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# Dune, Bluff and Beach Erosion due to Exhaustive Sand Mining – the Case of Santa Barbara Beach, São Miguel (Azores, Portugal).

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**ABSTRACT**

Coastal dunes are relatively rare features in the Azores islands and contribute to less then 1% to the total length of the archipelago's littoral zone, circa 844 km. Localised indications of aeolian activity, contemporaneous to the arrival of the first colonists in the 15th century have been found, but at present most of the coastal dunes are vegetated and stabilised. Dune sand has been exploited during the 20th century for industrial use, leading to severe damage or complete removal of a significant proportion of these features. In the 1950's the Santa Barbara area contained a rare and well-preserved example of an undisturbed active beach-foredune system, free of anthropogenic activities. It displayed a well-nourished beach profile margined by a coastal foredune and a climbing dune, which covered the adjacent bluff and extended landwards through an aeolian sand-sheet. Persistent sand mining between the early sixties and the late eighties, lead to volumetric depletion of the dune cover, lowering of the surface of the berm and triggering cliff erosion. In total, some 950,000 $m^3$ of sand has been removed, the dunes making up half of this figure. Although this activity was stopped in 1995 by legal enforcement, the erosive process still currently persists indicating a surpassing of the natural resilience and maximum vulnerability of the coastal dune system. At present the bluff retreats at very high rates (0.6 m/yr), the dune features were totally obliterated and the sandy beach has been reduced in width to a single swash ramp which floods during half of the tidal cycle.

**ADDITIONALINDEX WORDS:** *sand depletion, anthropogenic activity, coastal erosion, coastal resilience.*

## INTRODUCTION

The Azores archipelago is located in the North Atlantic between 36º 55'and 39º 43´ North and 24º 45' and 31º 17' West, approximately 1500 km away from Europe (Figure 1). It is formed by nine volcanic islands and a few islets scattered along 600 km and roughly aligned WNW-ESE that rise from the Azores Plateau, defined by the 2000m bathymetric contour.

The long fetch that characterises the Azores relative to the north Atlantic explains a high-energy wave climate where both sea and swell are relevant sources of energy to the coast. The steep submarine slopes and absence of shallow shelves produce localised patterns of wave shoaling, refraction and diffraction, which occur just before waves break (especially during storms). This leads to the fragmentation of the coast into a number of dynamic cells limited by virtually impermeable lateral boundaries in terms of sediment movement alongshore. Tides and tidal currents are minor contributors to coastal morphology and sediment dynamics.

Coastal dunes are relatively uncommon features in the Azores. They occur in the islands of São Miguel, Terceira, Faial and Graciosa and contribute less than 1% of the total length of the archipelago's littoral zone, circa 844 km. There are some indications of localised aeolian activity contemporaneous to the arrival of the first colonists in the 15th century, namely in the southern coast of São Miguel, at Pópulo beach, a few kilometers east of Ponta Delgada. At present all the coastal dunes of the archipelago are vegetated and stabilised or have been completely destroyed by natural or human causes.

The social and economic growth of the archipelago in the 20th century, and particularly in the last quarter of the Century, resulted in accelerated coastal development, which included the construction of communication infrastructures and buildings all of which required large volumes of sand. Given the local geological constraints, natural sand suitable for aggregate in construction works is a scarce natural resource. Constructors therefore used beaches and dunes as principal aggregate sources, exploiting the weaknesses of

