Internal structure of the aeolian sand dunes of El Fangar spit, Ebro Delta (Tarragona, Spain)

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Abstract

This paper presents an analysis of the dune field dynamics of El Fangar Spit in the Ebro Delta (Spain), associating it with the internal structure of dunes carried out with ground-penetrating radar and supported by data from topographic DGPS. These analyses are of great importance to ascertain the state of the internal structure of dunes as an important element in their stability and, therefore in their evolution. The internal structure shows accretion and progradation sequences of dunes over beach deposits, which depend on dune morphology (height, crest orientation) and location, as well as the processes acting on them.

Keywords: Ground penetrating radar, coastal dune, Ebro River Delta.

1. Introduction

Dunes are characteristic elements of sandy beaches in which there is great sediment availability. The dunes have importance from an ecological point of view, creating their own ecosystems, as well as a sediment reservoir available in times of adverse weather (Houston et al., 2001). The dune field constitutes a natural coastal defence, representing the main sand reserve for stormy weather. During winter the dunes are eroded by local storms, carrying sand offshore where it is temporarily stored in submerged sand bars forming the winter profile, thus diminishing the energy of the surge. In summer, the swell transports sand bars onto the shoreline building up the beach and the dunes are reconstituted again (Eisma, 1995; Charlier and de Meyer, 1998). Recognizing the importance of dune performance during storms, coastal engineers have developed a variety of numerical models for cross-shore sediment transport and dune erosion, a review of which is given Judge et al. (2003).

The dunes represent one of the elements that have suffered considerable destruction, mainly due to the massive human occupation of the coast, causing the erosion of many coastal zones (Nordstrom, 2000). At present, because of the concern about the effects of the climate change, and in particular the effect that the increase of sea level can cause in coastal zones, there is a tendency to regenerate dunes in the places where they have disappeared; this being the best mechanism of defence and conservation of beaches (Hesp, 2007; Tsoar and Blumberg, 2007). Therefore, studies of the structure, behaviour and evolution of dunes in different regional geographic settings are necessary.

Characteristics of dune ecosystems are conditioned by sedimentary dynamics and these are mostly determined by wind field and sediment properties. For this reason it is necessary to understand the internal structure of dunes in order to establish an evolutionary model, which will forecast the future of the dune system. It will then be possible to determine the control measures necessary to decrease dune erosion and contribute to the establishment of a sustainable management plan in the Ebro Delta (Sánchez et al., 2004). An understanding of dune history can assist management decisions of coastal dune lands by national and state park organisations, municipalities, and private landowners (Havholm et al., 2004).

Different methodologies have been used to determine aeolian dynamics such as aeolian sediment traps, anemometer towers, Digital Elevation Models from different years or months; but Ground Penetrating Radar offers the possibility to analyse dune evolution over the long term through revealing internal dune structure.

Ground penetrating radar (GPR) is a geophysical technique used to analyse the internal and geometric structures of sedimentary deposits (Bristow et al., 2000, 2005; Guha, 2004; Neal, 2004; Pedersen and Clemmensen, 2005; Costas et al., 2006; Aagaard et al., 2007). The high resistivity of aeolian sands facilitates the penetration of the electromagnetic waves emitted by GPR, favouring observation of the sedimentary structures and the geometry of dunes (Moura et al., 2006).

While the dynamics of El Fangar spit have been widely studied (Maldonado, 1972; Jiménez et al., 1993, 1997; Rodríguez, 1999, 2000; Rodríguez et al., 2003), research has hardly gone into depth with respect to the aeolian mechanisms, although some work has been completed on aeolian transport from theoretical equations (Guillén, 1992, CEDEX, 1996, Serra et al., 1998) that reveals its importance and its role in the processes which control the deltaic evolution.

2. Regional setting

El Fangar spit is located in the north-hemidelta of the Ebro River, in Tarragona on the Mediterranean coast, 170 km from Barcelona (Fig. 1). It is 2-km long sand spit with a maximum width of 1.4 km at its centre, which spreads to the northwest forming a bay. The inner coast of the bay presents a smooth slope easily overrun by seawater during episodic storm surges.

[FIGURE 1]

The formation of the Peninsula of El Fangar is principally due to transport and sedimentation of eroded material from old deltaic lobules, forming bars and beach ridges parallel to the coastline (Maldonado, 1972).The spit evolution shows significant accretion at its end, and it turns towards the continental coast progressively closing the bay (Fig. 2).The environment is micro-tidal, with an spring tidal range of 25 cm. The average offshore significant wave height (Hs) is 0.7 m, and the mean wave period (Tm) is 3.9 s (Jiménez et al., 1997). The eastern wave component, the higher and more energetic waves, are the predominant cause of morphological changes (Jiménez et al., 1993).

El Fangar spit morphology reveals evidence of continuous reshaping. It shows two different tendencies: the middle-south, joined to the deltaic body, exhibiting continued erosion, while the middle-north exhibits considerable accretion (Fig. 2). The evolution of El Fangar spit has been widely studied by Rodríguez (1999, 2000), and the principal conclusions are: (i) the shoreline regressions are produced due to the direct coastal incidence of easterly waves, and their limits are in the middle of the outer coast of El Fangar spit. At this point of null movement, the coastal orientation changes, also changing the evolutionary trend towards the area where the amount of sediment increases, building El Fangar Spit; (ii) the width at the beginning of El Fangar Spit is maintained; (iii) the bar tip has increased by 1280 m from 1957 to 2000, which represents an increase of 31 m/year; (iv) the increase of the area exceeds 180 ha, representing an increase rate of 4.3 ha/year. Taking into account the advance of the bar tip, if the hydrodynamic conditions permit, and considering a linear tendency, it has been estimated that the bay could be closed by approximately 2030.

[FIGURE 2]

The outer coast of the Peninsula of Fangar has a 6km-long dune system which represents the longest and the only active dune system of the Ebro Delta (Serra, 1998; Rodríguez et al., 2003). This provides a perfect nesting place for the bird life which colonizes the dune field in the spring and summer seasons (Rodríguez, 2000; Sánchez et al., 2004). The dune morphology is barchan type. Dune formation in the north hemidelta is related to the orientation of the coast, and to the predominant wind direction of greater intensity and frequency, coming from 315º (Fig. 3). The sand of the dunes extends from accretion areas to the end of the spit. Its exhibits a seasonality, where El Fangar spit is practically flooded by wave storms, seriously affecting the dunes, to be regenerated again by returning to its initial state in calm conditions.

