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Decadal Evolution of a Coastal Dune Field and Adjacent Beaches at North of Fuerteventura (Canary Islands, Spain)

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ABSTRACT

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This paper analyzes a certain area from two different approaches: a sedimentological one considering not only the classical parameters (e.g. grain size properties) but also aspects such as the ability of sediments to be blown or their foraminiferal content, and an evolutive approach which could be possible after correcting and georeferencing series of aerial photographs. The area includes different environments, such as current beaches, mobile dunes, semi-stabilized aeolian deposits and Pleistocene dunes. All them were sampled. This study area is specially interesting because the mobile dune field is prograding due to inputs from nearby beaches, while the leeward coast beaches are under erosion. Results show that even though there is an aeolian sand transport from the dune area towards the beaches, they are eroding mostly due to human factors.

ADDITIONAL INDEX WORDS: *Grain size, ASA parameter, foraminifera, georeferencing, coastal evolution.*

INTRODUCTION

The Northern coast of Fuerteventura (Canary Islands, Spain) is partially covered by three coastal dune fields, namely Corralejo, Majanicho and Cotillo-Tostón. All them have a similar origin related to marine sedimentary deposits and volcanic episodes (MECO and STEARNS, 1981; CRIADO, 1991; COELLO *et al*., 1992; ANCOECHEA *et al*., 1996; ZAZO *et al*., 2002, 2003), but in the last decades seem to be under the influence of different evolution trends.

Present paper deals with Cotillo-Tostón aeolian deposits and adjacent beaches, located at the NW coast of Fuerteventura, (Figure 1), which is very important due to the fact that most dune deposits in Canary Islands are under erosive patterns (ALCANTARA-CARRIO and ALONSO, 2002; ALONSO *et al*., 2002; HERNANDEZ *et al.*, 2002), while in this particular site the area covered by active dunes is steadily growing. The aim of this paper is to analyze the properties of the aeolian materials and the evolution of this area, including the links between the different sub-environments in the aeolian deposits and the adjacent beaches, located both northwards and southwards.

STUDY AREA

The Cotillo-Tostón aeolian deposit is one of the smaller ones in Canary Islands, with a total extension of 2.7 km^2, in which several beaches and basaltic outcrops are also included. Aeolian materials overlie basaltic lavas corresponding to the IV serie of FUSTER *et al.* (1968), dated in the Upper Pleistocene to Holocene (COELLO *et al*., 1992). Within the area covered by aeolian sediments, two different sub-environments can be distinguished: a northern sector completely covered by active dunes formed by marine sediments, moving towards the SSW due to the prevailing winds, and a central and southern sector where aeolian materials are partially stabilized, and where small nebhas and wind ripples are the only features indicative of aeolian activity (CRIADO, 1991).

Sediment transport is determined by meteorology. In this context, Fuerteventura island is characterized by trade winds towards about 205º (BARTON *et al.*, 2001), with average wind velocities of 17 km/h in winter and 24 km/h during the summer. There are also great scarcity of rains, with less than 100 l/m^2 in a normal year (AT HIDROTECNIA, 2002).

METHODOLOGY

Different sedimentological studies have been carried out, as well as the analysis of the evolution of the study area in the last decades. Regarding the former ones, a total of 29 samples of surface sediments from the aeolian deposits were collected, as well as 10 additional samples from nearby beaches, from both the North and West costs. 5 additional samples from previous aeolian deposits were also collected. From these samples, 3 of them belong to a lower stratigraphic position, separated from the sandy surface by a reddish terrestrial silty deposit containing hymenophter nests and gastropod shells. The remainder 2 samples were collected from Rosa Negra and El Quemado

