Sedimentary structure of the Nazaré coastal dunes (Portugal)

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***Abstract*—The internal structure of costal dunes located south of Nazaré was analyzed using Ground Penetrating Radar. These coastal dunes comprise stabilized dunes, located in the inner part of the dune field, and foredunes, both separated by a dry dune slack. The radargram analysis allowed the identification of five bounding surfaces that define six main aeolian sand units. The Units I, II, III and IV correspond to the progradation of foredunes seaward (NW), while Units V and VI represent the migration of a parabolic dune and a blowout, respectively, to southeast. A strong reflector separating Units I, II and III from Unit V is interpreted as a paleosoil, suggesting a break in aeolian sedimentation of unknown duration, but with sufficient time for soil development. The absent of the paleosoil over the Unit IV leave some doubts in relation to its relative age, although is indicative of the occurrence of an erosive event. Radar stratigraphic analysis provided a relative chronology of units that will be used as a framework for selecting sampling points for future absolute dating and sedimentological studies.**

Keywords- coastal dunes; GPR; stratigraphic units, Quaternary evolution, Portugal.

I. Introduction

During the last few decades, Ground Penetrating Radar (GPR) has been used with great success on dunes investigation [1, 2, 3, 4, 5, 6, 7, 8] providing good images of the internal structure of these sand bodies. This success is due to the fact that sand dunes have low conductivity and contain sets of cross-strata which are readily imaged by GPR [9].

In Portugal, GPR has been scarcely used in this type of research, the earliest publication dating from 2007 [10]. However, coastal dunes represent an important morphological element of the Portuguese coast, namely in the west coast north of Cape Carvoeiro (Fig. 1).

The aim of this study is to present results of GPR survey, in order to investigate the internal structure of Nazaré coastal dunes, to interpret formation episodes and to outline an evolutionary model of the dune system based on relative chronology of the main units.

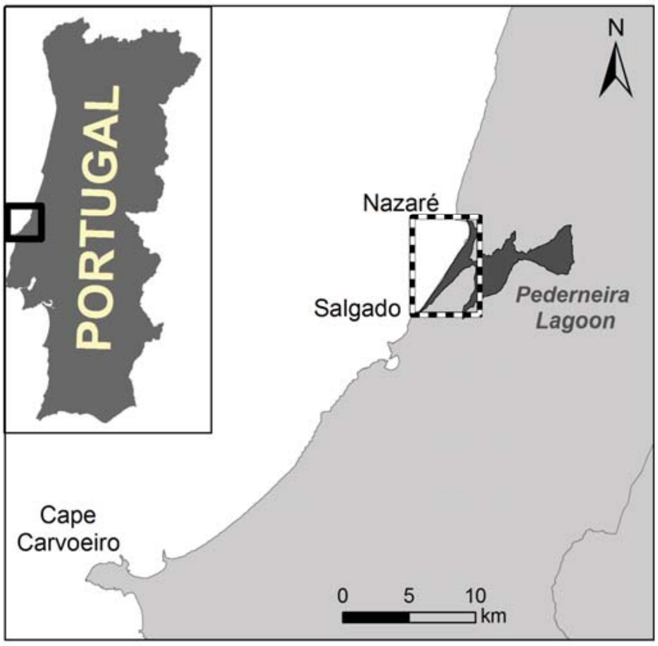

Figure 1 - Location map of the study area.

II. Study Area

The Nazaré-Salgado coastal stretch, located in central Portugal (Fig. 1), corresponds to the northern tip of a coastal cell that develops along 100 km between Nazaré and Cape Carvoeiro, trending N42ºE. It constitutes the littoral sector of the former Pederneira lagoon, which completely silted up from the late 19th century onwards (Fig. 1).

One essential morphological feature in this area is a ~5km long sand spit rooted south in active cliffs cut in Jurassic limestone (indicating northward extension) and capped by a beach-dune system aligned parallel to the general coastline

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trend [11] (Fig. 2). The orientation of parabolic dune ridges indicates that these landforms developed under prevailing NNW to NW winds.

The foredune is 5 km long and 150 m wide, it reaches about 15 m above MSL and is sparsely covered by herbaceous vegetation, among which *Ammophila* sp. predominates. This landform is affected by several active blowouts oriented NNW-SSE to NW-SE (Fig. 2). The northern sector of the foredune is interrupted by the Alcôa river outlet and its tip is fully controlled and artificialized by the Nazaré structures (Fig. 2). The parabolic dunes and the blowouts remain stabilized since, at least, 1957 as suggested by the comparison of aerial surveys.

The knowledge about the age and evolution of this dune system is poor; however, by comparison with other coastal dunes located along the Portuguese center/northern coast [12, 13, 14], the formation of the stable dune is believed to have occurred in the Late Pleistocene, while the development of the foredune may have occurred during the mid Holocene in tune with MSL stabilization.

