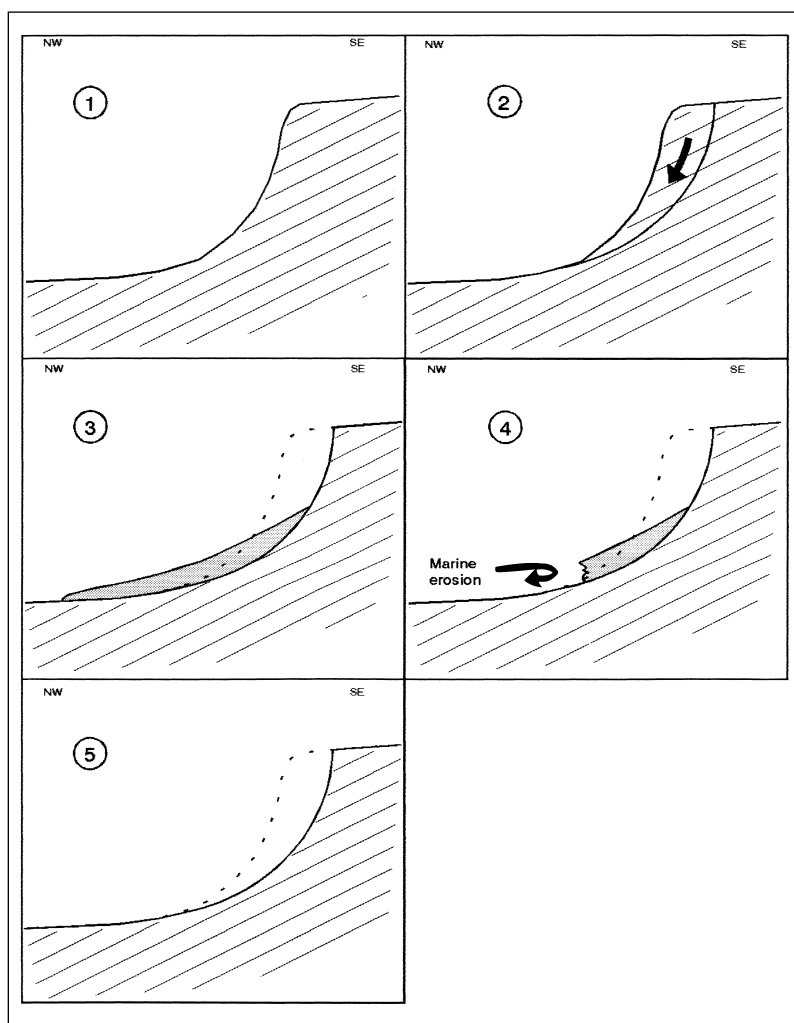


Figure 4. Indirect action of the sea in the destabilisation of the coastal slope

The rock slides that take place in CS D (figure 1) can be included in this case. Wave action is also important in the carrying away of the materials accumulated at the coastal slope base that come from the mass movements which occurred on the slope. These deposits, when covering the slope, act as a buffer against slope erosion, as indicated by Dias and Neal (1992). The transport role of the waves leaves the slope unprotected again, and therefore this is indirectly advantageous for the reactivation of mass movements (figure 4). We can find evidence of such action at all of the slide lobes in the area that are cut off by wave erosion. Between 1982 and 1989, the front of these lobes had retreated 3-6 m (table II).