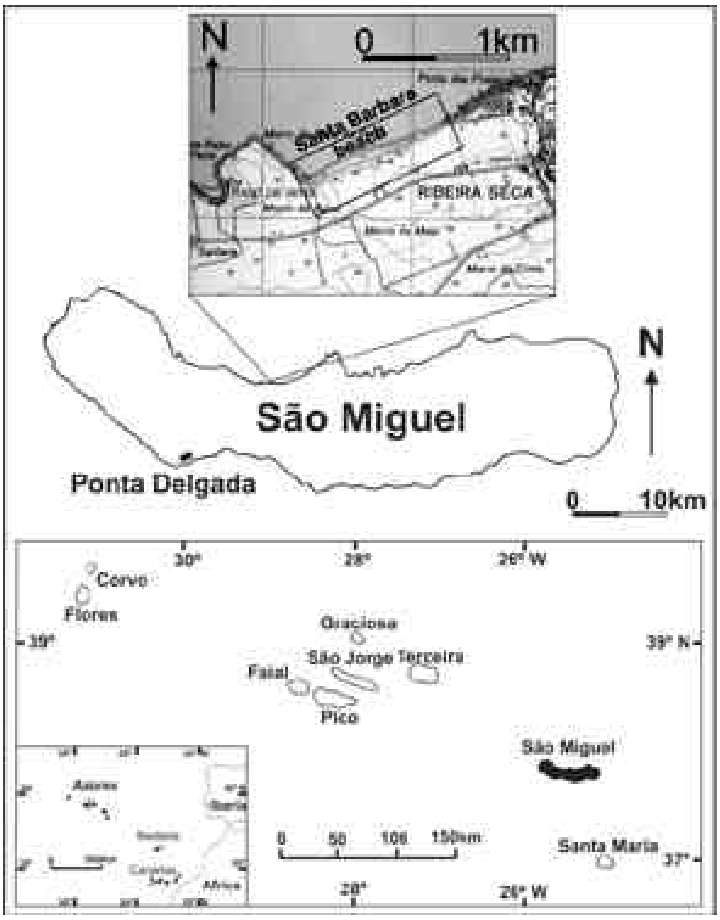


Figure 1. Location of the Azores archipelago and of the study area.

legal constraints to this type of mining activity as well as the inexistence of proper coastal management plans. This ultimately triggered uncontrolled erosion of these coastal features. This situation was only halted in the middle 1990's, yet by that time most of the mining sites had already been damaged or destroyed, with the nearby coast showing clear symptoms of sediment starvation.

At São Miguel Island, the Santa Barbara beach became the main source of sand for industrial purposes in the early 1960's, notwithstanding the absence of a specific permit and ignoring the few attempts of the local authorities to limit the extraction sites and control the rate of extraction. Sand exploitation reached a peak during the 1980's (circa 150,000 $m^3$/yr - LNEC, 1987) and was stopped in 1995 by legal enforcement.

## THE STUDYAREA

São Miguel is the largest (about 66 x 16 km) and the most populated island of the archipelago and the Santa Barbara area is located in its northern coast (Figure 1). The local geology is discussed in detail in ZBYSZEWSKI *et al*. (1958, 1959), ZBYSZEWSKI (1961), BOOTH *et al*. (1978), MOORE (1990), FORJAZ (1997) and WALLENSTEIN (1999). The local morphology is dominated by the slope of the Fogo composite volcano, one of the three active central volcanoes of S. Miguel. The shore is defined by an embayment, cut into thick plinian pyroclast deposits that mantle the northern slope of the volcano, some of which had accumulated during the last 5,000 years (BOOTH *et al*., 1978) the most recent corresponding to the eruption of AD 1563.

The Santa Barbara beach is the largest on the island and extends ENE-WSW for almost 1 km between Morro de Santana and the lava fan of Ponta das Praias (Figures 1 and 2); its backshore is defined by a bluff cut into trachytic ash, fall pumice and pyroclastic flow-deposits, rising some 20 m