[FIGURE 3]

The aeolian dynamic in the study area are determined by northerly winds. Various works in which the aeolian transport have been calculated from theoretical equations have been carried out (Guillén, 1992; CEDEX, 1996). All of them agree that the predominant direction of the aeolian transport is towards the SE, although the magnitude of the transport varies substantially between authors. Serra et al. (1998) used sediment traps concluding that aeolian transport is assessed at 40 m^3/m/year and in exceptional conditions even more. The average width of current dune field is 250 m; the aeolian transport adds 10 000 m^3/year to the sediment flux of the north hemidelta towards the SE. This value is almost a third of the drift transport towards the NW (Serra et al., 1998).

Considering the shape and average height of the dunes, which have been monitored by topographic surveys since 2005, it is possible to divide the dune field into four different areas (Sánchez et al., 2007) (Fig. 4): Zone 1, is located to the north, just where the bar dynamics change from an erosive to accretion tendency. It has the greatest activity, and has small isolated barchans with an average height of 1 to 2 meters; Zones 2 and 3, in the intermediate area, have lesser activity than zone 1 but the dunes of Zone 2 form barchanoid ridges, reaching of an average height of 2 – 3 meters, and in Zone 3 the shape oscillates between barchanoid and seif dunes increasing in height up to five metres; Zone 4, is similar to Zone 1, but has less aeolian activity where the dune morphology is barchan and the average height is 2.5 meters. Pye and Tsoar (1990) related these morphological changes to an increase in the sediment supply.

[FIGURE 4]

3. Materials and methods

As has been explained previously, the dune field of Fangar is being monitored by topographic surveys with Differential Global Positioning System (DGPS), seven having been completed between 2005 April and September of 2006. DGPS technology allows precision in position and elevation data to less than 10 centimetres. To obtain the topography with DGPS, two receptors are necessary, collecting data simultaneously. One of them remained at a point of known coordinates, and the other was carried in a backpack through the dune field. In this study, a topographic survey was carried out synchronizing with the acquisition GPR data.

To increase the knowledge of dune dynamics at El Fangar, a study of the internal structure has been performed by GPR survey. The method has been extensively used to analyse the internal and geometric structures of coastal dunes (Harari, 1996; Bristow et al., 2000, 2005; Van Dam et al, 2003; Pedersen and Clemmensen, 2005; Costas et al., 2006, Moura et al., 2006). Considering that the Ebro Delta is a protected area, this technique is especially useful due to its non-invasive character, avoiding environmental damage in very sensitive areas (Bristow et al., 2000; Havholm, et al., 2004; Girardi, 2005) in comparison with other techniques that use trenches to study internal structures (Girardi, 2005; Horwitz and Wang, 2005).

The GPR technique is based on the measurements of the subsurface response to high frequency (typically 100-1000 MHz) electromagnetic (EM) waves. A transmitting antenna on the ground surface emits EM waves in distinct pulses into the ground that propagate, reflect and/or diffract at interfaces where the dielectric permittivity of the subsurface changes. EM wave velocity data thus allow conversion of a time record of reflections into an estimated depth.

Reflections of EM waves are usually generated by changes in the electrical properties of sediments, variations in water content, and changes in bulk density at stratigraphic interfaces. Reflections can also be related to changes in EM wave velocity due, for instance, to the occurrence of voids in the ground. The penetration depth and resolution of the reflection data are both functions of wavelength and dielectric constant values, which in turn are mainly controlled by the water content of the materials (Daniels, 1996; Davis and Annan, 1989).

Data from this study were collected with the Subsurface Interface Radar (SIR) 3000 system developed by Geophysical Survey Systems, Inc. (GSSI). GPR measurements were made using a 200 MHz centre frequency shielded antenna in the monostatic mode, which is considered the best compromise between penetration depth and event resolution in sedimentary materials. All the profiles have been collected in a continuous mode with a distance interval between traces of 0.1 m and a total number of 1024 samples per scan. In this continuous acquisition mode, each trace of the radargram is the result of a 64-times stacking in order to improve the signal-to-noise ratio. A survey wheel attachment was used in order to obtain a measurement at exact distance intervals, in this case every 0.1 m. Thus, using the survey wheel we can be confident that the accuracy in the horizontal resolution of the survey is enhanced. Automatic gain control was employed during data acquisition and depending on the dune height, a time window of 50 or 100 ns two way travel time (TWT) was applied. The topography along the profile was obtained by means of a differential GPS and the data were used to correct the topography in the data processing.

Following the scheme proposed by Neal (2004), data processing comprised zero-time corrections, signal-saturation corrections, automatic gain control (AGC), band-pass filtering, static corrections and Kirchoff migration. Although published data for EM wave velocities in sedimentary materials are available, each specific study area displays particular dielectric features due to the inherent heterogeneities of any individual lithology, mostly in sedimentary rocks. For this reason, calibration surveys were necessary to obtain a mean EM velocity value applicable to all profiles so that a representative dielectric constant could be calculated. A calibration survey was carried out over a representative zone of the area, where a metallic bar had been horizontally introduced. Once the velocity data were obtained, a migration process was applied in order to collapse the diffraction hyperbolae and obtain true geometries and depths of the subsurface structures along the profiles. All data were processed, modelled and interpreted using REFLEXW 3.5 software. In all the profiles, the position of the antennae is represented on the horizontal axis, whereas depth is depicted with no scale exaggeration on the vertical.

As a general statement, GPR profiles exhibit a good signal-to-noise ratio over the whole time window. In addition to this, all GPR profiles show a much higher intensity at the central part, corresponding to the coastal dunes, than at the edges, where water-saturated sands are predominant. Moreover, a reflector located at a constant depth of about 0.7 m below the plain can be seen in all the profiles, although under the dune formations it is obscured by other reflectors. From direct field observations made at small trenches, the

0.7 m depth reflector closely matches the location of the water table. Conductive saline groundwater increases attenuation below the water table, as well as introducing interferences in the GPR diagrams, especially if the pores are filled with salt water. This would be the cause of some persistent repetitions of parallel reflectors present in the lower part of the records, in addition to deeper reflections that could be multiples of the air and ground waves at the top of the profile. For these reasons, the profiles have not been interpreted below the water table except where attenuation is low.