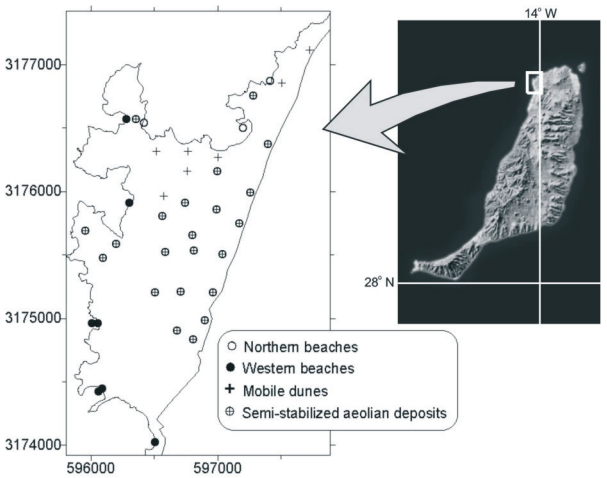

Figure 1. Location map of the study area and samples position, except those from Pleistocene deposits which are far away.

Table 1. *Results from sedimentological analysis.*

Environment	No. samples	Mean (∅)	Sorting	Skewness	Kurtosis	CO_3 (%)	ASA parameter
North coast beaches	3	1.12	0.47	-0.11	1.15	93.95	0.30
Active dunes	7	1.23	0.58	-0.04	1.01	97.15	0.52
Semi-stabilized aeolian deposits	22	1.41	0.58	-0.04	1.08	94.49	0.53
West coast beaches	7	1.63	0.57	-0.12	1.11	93.46	0.54
Ancient dunes	5	2.01	0.56	0.12	1.09	91.08	1.03

quarries, at a distance of 4 and 9 km respectively from Cotillo village, where Pleistocene sandy deposits have been quarried. All the samples were positioned by GPS.

Different analysis were carried out in order to determine the ability of sediments to be blown. Therefore grain size and specific gravity of sediment samples were needed. Grain size parameters were obtained after Folk and Ward's graphic method (FOLK and WARD, 1957) after dry shieving at 0.5 intervals. Due to the high proportion of calcium carbonate in the samples, specific gravity was estimated from the carbonate content, which was computed after measuring the released CO_2 when the sample reacts with ClH 10% (GUITIÁN and CARBALLAS, 1976).

On the other hand, the determination of foraminiferal content of 14 of the samples corresponding to the different environments was undertaken. All the foraminifera from a fixed volume of 3 cm^3 per sample were separated, classified and counted. Different cluster analysis were performed to correlate the samples between them: Dice coefficient (DICE, 1945) was used for cualitative analysis and Manhattan distance for quantitative ones (SNEATH and SOKAL, 1973; FELSENSTEIN, 1983). NTSYS software was used in both cases (ROHLF, 2002).

The evolution of the study area has been analyzed from aerial photographs corresponding to 1957, 1987, 1996 and 2002. All the photographs were conveniently digitized and corrected to avoid distortions due to geometry, differences in real scale and tilting (MOORE, 2000). ILWIS 3.1 software (VAN WESTEN, 1997) was used for georeferencing, as well as for computing superficial and lineal parameters.

RESULTS

Sedimentological Analysis

Grain size analysis show that mean grain size for all samples ranges between 0.28 to 2.22 , that is from coarse to fine sands, with an average value of 1.39. Nevertheless, instead of presenting the data of any individual sample, samples have been grouped according to the environment they were collected from. Table 1 presents average results corresponding to the grain size parameters, as well as carbonate content and the value of the ASA parameter (ALCANTARA-CARRIÓ and ALONSO, 2001), which will be discussed later.

Referring to the grain size results, no significant differences are shown between beach samples compared to those of the active dunes nor those from the semi-stabilized aeolian deposits, except for the mean size which shows a gradient in the four current environments, so that the finer samples correspond to the leeward ones (Table 1).

Something different happens with samples from ancient dune deposits, since in this case the average grain size is significantly finer (2.01) and positively skewed, which clearly corresponds with blown sand.

Foraminiferal Content

Nearly 2000 individuals were separated and classified into 59 species, 53 of them corresponding to benthic foraminifera grouped into suborders Miliolina (17 sp), Rotaliina (30 sp), Textulariina (5 sp) and Lagenina (1 sp). The remaining 6 species correspond to planktonic foraminifera grouped all them into Globigerinina suborder. Even though the number of planktonic species is relatively significant (10%), the number of planktonic individuals only account for 1.8% of the total, and 82% of these planktonic individuals correspond to samples from fossil dunes.