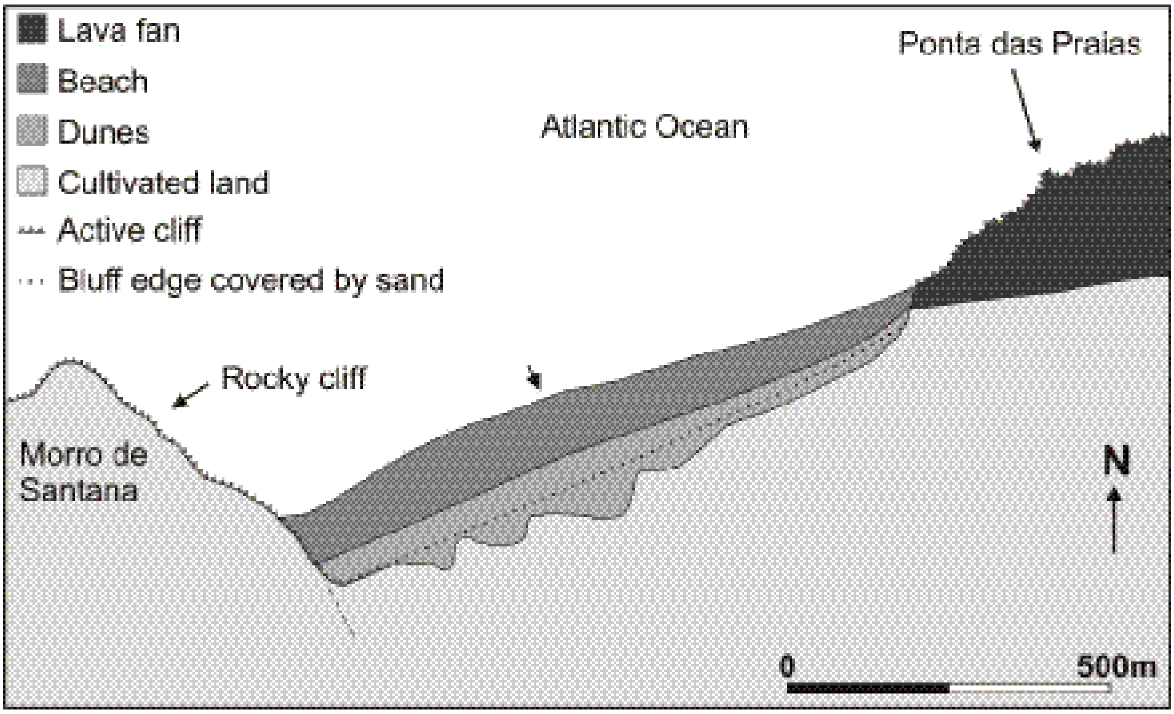


Figure 2. Geomorphological sketch of Santa Barbara beach in 1955, based upon aerial photography at an approximately scale of 1:11750. Arrow indicates location of the cross-section shown in Figure 3.

above mean sea level. The area is affected by a modal high-energy wave climate (Table 1) and the beach is fully exposed to northwesterlies, with the most damaging storms approaching from the north. A shallow submarine shoal located approximately 1200 m offshore at 5 m depth offers partial sheltering to storms approaching from NW and N (LNEC, 1987). The net littoral drift along the northern coast of São Miguel is directed eastwards (BORGES, 1995) although the sediment exchange between nearby cells is small, due to the combination of a strongly crenulated shore with a high-sloping nearshore.

Table 1. Simplified statistics of the wave climate offshore the northern coast of São Miguel (after PIRES, 1995); (s, [σ] - mean and standard deviation of significant wave height (annual average); $Hs_{max}$ - maximum significant wave height; $H_{max6}$ - highest wave height occurring in the series; $T_{pot}$ – mean equivalent power period; Vm - vector mean.

| Target location | s[σ] (m) | $Hs_{max}$ (m) | $H_{max6}$ (m) | Power ($Kwm^{-1}$) | $T_{pot}$ (s) | Vm (º) |
|---|---|---|---|---|---|---|
| Ponta do Cintrão 37º50.9'N 25º29.5'W | 1.9 [1.0] | 10 | 19.5 | 21.6 | 7.9 | 333 |

## METHODS AND RESULTS

The study of coastal changes at Santa Barbara relied on the comparison of aerial photography, following MARQUES and ROMARIZ (1991) and MARQUES (1991, 1994), and on field data obtained since 1999 onwards. The geomorphological description and cross section surveyed by BERTHOIS (1953) provide the oldest data set on this site that was used as initial reference. The aerial photographs of 1955, 1974, 1988 and 1998, at scales ranging between 1:5000 and 1:17000, provided 3 comparative periods, although quantitative information was limited by the quality of the images. Fieldwork consisted of seasonal monitoring of the beach morphology and adjacent bluff slope by means of transverse profiles surveyed between May 1999 and February 2001.