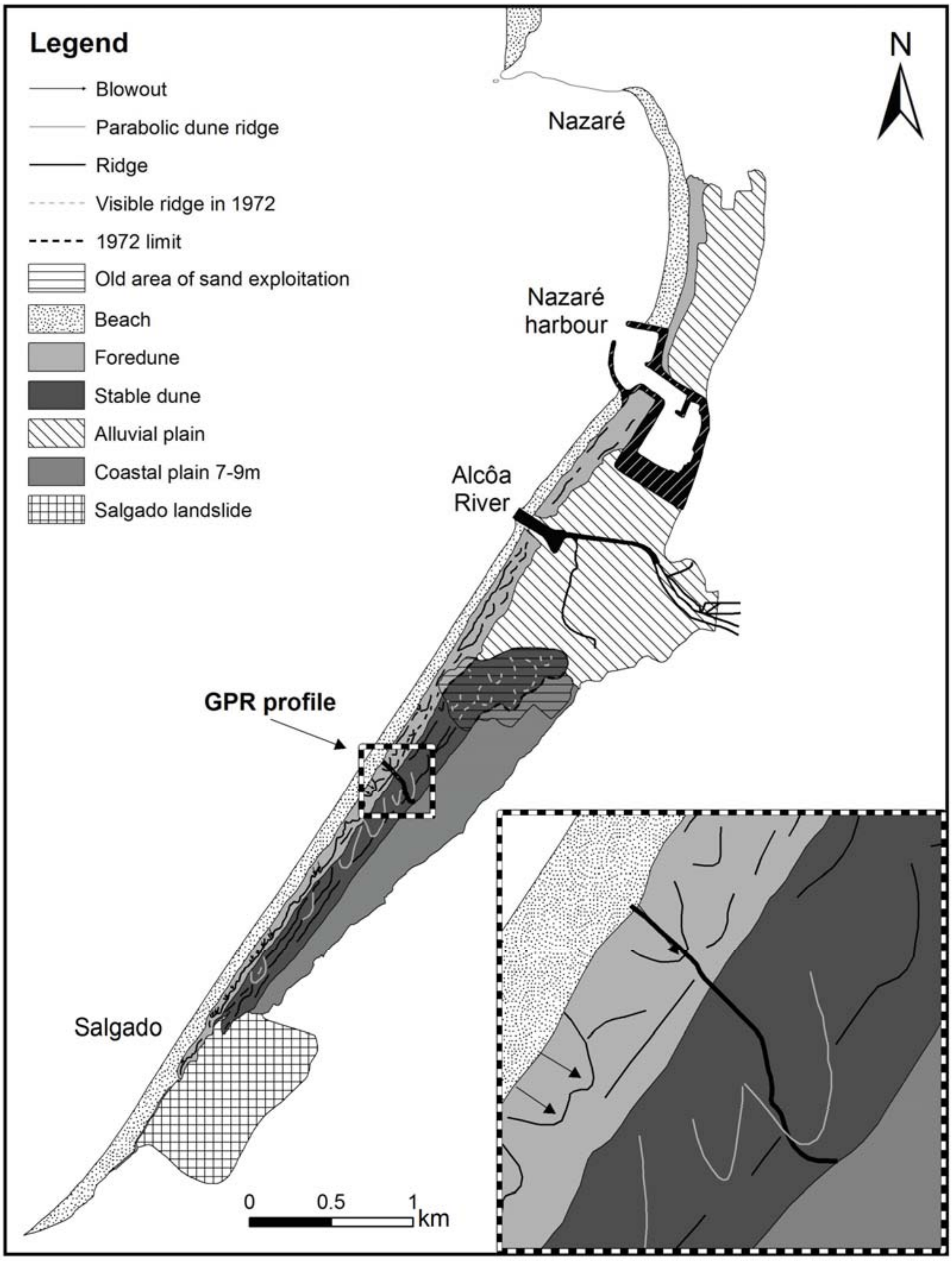

Figure 2 - Simplified geomorphological sketch, based on aerial photographs from 2002.

III. METHODOLOGY

A. Data acquisition

The GPR data were collected in November 2008 with the MALA Geoscience equipment using a shielded ground coupled antenna with 100 MHz (nominal frequency), in a constant offset mode (Fig. 3). Data have been acquired with a step-size of 0.1 m and 0.5 m antenna spacing. The GPR data were collected along a 339 m length, NW-SE profile, located on a footpath (Fig. 2). The maximum signal penetration was about 280 ns (two-way travel time). A topographic survey of that profile was carried out using a DGPS-RTK (GPS900 Leica).

Figure 3 - Equipment used in the acquisition of the GPR profile.

