Chapter 3

STUDY AREA

3.1. LOCATION OF THE STUDY AREA

The study area is the Ria Formosa barrier island system located in the Algarve, southern Portugal (Figure 3.1). The present configuration of the system consists of two peninsulas and five islands that extend over 55 km. The backbarrier area consists mainly of salt marsh and small sandy islands covering 8.4×10^7 m^2 (Andrade, 1990). Connection between the ocean and the backbarrier area is made through six tidal inlets. The barrier island system has a cuspate shape, with two flanks separated by Cape Santa Maria: western flank (shoreline orientation NW-SE), and eastern flank (orientation NE-SW; Figure 3.1). The western flank includes Ancão Peninsula and part of Barreta Island; and the eastern flank consists of the rest of Barreta Island together with Culatra, Armona, Tavira, and Cabanas islands, and Cacela Peninsula.

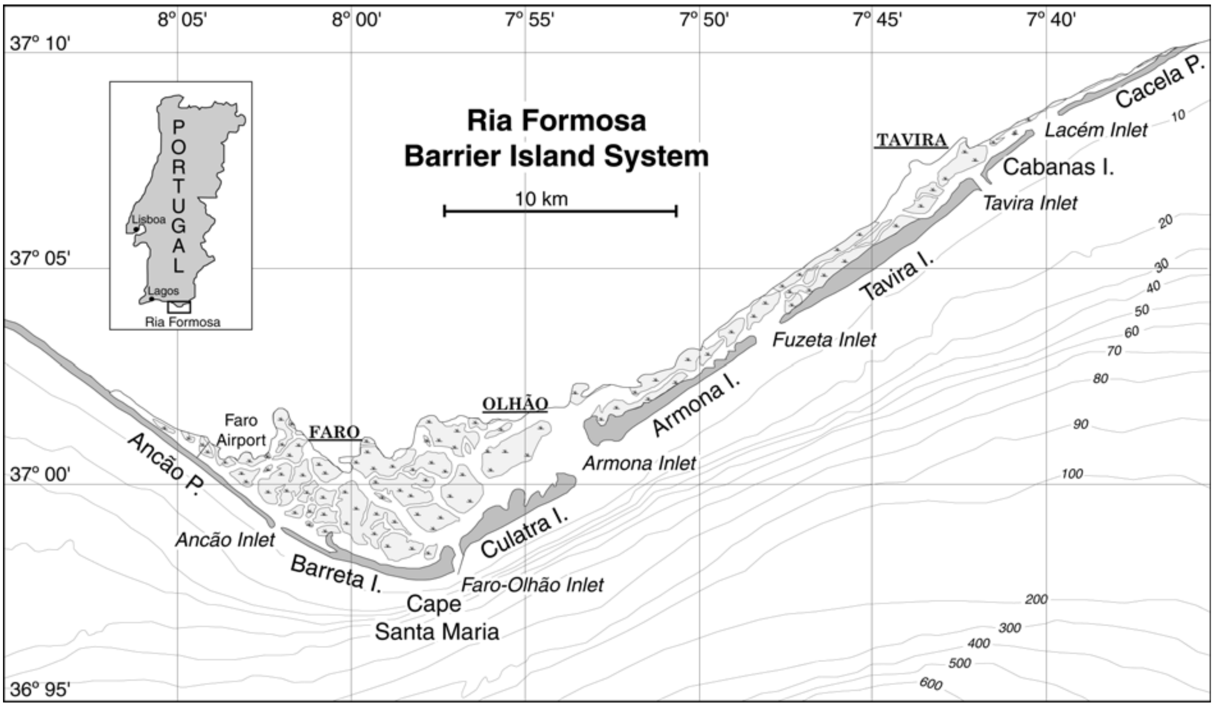

Figure 3.1. Location of the Ria Formosa barrier islands and tidal inlets (names in italic), mainland cities (underlined) and bathymetry of the adjacent continental shelf (in meters). P.=Peninsula; I.=Island.

3.2. FORCING MECHANISMS

3.2.1. CLIMATIC SETTING

Data collected by two meteorological stations located in the study area (Faro-Airport and Tavira, Figure 3.1) were compiled by INMG (1991). These data included wind, air temperature and rainfall from 1970-1980 for Faro-Airport and from 1951-1980 for Tavira.

Dominant winds are from the westerly quadrant (including SW, W and NW) both for Faro (51% of the time) and Tavira (38% of the time). During autumn and winter the dominant winds are from the northerly quadrant (including NW, N, NE) for Faro (43% for autumn and winter) and Tavira (40% for autumn and 43% for winter). During spring westerly quadrant winds are dominant (Faro: 62% and Tavira: 44%), while during summer the westerly winds are dominant for Faro (61%) and the southerly winds are dominant for Tavira (49%). The percentage of “Levante” events (E-SE winds) varies between 9% (Tavira winter) and 25% (Faro autumn).

Annual average wind speed is higher in Faro than in Tavira, the opposite occurs with the frequency of calms (Table 3.1). There are no significant differences in the average wind speeds for Faro or Tavira between the autumn-winter (12.7-13.8 km/h for Faro and 8.7-9.8 km/h for Tavira) and the spring-summer (14.1-12.6 km/h for Faro and 10.1-9.4 km/h for Tavira). Strong winds occur more frequently in Faro (67% of the time from W-SW) than in Tavira, and very strong winds only occur in Faro (Table 3.1).