During the field survey, 14 GPR profiles with a total length of 1120 m were carried out. The location of the profiles was planned according to the different zones of dune activity. This paper shows only 5 profiles (Fig. 4) chosen from 14 GPR profiles, to explain the internal structure of the dune field at El Fangar Spit.

In addition, to understand the present aeolian dynamics the monthly wind roses from April to September of 2006 (Fig. 5), as well as the wave roses (Fig. 6) and the sea-level variations (Fig. 7) for the same period have been analyzed. All these data have been made available by the Red de Instrumentos Oceanográficos y Meteorológicos (XIOM) of Generalidad de Cataluña. The meteorological station is located in the Port of L´Ampolla about 6 km from the El Fangar dune field. The data are provided for every 10 minutes. Fig. 5 shows monthly wind roses from April to September of 2006, which reflect wind direction changes in the months of summer. The wave roses in Fig. 6 present the hourly significant heights of the waves. The buoy is directional, anchored in the Cabo de Tortosa approximately one km from the El Fangar coast. The tide-gauge data are correlated with the same time period of the meteorological station.

[FIGURE 5]

[FIGURE 6]

[FIGURE 7]

4. Results

4.1 Topographic surveys

From topographic surveys with DGPS, different Digital Elevation Models (DEM) have been obtained, which have been used to estimate field dune movement (Fig. 8). Migration rates were calculated between each survey by superposition of MDT with a Geographic Information System (GIS). The method used can be seen in Sánchez et al. (2007).

[FIGURE 8]

4.2 Ground Penetrating Radar survey

To explain the internal structure of the dunes a profile from the GPR survey in each zone is shown (Fig. 4).

4.2.1 Zone 1

Profile 1 (Fig. 9) was acquired in zone 1, parallel to the prevailing wind direction and parallel to the shoreline, cutting two barchan type dunes lengthwise. In this profile, the reflectors are parallel and sub-horizontal by foreset accretion. At a horizontal distance of between 10 and 20 m, truncations in the radargram sequence can be observed. In the interdune zone (20 – 30 m distance), the reflectors are sub-horizontal, showing vertical accretion. From 38 m there are onlap relations associated with dune migration towards the SE.

[FIGURE 9]

Profile 2 (Fig. 10), is perpendicular to profile 1, perpendicular to the shoreline, and parallel to the dune crest. The reflectors stay sub-horizontal, showing foreshore accretion, but at 28 m and 32 m distance there are convex-up reflectors which maintain onlap relations in the lateral ones, adapting to a morphology of the underlying beach, represented by a continuous reflector. Over this formation dune radar facies are developed showing parallel lamination.

[FIGURE 10]

4.2.2 Zone 2

Profile 3 (Fig. 11) was carried out parallel to the shoreline and predominant wind direction of greater intensity. It is possible to distinguish two radar facies, separated by the water table. The lower is defined by continuous low angle reflectors that correspond to beach facies (Bristow et al., 2000; Bristow and Pucillo, 2006), and overlapping this is another dune facies, showing discontinuous reflectors, dipping in the wind direction at a low angle forming cross-stratification typical of the movements of the migration of the dune. At a horizontal distance of 68 m, it is possible to distinguish a wedge geometry from avalanching due to brink reactivation by the prevailing wind.

[FIGURE 11]

4.2.3 Zone 3

Zone 3 is represented by profile 4 (Fig. 12). The internal structure is similar to the previous one. Below the water table, there are low-angle reflectors and parallel lamination due to foreset accretion. Above the water table, the modification of wind flow around the main dune body is shown by short SE-dipping reflectors forming cross-stratification, which are interpreted as dune progradation (e.g. Pye and Tsoar, 1990; Bristow et al., 2000; Pedersen and Clemmensen, 2005; Bistow and Pucillo, 2006). On the rearslope face, there are sets of trough cross-stratification scour and fill. Also, a wedge geometry at 58 m distance overlaps the previous unit.

[FIGURE 12]

4.2.4 Zone 4

Profile 5 (Fig. 13) in zone 4, was carried out over two small Barchan dunes separated by an interdune depression. In general, all the units are laterally continuous and are characterized by sub-horizontal reflectors. These radar facies are interpreted as foreslope accretion. Onlap reflectors are found at a distance of between 30 to 40 m, and 70 to 80 m. In addition, a small unit of trough cross-stratification from scour and fill is present in the slipface of both dunes. The presence of different partially overlapping units on the dune crest is interpreted as being due to rearslope and active dune migration during periods of increased sand mobility.

[FIGURE 13]

4.3 Wind and Wave Roses

The analysis of wind roses of April to September of 2006 (Fig. 5) shows that the main wind direction has a north component, but emphasizes the change in June when there is a greater wind frequency from E-ENE, with speeds greater than the speed threshold of movement (4 m/s according to Serra et al., 1998). In July and August a wind storms from the SW direction and with speeds greater than 10 m/s are also observed. The wave roses of these months are analyzed (Fig. 6) in the same way, distinguishing two storms from the E, with significant wave heights greater than 1.5 m, which agrees with the surge elevations caused by meteorological tide (Fig. 7), and favouring waves of high energy which affect the field dune.

5. Discussion

According to Sánchez et al. (2007), and considering the migration rates shown in Fig. 8, the dune field of El Fangar spit is highly active, distinguished by different zones defined by dune activity linked to coastal and aeolian processes. The internal structure reveals the dynamic history of dunes. If the DEM obtained from the topographical survey with DGPS in April of 2006 (Sánchez et al., 2007), and those obtained with the GPR data from September of 2006 are compared, it is possible to determine that associated aspects of the existing structures in each profile are derived from events that happened between the dates compared (April to September 2006) using wind and wave roses (Figs. 5, 6). The evolution obtained by means of topographic data shows that zones with low heights have migration rates higher than zones with higher dune height. Then, to explain the internal structure it is necessary to establish a relationship with the dune height, suggesting that low height (zones 1 and 4) involves significant migratory activity, while a height increase (zones 2 and 3) leads to a decrease in dune migration, showing a more developed internal structure.