B. Data processing

The ReflexW software was used to process the data and to correct the topography. Basic data processing used to produce the radargram includes time-zero correction, dewow filtering, subtracting average, div. compensation (Gain) and static correction.

Two-way travel time values were converted to depth assuming a constant electromagnetic underground wave velocity of 0.12 m/ns. This is a typically value determined in dry sand [5], [15], [16], [17] and is within the range of velocity values found by the adaptation of diffraction hyperbolas. Thus, the estimated penetration reached 16.8 m depth. The profile data was migrated in order to obtain a more realistic subsurface imaging.

IV. INTERPRETATION

In general, the radargram shown in figure 4A displays multiple dipping reflections exhibiting different directions and dip angles. A strong continuous and sub-horizontal reflection, located at the base of dune, was interpreted as representing the water table, suggesting the presence of a freshwater aquifer at the bottom of the imaged profile. Between 80-120m (in relation to the beginning of the profile), it is possible to observe the behavior of this reflection to follow the topography. This can be due to velocity variations caused by changes on water content or static correction errors. Since topographic survey was carried out on the same trail of the GPR acquisition, we consider that the topographical errors are minimal and the first hypothesis is more likely.

According to the geometry, continuity and termination of the reflections, five bounding surfaces (1 to 5) were interpreted and six stratigraphic units have been identified: Unit I to Unit VI (Fig. 4B). Only three bounding surfaces (1, 3 and 5) are represented by a well defined reflection.

The surfaces 1 and 2 dip toward the west, surface 3 has an undulating form, the subsequent surface (4) has a sub-horizontal attitude and surface 5 dips to west.

Interpreting the bounding surfaces as time-lines, a relative chronology for the dunes is suggested here based upon cross-cutting relationships and superposition. The oldest Unit (I) contains NW- and SE-dipping reflections at a low angle and attains a maximum thickness of 14 m. During its formation, several reactivation phases seem to have occurred as evidenced by the reshaped surfaces identified on figure 4B. Most of the SE-dipping reflections occurred in the younger reactivation phases indicating sand migration to southeast. These younger phases were responsible for the increase in height of the dune crest.

Units II and III contain sub-horizontal and NW- dipping reflections and attain a maximum thickness of 10 and 6 m, respectively.

Unit IV, located at the western part of the profile, is characterized by NW-dipping reflections and has a maximum thickness of 6 m.

A continuous, high amplitude and wavy reflection separates the stratigraphic Units I, II and III from Unit V. This bounding surface (3) is interpreted as an organic-rich paleosoil with high water content. The presence of this surface induces signal attenuation in the underlying units.

Units V and VI comprise reflections with an apparent eastward dip, which are interpreted as sets of cross-stratification, indicating periods of dune migration to southeast. The maximum thicknesses attained are 9 and 6 m in Unit V and Unit VI, respectively. It is possible to observe, in both units, a changing in the apparent dip angles of the imaged cross-stratification due to the increase of sand accretion or small changes in wind direction. These changes in the apparent dip are interpreted as reshaped surfaces (Fig. 4B) and mark a new migration phase of the dune.

V. DISCUSSION AND CONCLUSIONS

The interpretation of the radargram collected along the coastal dune system located south of Nazaré (Fig. 4B) suggests a complex depositional history, with six main units.

Units I, II and III represent the progradation of the foredune system seaward (NW), separated by interdune depressions (ridge and swale morphology). These units were probably formed in the Late Pleistocene in a context of MSL lower than present and high sediment availability in a coastal plain, exposed to the action of winds.