Results from these studies are shown on table 2, from which it can be observed the great difference between samples from the modern aeolian deposits (both active dunes and partially stabilized deposits), compared to the beach and fossil dune deposits. In the former one the number of species is much smaller, as well as it is the density of foraminifera (7.2 individuals/cm^3 compared with 47.6 and 93.5 individuals/cm^3 from the beaches and the fossil dunes samples respectively).

Regarding the more characteristic species for each environment, *Cibicides refulgens* and *Lobatula lobatula* are the most abundant ones (Table 2). These two species are particularly important in the samples from previous aeolian deposits, where only these species represent nearly 70% of the total individuals. On the other hand, some very rare species in this area have also been found, such as *Trichohyalus aguayoi* (Bermúdez) and *Trochammina inflata* (Montagu) (Figure 2). These species are characteristic of non energetic coastal environments with big oscillations in salinity, such as coastal lagoons, swampy areas and mangroves (TUFESCU, 1969; MURRAY, 1991). In this case both species are present in one sample from a modern beach located northward, which points out to the occasional formation of salty lagoons, probably after stormy events. Also included in Figure 2 is *Truncorotalia truncatulinoides* (D'Orbigny), one of the planktonic individuals.

Table 2. *Results from foraminiferal studies.*

Environment	No. samples	No. species	No. individuals	Density (indiv/cm^3)	Characteristic species (Density in brackets, indiv/cm^3)
Active dunes	2	12	43	7.2	*Quinqueloculina berthelotiana* D'Orbigny (1.7) *Cibicides refulgens* Montfort (1.5)
Semi-stabilized aeolian deposits	4	19	85	7.1	*Cibicides refulgens* Montfort (1.8) *Bolivina punctata* D'Orbigny (1.2)
Ancient dunes	4	39	1122	93.5	*Cibicides refulgens* Montfort (42.9) *Lobatula lobatula* (Walker & Jacob) (21.1)
Beaches	4	41	571	47.6	*Lobatula lobatula* (Walker & Jacob) (5.1) *Rosalina vilardeboana* D'Orbigny (4.9)