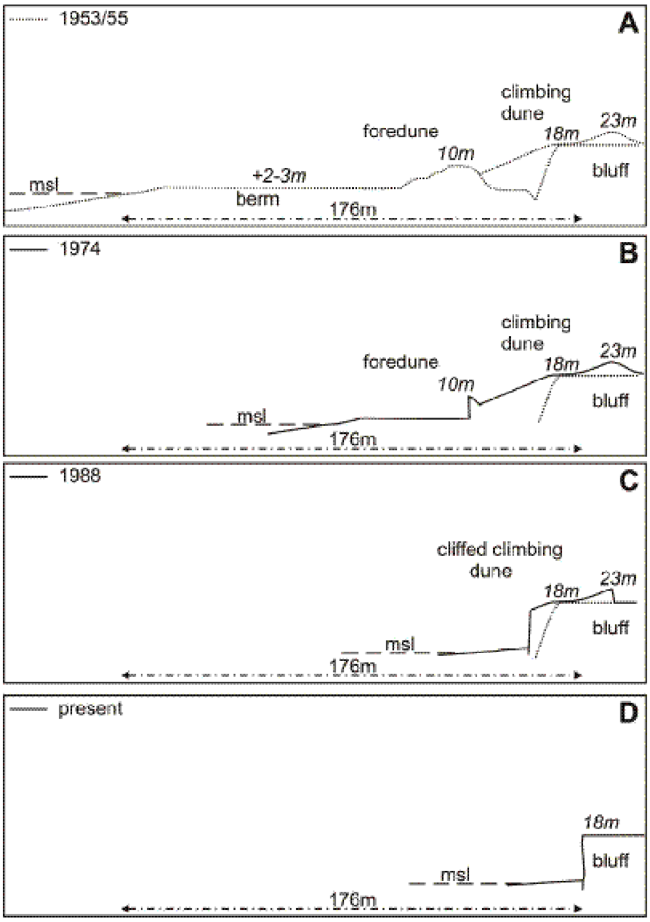


Figure 3. Cross-sections of Santa Barbara beach (numbers in italic refer to elevation above mean sea level). A – Cross section after BERTHOIS (1953) and based upon interpretation of aerial photographs of 1955; B, C – cross sections based upon photo-interpretation (1974 and 1998); D – cross section based upon field surveys.

In the 1950's the Santa Barbara area was one of the rare and well-preserved examples of a sandy undisturbed active beach-foredune system of the Azores, free of anthropic action. It displayed a well nourished and reflective beach profile, consisting of a steep beach face and a single berm, limited by a poorly vegetated foredune, which rose some 10 m above mean sea level. Beach and dune sediments consisted of grey-black medium, well-sorted sand. Shoreward, the dune was separated from the terrestrial margin by a climbing dune that covered the original slope and upper edge of the adjacent bluff and extended landwards through a thin aeolian sand-sheet, reworked by wind to produce small nebkas (Figures 2 and 3A). The morphological sketch of BERTHOIS (1953) identifies an ephemeral trough, deeply incising the upwind face of the climbing dune (Figure 3A) and connected with the beach through blowout corridors, which were completely infilled with aeolian sands by 1955. Both the climbing dune and sand sheet extended in continuity laterally, the cliff edge being visible only at the extremes of the embayment, its location beneath the sand controlling a slope-break in the dune. We estimate that in 1953 the volumetric retention above mean sea level in both the subaerial beach and dune structures amounted to circa 1 x $10^6$ $m^3$.

The documents of 1953 and 1955 show only minor changes to this geomorphological arrangement, attributed to seasonal morphodynamics of the beach and rapid sediment exchange with the dunes. According to the documentary record, sand mining began in the mid-1960's with the sand initially dredged from the high berm and foredune. This procedure persisted until the middle 1970's causing the shortening of the berm's width to half of its 1955's length, implying a new dynamic (im)balance of the local sediment budget. The beach preserved the beachface slope and the berm height throughout the seasonal morphodynamic cycle and the longer-term sedimentary deficit was absorbed by means of the shrinkage of the total length of the subaerial beach. The dismantling of the foredune appears not to have been balanced by any significant beach-sourced inputs, which, if present, would have contributed to the volumetric depletion of the beach. No information on the submarine section of the beach exists to allow characterisation of the complete profile. The aerial photographs of 1974 show partial exposure of the landward cliff in the eastern section of the beach and comparison with previous aerial photographs suggests the incipient establishment of localised cliff recession, its intensity averaging 0.1 m/yr since 1955 onwards. These photographs also depict the near-complete destruction of the foredune, which is now only represented by a small fragment of the original sand mound and is formed into a high vertical scarp facing the ocean (Figure 3B). Sand mining during this period accounted for the removal of some 220,000 $m^3$ (20,000 - 22,000 $m^3$/yr) of sediment above mean sea level.