Profiles 1 and 2 are located to the north, just where the bar dynamics change from erosive to accretionary tendency. It has the greatest dune activity since they are directly facing north winds. In relation to profile 1 it is possible to point out that the first 14 meters are developed on top of that which, in the DEM of April of 2006, was occupied by sand flats (Fig. 14). This can explain the different relations associated with wind reactivation and the advance of dune towards the SE that are observed in zone 1 (Fig.8). During months of May, July and August of 2006 episodes of southerly wind of great intensity took place (Fig. 5), affecting the dune morphologies and changing the direction of the crests (Fig. 15). These changes are registered in the internal structure of the dunes in form of truncations like those observed between the 10 and 20 m distance in profile 1.

[FIGURE 14]

[FIGURE 15]

Given the low height of the dune in zone 1, it is possible to distinguish in the base of the radargram of profile 2 (Fig. 9) different shapes that can be explained as positive relief of the beach ridges (Neal and Roberts, 2000) forming El Fangar Spit, which are covered by dunes.

In comparison with zone 1, the height and complexity of the dunes increases in zone 2 and zone 3, which contain dunes of greater size, implying a decrease in dune migration (Sánchez et al., 2007). The radar facies of both zones show structures in line with the previous findings, presenting radar facies which are more continuous laterally, with low angle foresets associated with dune accretion, following a normal sequence with a low grade of mobility, and being more developed. The cross-stratification in the radar facies of dune is interpreted as dune progradation showing different phases of dune reactivation (e.g. Pye and Tsoar, 1990; Bristow et al., 2000; Pedersen and Clemmensen, 2005; Bistow and Pucillo, 2006). Beside this, wedge geometry overlaps the previous unit with trough cross-stratification from scour and fill. This could correspond to the resulting deposit from a small avalanche of the windward face of the dune due to reworking by the prevailing wind (Bristow et al., 2000).

Zone 4 is located to the south of the dune field, and it exhibits smaller dunes than the others. This is because the wind and the sediment, coming from the north, previously feed the dune bodies of zones 1, 2 and 3. In this way, a lesser amount of sand arrives to form the dunes of this zone. The radar facies on GPR profiles across the dune in zone 4 contain trough cross-stratification cut and fill, and roll-over structures; all of them associated with active dunes, with reworking by winds. The shoreline trend is different in the four areas, the erosion rate of the coastline diminishing from the south towards the north (Jiménez et al., 1997; Rodríguez et al., 2003). This is also reflected in the coastal orientation, so that the northern formation receives more oblique waves coming from the east, zone 4 being the nearest to the coastline and more affected by waves (Fig. 16).

As a result the dune formation located to the south of the dune field presents greater problems because of the effect of the waves, being clearly reflected in their internal structure where it is possible to distinguish truncations due to erosion by wave storms events (Fig.12) (Bristow and Pucillo, 2006; Costas et al., 2006; Moura et al., 2006).

[FIGURE 16]

6. Conclusion

The internal structure of dunes can be explained by the dune activity and aeolian and wave dynamics. Zone 1 shows small and low dunes, but high aeolian activity because they are the first to face effective winds from the NW. The internal structure of these dunes shows intense migratory activity in response to wind direction, towards the SE. In addition, a bar from accretion of sand that forms El Fangar Spit has been observed at the base of the dune.

The intermediate area of the dune field, showing less activity than the zone 1, exhibits two zones (zones 2 and 3) in line with the dune type. In both cases, the dunes are higher than in other zones, and have a low migration rate. An important foreshore accretion is observed in the GPR profiles, as well as superficial activity marked by cross-stratification, due to wind action.

Zone 4, located to the south of the dune field, presents very small dunes. Due to its position in relation to coastal orientation, they are influenced by northerly winds and they are also affected by easterly waves of greater energy. These are the cause of significant erosion of coastline in this zone. This activity is reflected in the dune internal structure, showing different truncations by storm waves.

From the GPR data analysis it is possible to confirm that the morphology and the geometry of the dune bodies adapt themselves to meteorological conditions. This allows us to make an extensive study of dune activity and to obtain models of coastal dune development, in order to advise on the most effective mechanisms for the management and maintenance of the dune fields.

The structure of dunes is the result of the processes that occur in the zone during a short period of time. Having DEMs of dunes from previous surveys, as well as data of wind and waves of months previous to the acquisition of radargrams, facilitate interpretation of the internal structure in relation to recent dynamics. In zones such as the Fangar Spit, where during the months of April to August there is no access in order to allow the nesting of birds, the GPR technique turns out to be helpful in understanding the significance of dynamic processes during this period when it is not possible to study dune topography directly.

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Figure captions

Figure 1. Location of the study area in the Iberian Peninsula.

Figure 2. Coastline variation in 40 years. Different values of erosion and accretion are shown, according to Rodríguez, et al. (2003).

Figure 3. Wind rose of the delta of the Ebro, 1992-2007. Hourly data coming from the Fangar weather station belonging to the Red de Instrumentos Oceanográficos y Meteorológicos managed by Generalidad de Cataluña.

Figure 4. Position of profiles and dune field division (Sánchez et al., 2007).

Figure 5. Wind roses from April to September 2006. Data acquired every 10 minutes coming from L'Ampolla weather station belonging to the Red de Instrumentos Oceanográficos y Meteorológicos of Generalidad de Cataluña.

Figure 6. Wave roses from April 2006 to September 2006. Data acquired every hour coming from Cap Tortosa directional buoy belonging to the Red de Instrumentos Oceanográficos y Meteorológicos of Generalidad de Cataluña.

Figure 7. Sea-level variation from April to September 2006. Data acquired every 10 minutes coming from L'Ampolla tidal gauge belonging to the Red de Instrumentos Oceanográficos y Meteorológicos of Generalidad de Cataluña.

Figure 8. Migration rates from September 2005 to September 2006, obtained by DEM comparison (Sánchez et al., 2007).

Figure 9. Profile 1, parallel to wind direction. In this profile it is possible to distinguish reflectors (A) parallel and sub-horizontal by foreset accretion; truncate reflectors (B) associated with storm events, and in onlap relations due to dune migration towards the SE.

Figure 10. Profile 2, perpendicular to profile 1. This profile presents parallel lamination (A) adapting to underlying shapes which are interpreted as beach ridges (B) that form El Fangar Spit.