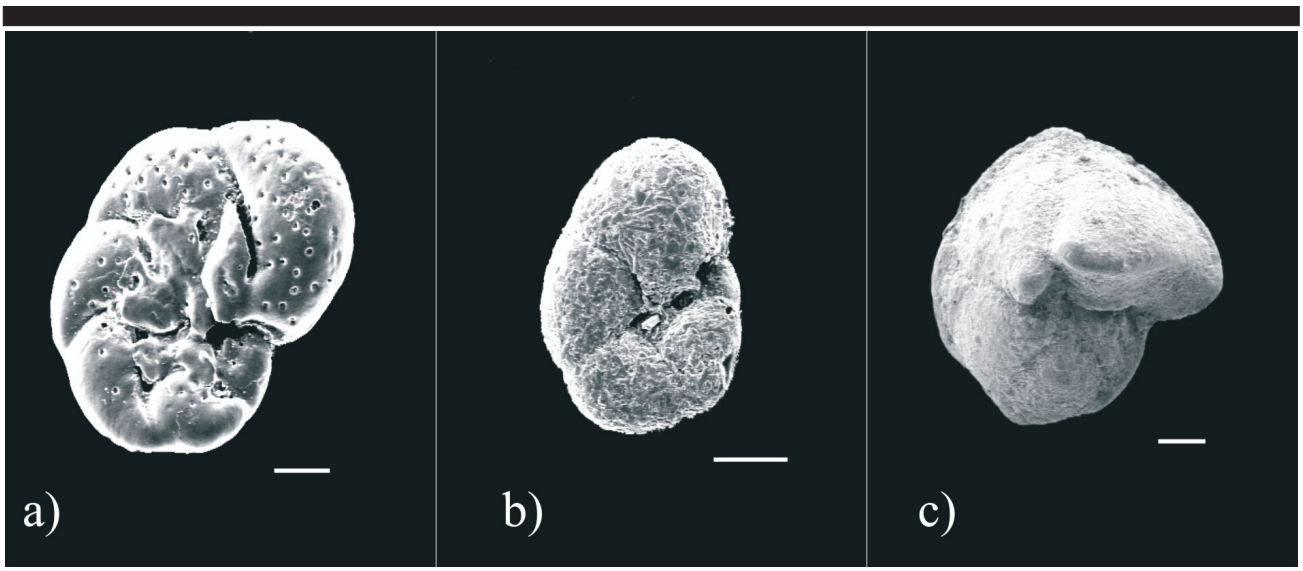

Figure 2. a) Trichohyalus aguayoi (Bermúdez), 1935. Scale bar=50µm b) Trochammina inflata (Montagu), 1808. Scale bar=100µm c) Truncorotalia truncatulinoides (D'Orbigny), 1839. Scale bar=100µm.

Evolution of the Study Area

Three parameters have been considered regarding the evolution of the study area: two of them referring to the active dunes and the last one to the southward beaches.

The first parameter is the area covered by active dunes, which has been calculated from the different photographs thanks to their lighter color compared to the slightly darker semi-stabilized deposits. Related to this parameter is the movement forward of the active dunes front, as they are pulled by wind towards the SSW. It can be seen from Figure 3 and Table 3 that the active dunes are clearly in progradation during the last decades, since in 1957 the area covered was 96.400 m^2, and 45 years later it was 253.000 m^2.

This increase can only be explained considering important sedimentary inputs from northwards beaches. Nevertheless the growth rate is steadily decreasing, since at the beginning of the studied period the average growth of the mobile dunes area was higher than 4.100 m^2/year and in the last years it is only 1.650 m^2/year (Table 3). Something similar happens with the dune front advance, which has decreased from nearly 11 m/year to 4.3 m/year.

The third parameter considered takes into account the evolution of the southward beaches. Comparison of corrected photographs between 1957 and 1996, measured at different locations of the beaches, shows an average onshore migration of the shoreline of 43 meters.

DISCUSSION

Sedimentological Aspects

Grain size

There is a clear gradient in mean size referring to the four present day environments. The coarser samples correspond to the northern beaches which are the source area of marine sediments (1.12 , Table 1). These beaches are clearly related to the mobile dunes, where the average grain size is slightly finer (1.23). In the southward direction are located the semi-stabilized aeolian deposits, where average grain size is even finer (1.41). Finally, beaches located in the west coast present finer sediments (1.63). This trend seem to denote a net aeolian transport towards the South, so that the sediments become finer as they are moved over longer distances.

ASA parameter

The Aeolian Sediment Availability Parameter (ASA) was defined by ALCÁNTARA-CARRIÓ and ALONSO (2001), as a simple parameter which could explain the ability of sediments to be blown by wind, considering both textural and compositional characteristics of the samples. It was defined as

$$ASA = 0.62\, M_z - 0.69\sigma_I + 1.35\, Sk_I -, 0.10\, K_G + 3.25\, C - 2.85$$

where mean size (M_z), sorting ($_I$), skewness (Sk_I), and kurtosis (K_G) are expressed in phi (Ø) units while carbonate content (C) has one as 100 %. It was defined considering more than 240 samples from a great diversity of aeolian environments and wind situations.

From table 1 it is possible to see that most of environments have samples with ASA values in the range 0.4 - 0.8, corresponding to areas covered with the appropriate sediments to be blown under relatively intense winds (ALCÁNTARA-CARRIÓ and ALONSO, 2001). Sediments from northern beaches present ASA values of 0.3, indicative of low aeolian sediment availability and, therefore, these sediments can only be blown by very strong winds.

Something different happens with samples from fossil deposits, in which the high values of the ASA parameter are indicative of sediments which could be transported even by weak windy conditions.