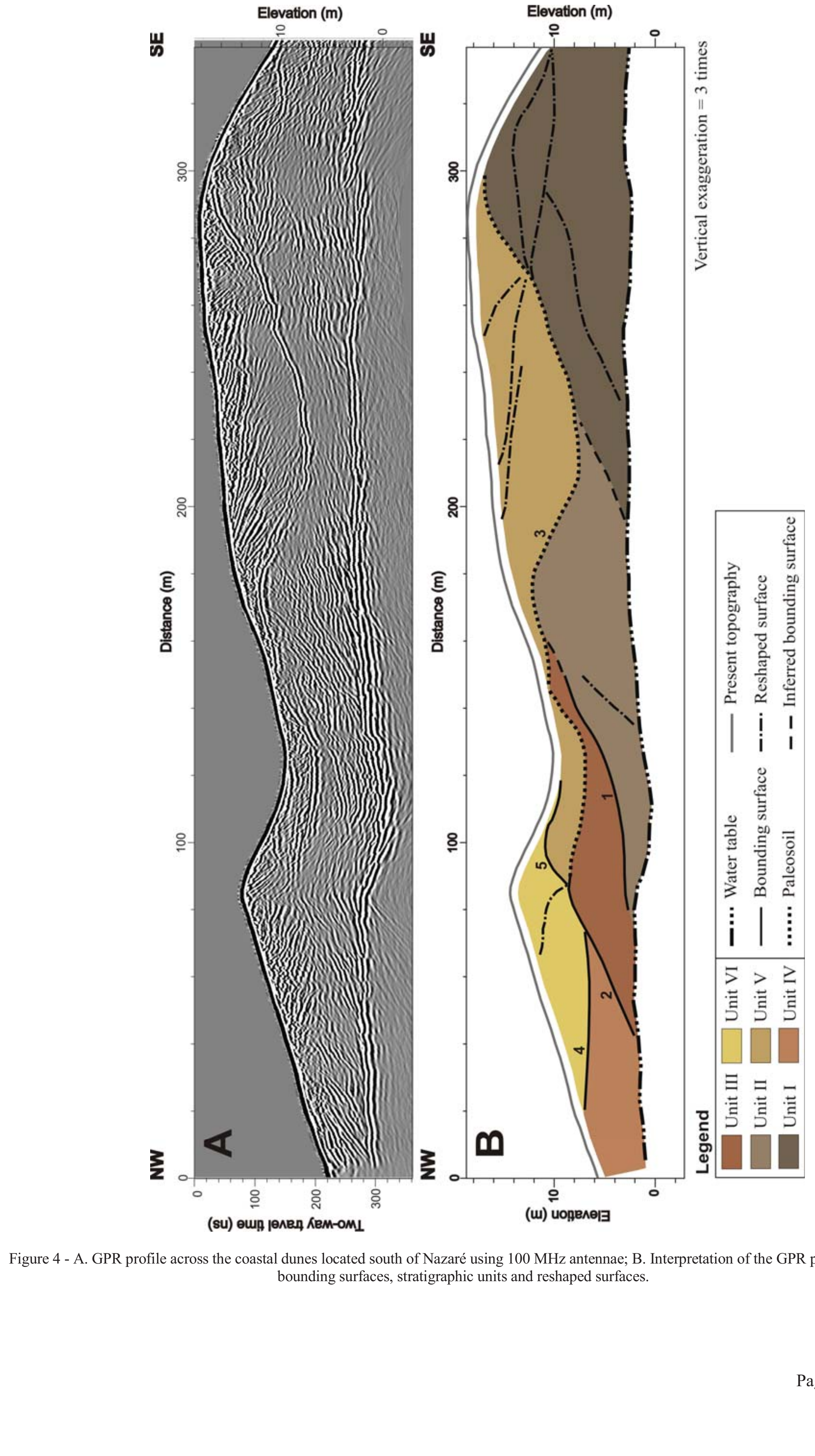

Figure 4 - A. GPR profile across the coastal dunes located south of Nazaré using 100 MHz antennae; B. Interpretation of the GPR profile showing major bounding surfaces, stratigraphic units and reshaped surfaces.

Several episodes of reactivation seem to have occurred during the growth of the foredunes, as evidenced in figure 4B.

The Unit IV corresponds, as well, to the progradation of the foredune to NW, however, the existence of an erosional event identified as bounding surface 4 and the absence of the paleosoil (3) covering this unit leave some doubts in relation to its relative age. In this stage of knowledge and without datings, it's impossible to know if this unit is oldercontemporaneous or younger than the paleosoil. Although, in all situations, an episode of erosion (4) occurred after the deposition of the Unit V, due to the proximity to the coastline (high-energy event), probably after the stabilization of the Holocene MSL. This event was responsible for the erosion of the foredune crest and probably of the paleosoil (?).

Following the deposition of Units I, II, III and IV(?) aeolian sedimentation ceased during a long period of time, allowing the development of a thick and continuous soil layer (3).

After a period of stabilization, a new episode of dune sedimentation has occurred (Unit V), covering the paleosoil and leading to the infill of the former interdune depressions. According to the geomorphological sketch (Fig. 2), this unit represents the migration of the parabolic dune to southeast driven by wind deflation of the former foredune. Unit V corresponds to the sedimentary structure of two elements of the parabolic dune, namely the southern dune limb and the slipface.

Finally, Unit VI represents the internal structure of two sections of a blowout, namely the deposits below the deflation basin (sub-unit below the reshaped surface) and the depositional lobe (sub-unit above the reshaped surface).

The sedimentary structure of the Nazaré coastal dune system is composed by six units as interpreted in figure 4B, deposited in four evolutionary stages: 1) progradation of the foredunes seaward (to northwest); 2) stabilization of the dune system and development of a paleosoil; 3) migration of the parabolic dune to southeast; and 4) development and migration of an active blowout to southeast.

This interpretation should be regarded as preliminary and needs complementary research, namely on: (1) sedimentological characterization of the deposits; (2) correction of the reflectors depth; (3) OSL dating of the different units identified and ^{14}C dating of the paleosoil.

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