Figure 11. Profile 3, parallel to wind direction. It is possible to distinguish the beach facies (A) defined by continuous low angle reflectors, and dune facies (B) forming cross-stratification dipping in the wind direction. The rearslope face presents an activation wedge (C) due to an increase in the activity of the wind.

Figure 12. Profile 4, parallel to wind direction. This profile present parallel lamination (A) by foreset accretion, where the dune facies are developed (B) with cross stratification parallel to the wind direction. Sets of trough cross-stratification (C) are present in the rearslope face, and a wedge geometry (D) caused by at deposit from a small avalanche.

Figure 13. Profile 5, parallel to wind direction. Shows two dunes separated by an interdune depression (A) with parallel lamination. It is possible to distinguish

truncations (B) associated with dune overwashing, and overlapping units (C) in the rearslope face associated with dune migration.

Figure 14. Location of Profiles 1 and 2 in April 2006.

Figure 15. Barchan dunes with three brinks oriented in three different directions.

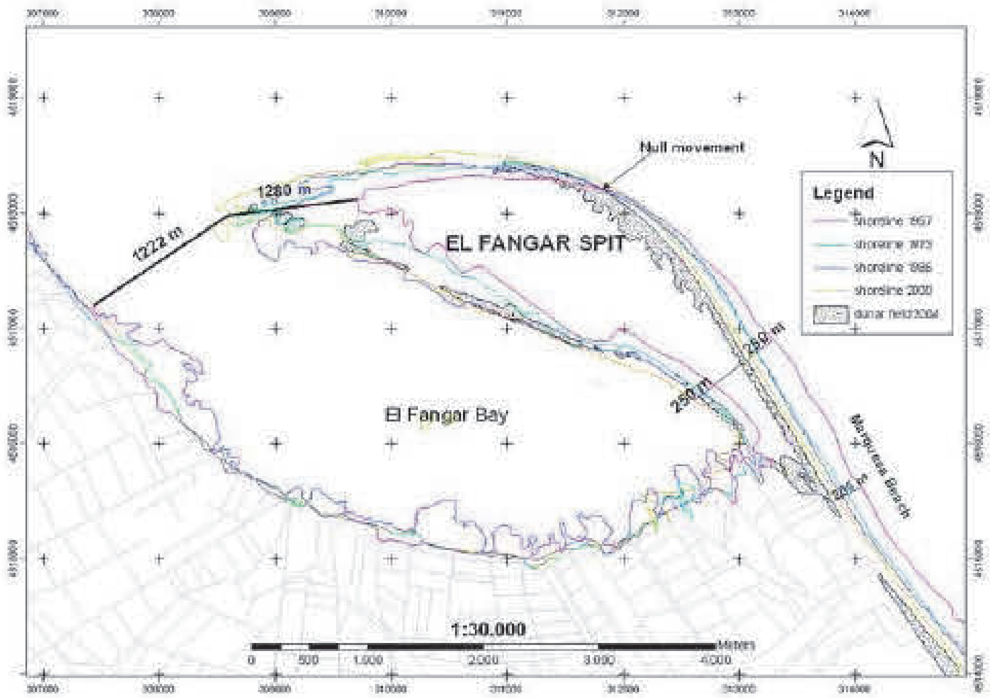
Figure 16. Inundation of the dune field during periods of storm.

Figure 1

Barcelona
Tarragona
N
Study Area
Deltebre
Amposta
EBRO DELTA
Sant Carles de la Ràpita
Mediterranean Sea