Foraminifera

The relative abundance of planktonic *vs* benthic foraminifera perfectly agrees with ALCÁNTARA-CARRIÓ *et al.* (2000), who found that the relative abundance of planktonic foraminifera

Table 3. *Evolution of the active dunes*.

Year	Area covered by mobile dunes (m^2)	Dunes front displacement (m)	Period	Elapsed years	Difference in area covered by mobile dunes (m^2)	Area difference/year (m^2)	Displacement/year (m)
1957	96.405	0	1957-87	30	124.166	4.139	10,.5
1987	220.571	315	1987-96	9	22.539	2.504	11,.3
1996	243.110	417	1996-02	6	9.890	1.648	4,3
2002	253.000	443	1957-02	45	154.819	3.480	9,8

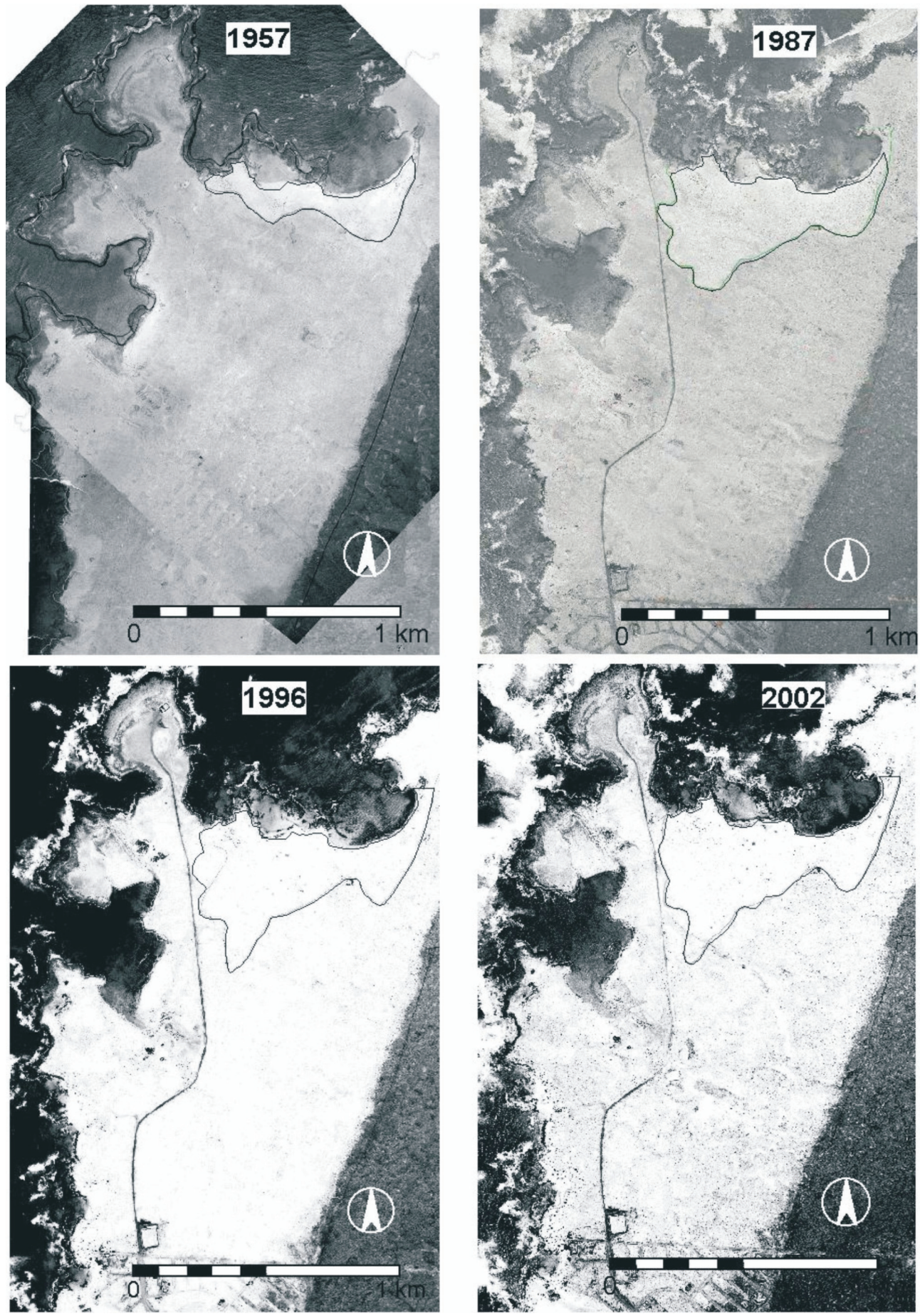

Figure 3. Extension of the active dune field in 1957, 1987, 1996 and 2002, clearly prograding over the semi-stabilized aeolian deposits. Dark area in the lower right corner is a lava flow. Erosive beaches are located just south of the area shown in these photographs.

was much higher in Pleistocene deposits than both in Pliocene and modern aeolian deposits.

On the other hand, USERA *et al*. (2003) have shown the correlation between the different samples referring to their foraminiferal content by means of cluster analysis. These authors have shown that the greater correlation takes place between samples from fossil deposits. Furthermore, they have also got relatively well correlation values between samples from current deposits, both from beaches and aeolian deposits, independently of the place they were taken from. This fact indicates that all these materials are mixed.

There is also a correlation component due to tafonomic factors, since samples with a significant amount of broken shells are clearly correlated, specially when using the Manhattan distance (FELSENSTEIN, 1983).

Evolutive Aspects

Mobile Dunes Evolution

No significant changes have taken place in the beaches nor in the inshore located northward of the study area, which are the source area of sediments that feeds this dune field. Therefore, we can assume that the sedimentary inputs are nowadays similar to those 40 years ago, and the growth rate decrease shown in table 3 can be explained with a height increase of the dunes area.

Beach Evolution

These beaches are nearly reflective, with a relatively high foreshore slope and therefore the effect of tide at the time the photographs were taken can be neglected. Consequently, the shoreline onshore migration of 43 meters reveals an erosive rate of 1.1 m/year.