At the base of the Castelejo cliffs, there is a shore platform that, at least between 1983 (when one of the authors, A. R. Pereira, began to study this area) and 1987, was simply covered with boulders and cobbles. After that, a natural sand supply began

that covered the shore platform with a thickness of approximately 1.5 m, forming a beach. The strong wind that is felt on this coast (from December to March, the southwest and western winds, and in summer the north wind, reach an average speed that surpasses 20 km/h) supported the transportation of the fine sand grains and their deposition at the base of the coastal slope, thus fossilising the cliffs, and forming climbing dunes that sometimes rise above 20 m high. These dunes are not only made up of eolic sands, but they also include slope deposit. This deposit, composed of small, thin plates of schist and heterometric pieces of grauwacke, comes mainly from the high-frequency, low-magnitude rockfalls that occur in some sectors of the coastal slope. If we make an incision in the climbing dunes, it is possible to note that there is an alternation between short episodes of strong wind, which provoke a sand accumulation against the cliff, with periods where the arrival of slope de-

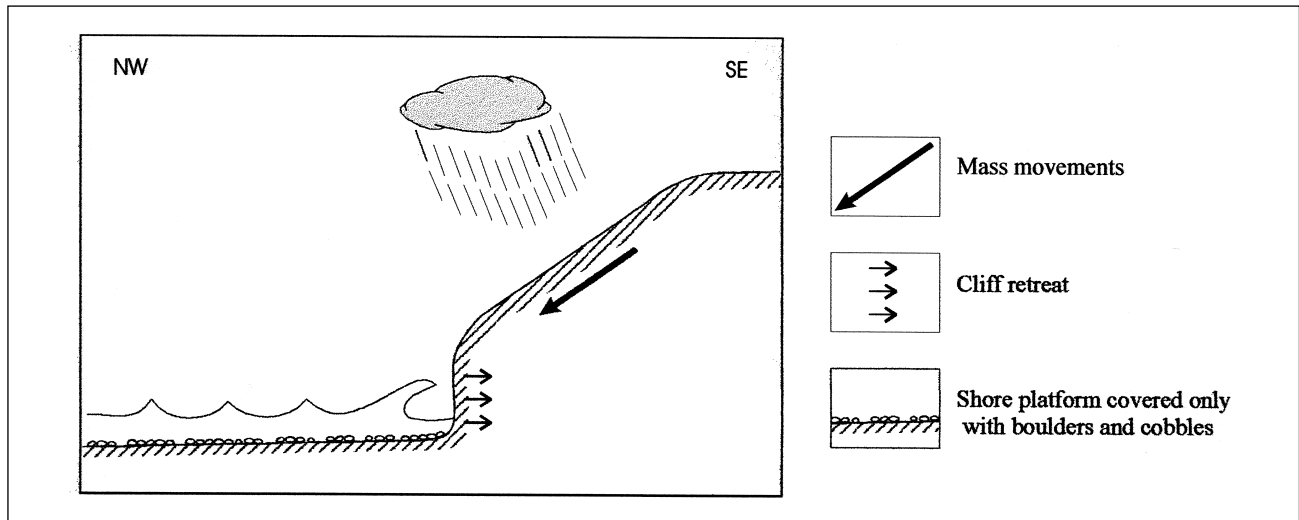


Figure 5. Scheme of the sea storms phase at Castelejo

posits is predominant. Consequently, these climbing dunes are the result of the interaction between two processes (eolic and mass movement), and they therefore present a particular sedimentological composition.

DISCUSSION

Our observations in this area enable us to consider that the coastal slope’s evolution is very closely connected with beach dynamics, namely with the shore platform covering, sometimes with boulders and cobbles and sometimes with sand.

We clearly recognised the existence of a two-phase cycle. These phases should not be connected with human actions, because there were no major human changes in the sediment transport of the regional watercourses, nor important coastal occupation that could disturb the coastal dynamic. The duration of each of these phases seems, therefore, to rely essentially on the wave climate, namely on the frequency and intensity of the sea storms.