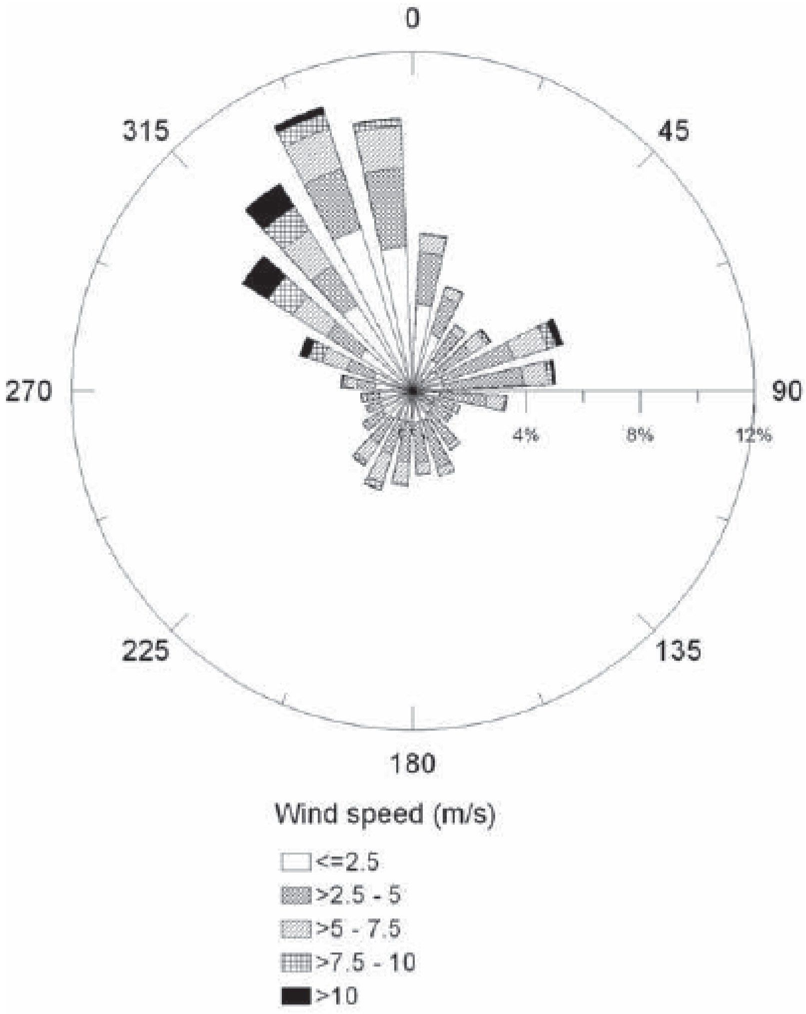
634

Figure 2



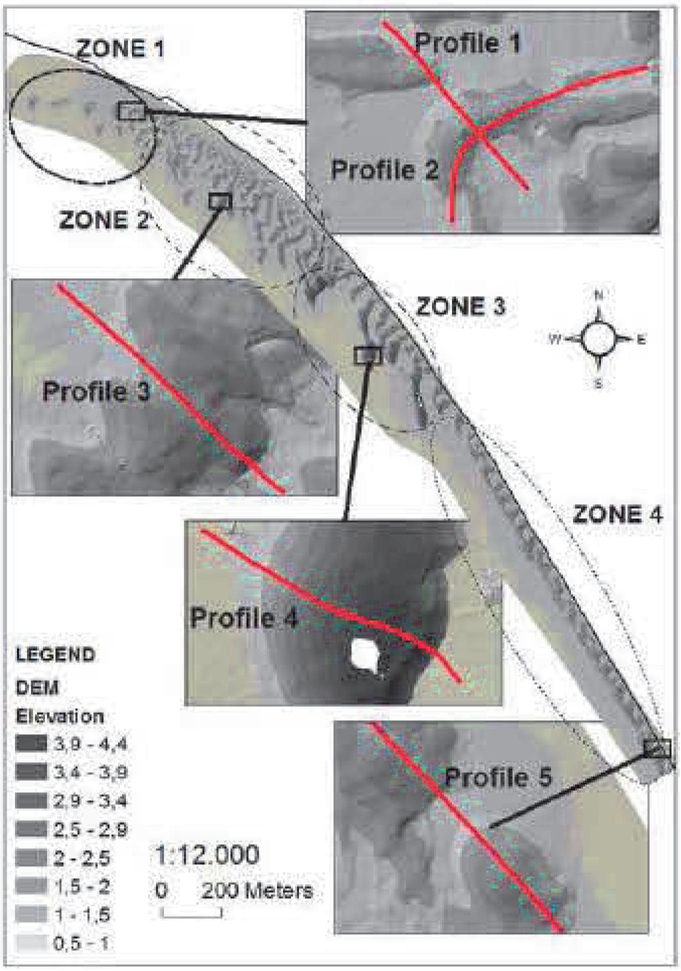
Null movement
Legend
1280 m
1222 m
EL FANGAR SPIT
El Fangar Bay
250 m
1:30.000
0
500
1.000
2.000
3.000
4.000
Meters

Figure 3



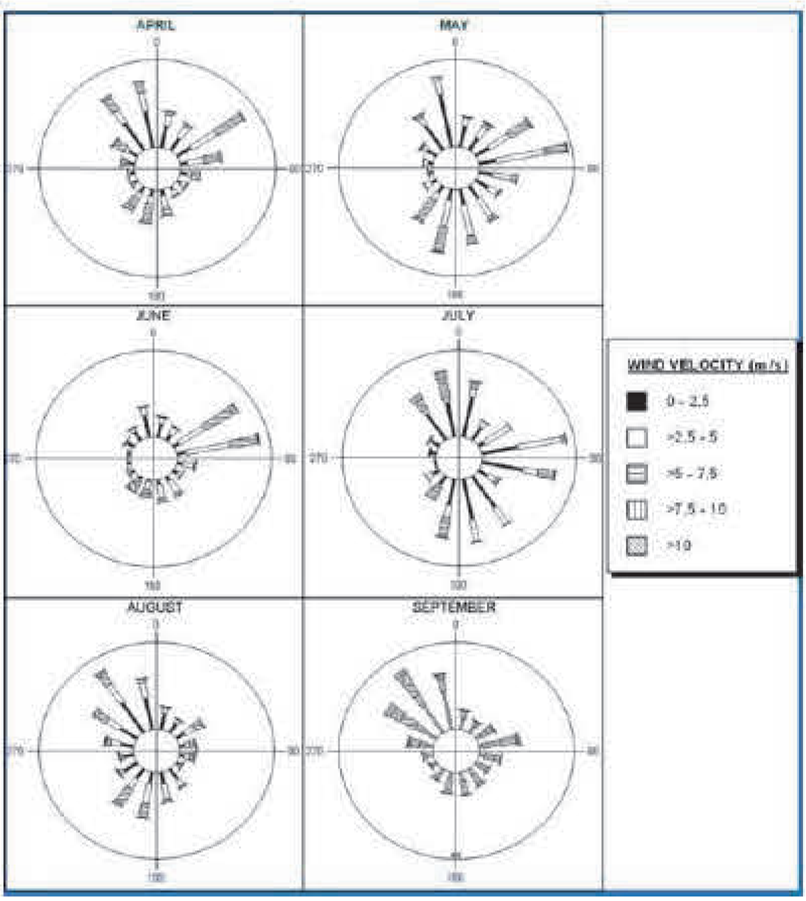
636

Figure 4


ZONE 1
Profile 1
Profile 2
ZONE 2
ZONE 3
N
W
E
S
Profile 3
ZONE 4
Profile 4
LEGEND
DEM
Elevation
3,9 - 4,4
3,4 - 3,9
2,9 - 3,4
2,5 - 2,9
2 - 2,5
1,5 - 2
1 - 1,5
0,5 - 1
1:12.000
0 200 Meters
Profile 5

637

Figure 6


APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
WIND VELOCITY (m/s)
0 - 2.5
>2.5 - 5
>5 - 7.5
>7.5 - 10
>10