In this case important changes have happened, since the beaches located leeward of the study area become urbanized in the 70s (see lower part of photographs in figure 3). From previously discussed results, particularly the grain size trend consisting of finer sediments towards the south, the good values of the ASA parameter in all the samples except those at the northern beaches- and the good correlation in the foraminiferal content for samples from beaches and current deposits, allow us to conclude that the sediment inputs to these beaches are mostly due to aeolian sand transport. Therefore, the erosive trend shown at the leeward beaches can only be attributed to the interruption of this transport by the new road courses.

CONCLUSION

The aim of this paper was to analyze a certain area from two different approaches: a sedimentological one considering not only the classical parameters (*e.g.* grain size properties) but also different aspects such as the ability of sediments to be blown or their foraminiferal content, and an evolutive approach which could be possible after correcting and georeferencing series of aerial photographs.

First conclusion is that both approaches are complementary and necessary in order to explain what is happening at a certain study area. In this particular case the erosion shown at the leeward beaches could have not been explained without results from the sedimentological analysis.

Other specific conclusions for this study case can be outlined as follows:

- Grain size characteristics are quite similar for samples from the different current environments, and much finer and better shorted for the ancient dune deposits.
- Carbonate content for all samples is very similar, higher than 90% in any case.
- Values of the ASA parameter denote that samples from northern beaches are not able to be blown, except under strong winds. The rest of samples can be blown under weaker winds.
- There is a quite important amount of foraminifera in the samples, both benthic and planktonic ones. The more abundant ones are *Cibicides refulgens* and *Lobatula lobatula*, present in samples from any kind of environment.
- The area covered by mobile dunes has been growing in the last 45 years due to the input of marine sediments from the northern beaches. This growth is 156.600 m^2, and the dunes front has advanced 440 m in the SSW direction pulled by wind.
- Beaches in the SW coast have suffered an erosion of 43 meters. Since sediment inputs to these beaches are mostly due to aeolian sand transport, this erosion is due to the interruption of this transport by the new road courses.

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