A second period of sand mining existed between 1974 and 1988, when the rates of extraction reached maximum values (circa 54,000 $m^3$/yr on a 14-year average and above mean sea level; the report of LNEC (1987) mentions 150 000$m^3$/yr as peak extraction volume in the same period) and the borough sites were expanded to include the foreshore and the shallow nearshore as well as the climbing dune and the cliff-top sand-sheet. This enhanced the starvation of the beach and both morphological and sedimentological responses are clear in the 1988 photographs. The climbing dune developed a high tide cliff and was reduced to less than 1/5 of its original volume (Figure 3C); shingle (previously resting beneath the sand) replaced sand as sediment infill in the eastern half of the beach, where it was reduced to a bluff-toe accumulation. In 1988, the berm width had shrank to some 12 m in the western section of Santa Barbara beach and the cliff-top sand sheet had been almost completely removed, exposing and reactivating the underlying cliff, which showed generalised erosion that also increased in intensity by 30% (0.13 m/yr).

Between 1988 and 1995 the volumetric depletion of the beach and dune continued, notwithstanding the significant drop of contemporary extraction rates, which came to an end, by legal enforcement, in 1995 – too late for the cliff-top sands, which had been completely removed by this time (Figure 3D). The differences in time scales of coastal response are interpreted as a result of local resilience thresholds having been disrupted due to man-induced, rapid exhausting of sediment. Consequently this set up an imbalance between the residual morphology of the embayment and the forcing capacity of waves. Since 1995 onwards the general erosive response persisted, now free of any direct anthropogenic forcing, and corresponding solely to hysteresis. The remnants of the beach and foredune have been completed obliterated by wave erosion. The rates of cliff recession peaked to 0.6 m/yr between 1988 and 1998.

The volumetric estimates indicate that a total of 950,000 $m^3$ of sand has been extracted from the Santa Barbara subaerial beach and dunes since 1953 and "natural" erosion accounts for the remnant volumetric depletion (50,000 to 150,000 $m^3$), i.e. the sediment losses by man-induced causes exceeded the effects of natural processes by a factor of 9. At present, waves reach the cliff toe in each high tide and actively maintain cliff recession, which is steadily growing in intensity during the last 6 years. Sand, quite similar in texture to the first observations of BERTHOIS (1953), is an ephemeral component of the intertidal zone, occasionally accumulating there during prolonged fair weather periods. In this case, the beach reduces to a single swash ramp, drowned during half of each tidal cycle, which extends into the nearshore through a low-tide sandy and shingle platform.

## DISCUSSION AND CONCLUSIONS

The intensive mining of sand from the Santa Barbara beach and dune system appears to have been the initial cause of the establishment and growth of a generalised erosive regime, which initially affected the sediment infill of the beach and dunes but later propagated to the landward margin of the embayment. According to the available information the total volume of sand extracted from this site amounts to some 950,000 $m^3$. This is most certainly an underestimated figure, given that it considers only the volumetric depletion above mean sea level; this is confirmed by the indication of a peak extraction rate of 150,000 $m^3$/yr computed from the exploitation's manifests (cf. LNEC, 1987). The documents dated previously to the mining activity indicate that this coastal system was in dynamic equilibrium in sedimentological and morphological terms and well adapted to the total available sediment volume and modal wave energy. Given the absence of relevant external sediment sources it must be concluded that sediments of the beach and dune have been trapped inside the local coastal cell for a long residence period. The rapid morphological changes observed in the back dunes in the early 1950's indicate that aeolian activity and the adjacent dune acted as temporary stores and participated in the short-term budget of this coastal cell, essentially characterised by cross-shore sediment movement.