638

Figure 6

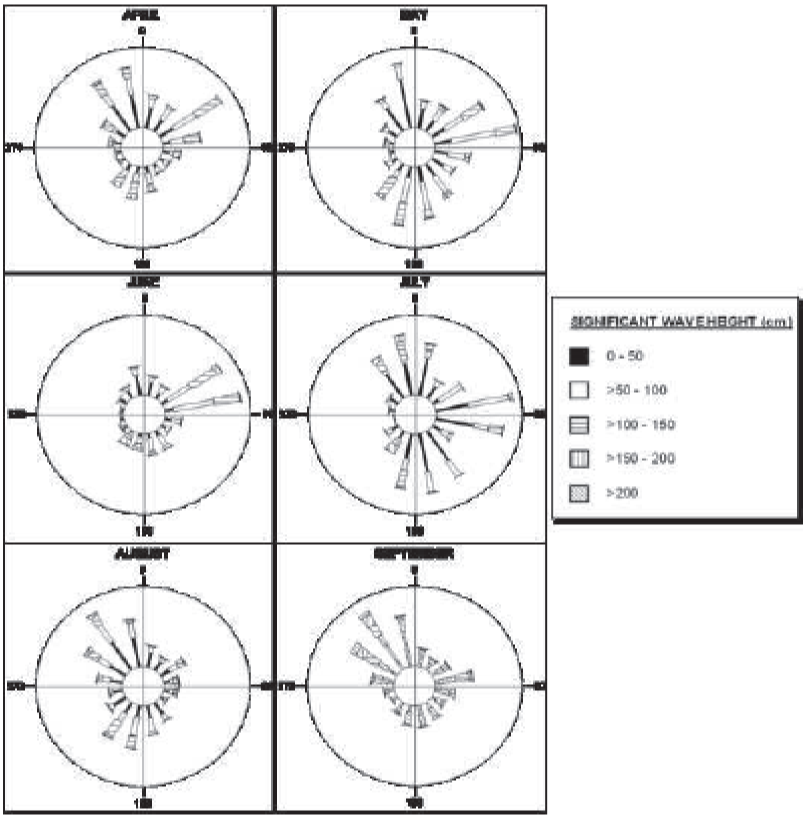


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Figure 7

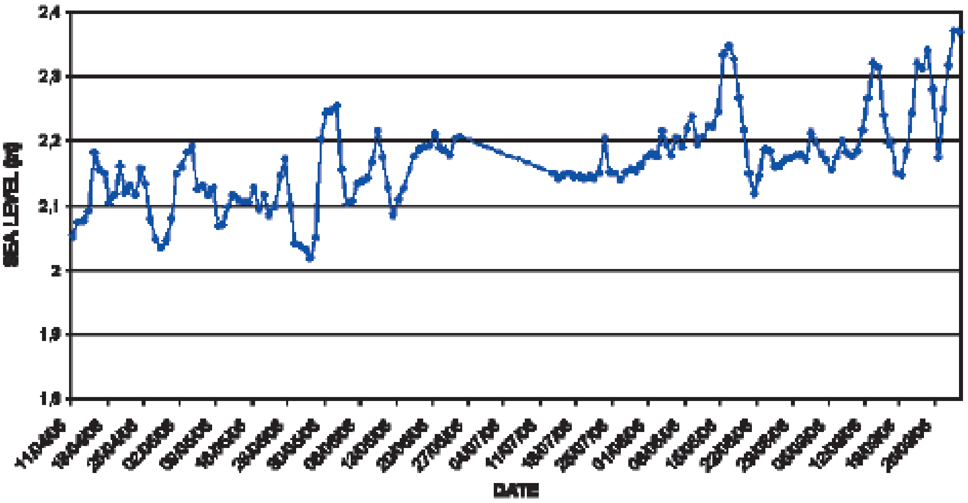
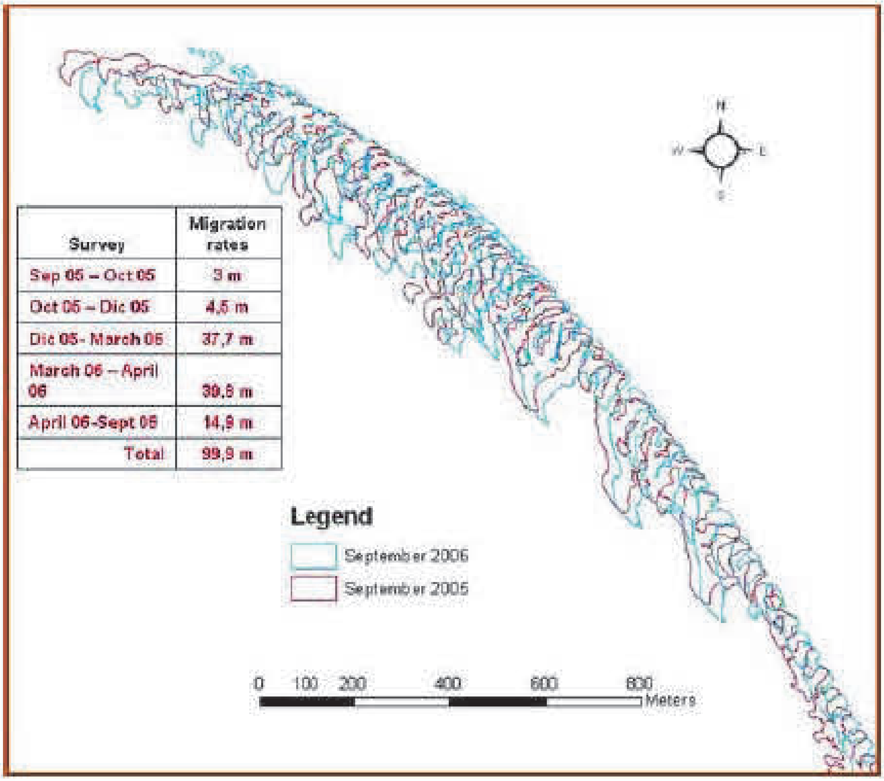
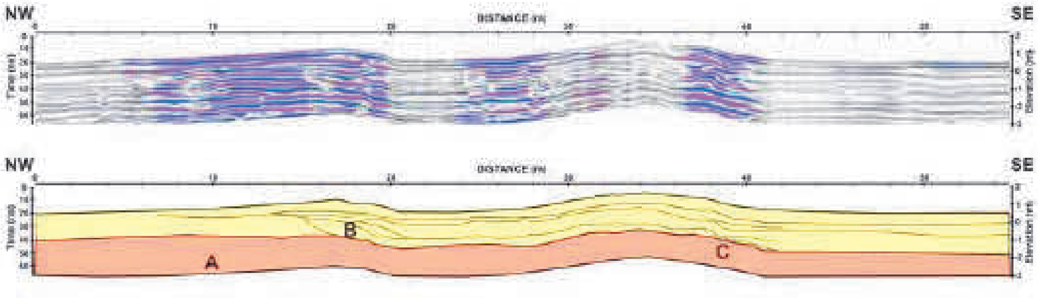