There is a sea storms phase, correlating to a period of fluctuating duration, where series of sea storms reach the area, sufficiently energetic to take away the sand and leave the shore platform with boulders and cobbles only (figure 5). In this situation, the cliff remains unprotected, and so the

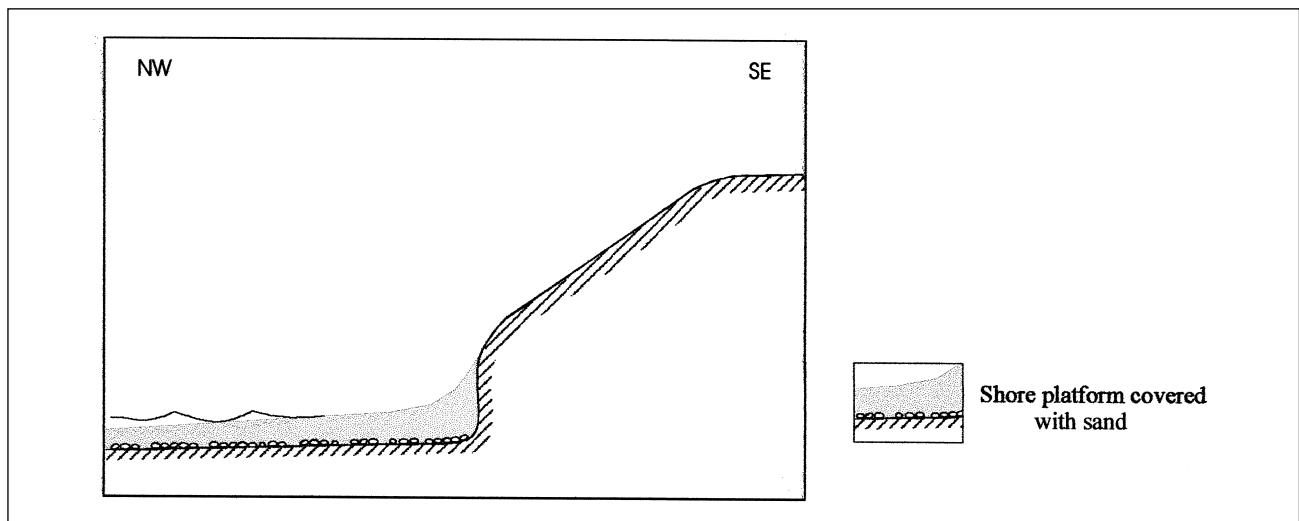


Figure 6. Scheme of the calm phase at Castelejo

waves reach it with violence, using the boulders and cobbles to attack its base. The cliff's retreat, as indicated above, provokes the destabilisation of the rest of the slope. Often, these sea storms occur along with heavy rainfall, capable of triggering mass movements on the slope. Therefore, there is a convergence of situations that causes an intense activity of the marine and subaerial processes. Under these circumstances, the retreat of the entire coastal slope reaches higher magnitude, either by wave action, or by mass-movement events, whose deposits are carried away by the sea, increasing slope instability. The Castelejo coastal system remained in such a phase from the late 1970s until 1986.

There is another phase, a calm phase, without sea-storm events having a significant impact on the coastal dynamic. In this phase, the shore platform is covered by sand (figure 6). The fine sands are selected by the wind and carried away to build climbing dunes, fossilising the cliff that was cut in the previous phase. As Sunamura (1992) also recognised for other places in the world, the beach then begins to act as a defence against the swash current, which rarely reaches the cliff base. On the other hand, the covering of the cliffs by the climbing dunes acts as a shield, and consequently cliff erosion is much reduced. However, we must stress that in the coastal slope sectors where there is a propitious geological structure, even during this calm phase, evolution by subaerial processes with high-frequency, low-magnitude rockfalls still persists, leading to the creation of the coluvio-eolic deposits noted above. In Castelejo, a calm phase began in 1987, and ten years later still continues.

This example indicates the influence of wave climate on the evolution of coastal systems. Research on the wave climate of the past two decades that is being carried out on the Portuguese coast will surely help to determine more exactly its impact on the dynamic of the cycle described. We hope that human pressure does not increase in this area, because as it is, Castelejo is an excellent place to study

the interaction of the natural processes of land-forms evolution.

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