The initiation of sand mining triggered contemporaneous volumetric and morphological adaptation of the beach. During the first decade of mining, characterised by small extraction rates, the adaptation response appears to have coped with the sediment depletion, preserving the modal morphodynamic arrangement of the beach and consisted essentially of shrinkage of the berm's length. This suggests that a surplus amount of sediment was present in the backshore dunes, acting as a buffer to absorb disturbance induced by extreme events. It is also plausible that some contribution from the submarine beach may have existed. The increase of the mining efforts between 1974 and 1988 disrupted the local resilience of this system and this was accompanied by generalised and intense erosion but also by a change in morphology. The beach developed a dissipative profile, in order to cope with the enhancement of the horizontal penetration of waves, implying widespread lowering of the surface and simplification of the subaerial beach profile. Similar responses are reported by NORDSTROM (2000) in sand beaches following the development of an adjacent landing strip and the construction of sea walls, which increase the reflectance of the shore. In Santa Barbara, no defence structure has been constructed but the bluff acted as a functional equivalent, once the morphological transformation of the beach (induced from mining) allowed waves to reach its landward edge more frequently. Simultaneously, the total length of the subaerial profile began to grow steadily (but slowly) at the cost of bluff erosion, which is once again an adaptation response commensurate with the search for the adequate length of an equilibrium dissipative profile. A major equilibrium threshold appears to have been exceeded in the late 1970's – early 1980's, corresponding to a morphodynamic switch towards a predominately dissipative arrangement, which triggered a catastrophic erosive response. This type of coastal response, typical of brittle systems and characterised by a succession of metastable equilibria and punctuated by events of rapid and irreversible change, following persistent changes of the local sediment budget, has been described in other sections of the Portuguese coast and elsewhere (cf. ANDRADE and FREITAS, 2000).

Since the beginning of sand mining at Santa Barbara, the recession rate of the bluff has increased by a factor of 2.3, indicating that the aforementioned equilibrium state is still far from completion. Once the morphodynamic arrangement of the beach changed, erosion became irreversible. Sand losses to mining have been added to by losses to the nearshore in order to build the low-tide platform that has been growing steadily until the present. The similarity in texture between the sediments of the foreshore, reported by BERTHOIS in 1953 and those presently found in the intertidal swash ramp, suggests that the source of sediment has remained virtually unchanged during the last 50 years. Also, the erosion of the cliff has not been a significant new sediment source to the neighboring beach. This is due to poor compatibility in texture and composition between the beach sediment (essentially mineral or lithic dense sand) and the waste produced by cliff retreat (largely dominated by silt-sized particles of acidic and vesicular pumice and ash). After reworking by the extremely efficient segregation filtering effect of waves, only a small fraction of the waste material has an adequate hydraulic diameter and can therefore be retained in the beach system Therefore, a new distribution pattern of the remnant available sediment, added to by minor inputs of the cliff-source has been developing, and is still contained within the same coastal cell and corresponds to a net offshore loss of the subaerial beach. The major volumetric changes observed at Santa Barbara have had no counterpart in adjacent pocket beaches, confirming that the longitudinal sediment transfers are virtually null and that this coastal cell is essentially actuated by the cross-shore component of wave power.

The hysteresis that characterises the coastal system determines that the most important responses of the coast were on different time scale in relation to the forcing factors driving the system. This may also explain the persistence of sand losses even after the cessation of mining activities - these sediments have been accumulating in the low-tide platform.

Once the beach was completely starved of sediment, the retreat of the bluff rose to very high rates (0.6 m/yr) and the present-day remnant of the beach is quite similar in shape, retention volume and seasonal character to developed beaches lying in front of steep revetments and sea walls.

Assuming a net value of € 40 per cubic meter of extracted sand and that the corresponding net profit is about 60% of this figure (an overestimated assumption) the total net return of sand mining at Santa Barbara amounts to some € 380,000 on a yearly average. This figure is strikingly small when compared with the potential profit and social benefits that might have been gained if the mining had not happened and the site thoughtfully developed for recreational and tourist use. The ability of mankind to transform coastal landscapes is well known and the case of Santa Barbara emphasizes its most prejudicial consequences, due to the absence of a clear policy of sustainable development and any kind of appropriate management plan. This is compounded by a shortsighted perspective on the potential value of the coast as a natural resource.

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