Figure 8



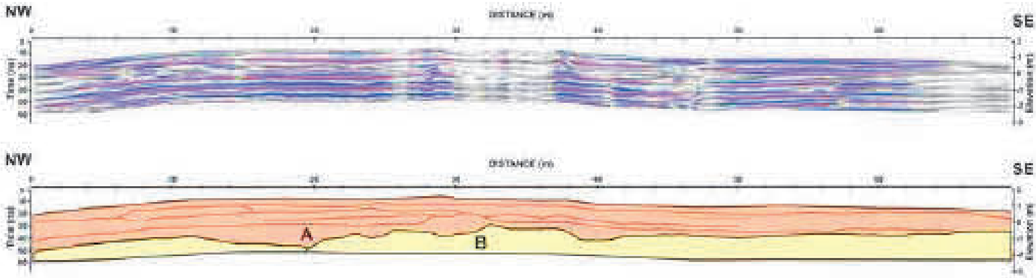
Survey	Migration rates
Sep 05 – Oct 05	3 m
Oct 05 – Dic 05	4,5 m
Dic 05- March 06	37,7 m
March 06 – April 06	39,8 m
April 06-Sept 06	14,9 m
Total	99,9 m

Figure 9



642

Figure 10



643

Figure 11

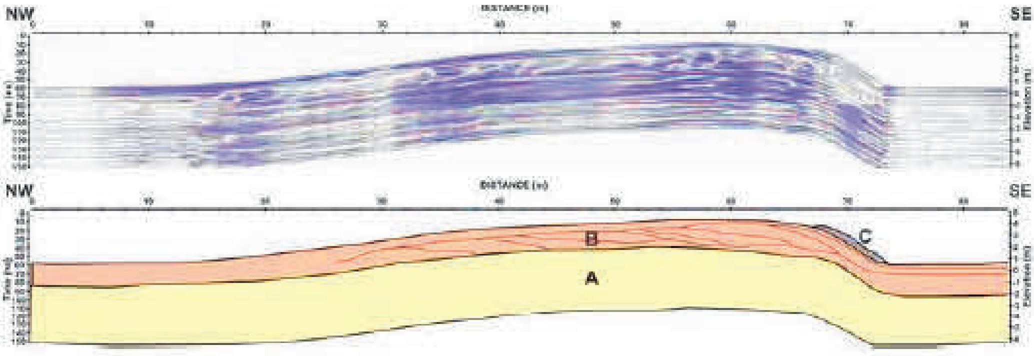


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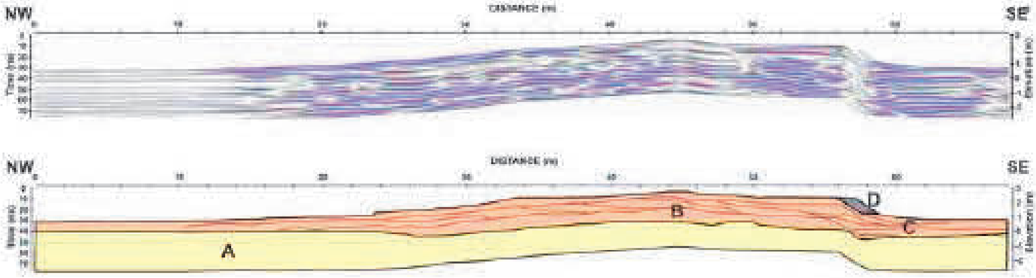
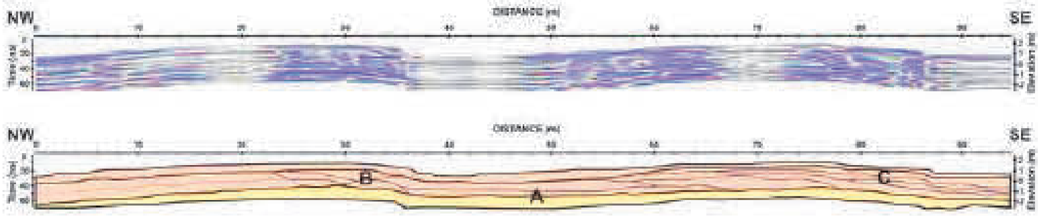
Figure 12



645

Figure 13



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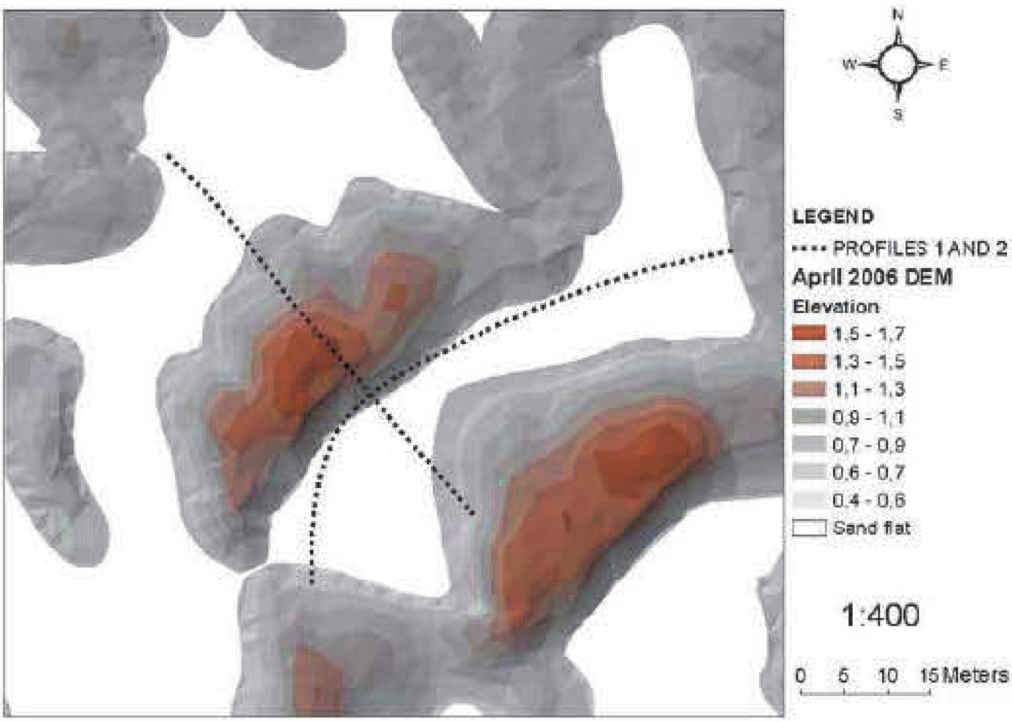

647

Figure 15

648

Figure 16

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