The average annual value of the air temperature is 17^{o}C both for Faro and Tavira (INMG, 1991). The values of the average monthly temperature vary regularly over the year, with a maximum in August (23.2^{o}C for Faro and 23.6^{o}C for Tavira) and a minimum in January (12.0^{o}C for Faro and 11.3^{o}C for Tavira). The minimum air temperature was attained in Tavira, and the maximum was attained in Faro (Table 3.1).

In terms of rainfall, the Ria Formosa can be considered as a semi-arid area (Faria *et al.*, 1981). According to Cunha (1985), there is an increase in rainfall from the west to the eastern areas of the Ria Formosa, with an annual range between 450 mm and 590 mm. The maximum number of consecutive days without rain was higher in Faro. The maximum number of consecutive days with rainfall and the maximum daily rainfall were higher in Tavira (Table 3.1).

Table 3.1. Climatic data for Faro-Airport and Tavira meteorological stations.

	Faro	Tavira	Source
Average annual wind speed (km/h)	13.2	9.7	INMG, 1991
Frequency of calms	2.4	11.9	INMG, 1991
# days with strong wind/year*	34.7	2.2	Cunha, 1957
# days with very strong winds/year**	4.6	0.0	Cunha, 1957
Average air temperature (^{o} C)	17.0	16.9	INMG, 1991
Maximum air temperature (^{o} C)	44.3†	41.2‡	† IM, 2004 ‡ INMG, 1991
Minimum air temperature (^{o} C)	-1.4	-2.1	INMG, 1991
Total annual average rainfall (mm)	513.6	586.6	INMG, 1991
Maximum daily rainfall (mm)	118.5	132.8	INMG, 1991
Maximum number of consecutive days with no rainfall	188	160	Machado, 1980
Maximum number of consecutive days with rainfall	14	23	Machado, 1980

* strong wind (wind > 36km/h); ** very strong wind (wind > 55km/h).

3.2.2. OCEANOGRAPHIC SETTING

The study area is mesotidal, with a mean tidal range of about 2 m that can reach up to 3.4 m during spring tides. An analysis of two years of records from a tidal gauge on the Algarve Coast (Lagos, Figure 3.1) showed a maximum observed storm surge level of +0.75 m (Gama *et al.*, 1994). The return period of a sea level 2.23 m above MSL is 10 years (Gama, 1996).

Offshore wave climate is dominated by west-southwest waves (71% of occurrences; Costa *et al.*, 2001). SE waves (locally called “Levante”) that consist of short period waves generated by regional winds are also frequent (about 23%, Costa *et al.*, 2001). Wave energy is moderate with an average annual significant offshore wave height of 1.0 m and average peak period of 8.2 s (Costa *et al.*, 2001). Storm events are defined as events with significant offshore wave height greater than 3 m (e.g., Pessanha and Pires, 1981; Melo, 1989; Costa, 1994). Between 1986 and 1993, storm conditions corresponded to 1% of the offshore wave climate (Costa, 1994). SW storm waves have an average significant wave height higher than Levante storms (Costa, 1994). A 5.0 m SE storm has an estimated return period of 50 years, while a 5.7 m SW storm is expected every 5 years (Pires, 1998).

The cuspate shape of the Ria Formosa system produces two areas with different exposure to wave action. The western flank of the Ria Formosa is directly exposed to the W-SW dominant and more energetic waves but is protected from Levante waves. On the contrary, the eastern flank is exposed to Levante waves but sheltered from the W-SW dominant waves that arrive very refracted.

Net littoral drift and longshore currents in this area are typically from west to east. Several authors have presented estimations of net littoral drift for the western and eastern flanks. For the western flank, the estimates range from 6,000 m^3/year (Andrade, 1990) to

300,000 m^3/year (Consulmar, 1989 *in* Bettencourt, 1994). The differences in estimations are due to different data sources and methods used. Vila-Concejo *et al.* (2003) calculated the gross longshore transport at Ancão Inlet using the accumulation rates during the first year of the relocated inlet evolution (1997/98) and obtained 380,000 m^3. Studies made with tracers indicate the same range of values (950 m^3/tide, during calm-moderate winter SW conditions, Vila-Concejo *et al.*, 2004). This seems to be indicative that the order of magnitude of the values obtained by Consulmar (1989 *in* Bettencourt, 1994) is more appropriate. For the eastern flank, the estimated net littoral drift ranges from 30,000-80,000 m^3/year (Bettencourt, 1994) to 250,000 m^3/year (Granja *et al.*, 1984).

3.3. GEOLOGY AND GEOMORPHOLOGY

The general characteristics of the geology and geomorphology of the Ria Formosa barrier islands and tidal inlets are described in the next section. The Barreta Island was the study area for *in-situ* overwash sediment transport measurements (Chapter 4), washover plain evolution monitoring (Chapter 5) and washover sediments textural analysis (Chapter 6); therefore the characteristics of this barrier will be detailed in a separate section.

3.3.1. RIA FORMOSA GENERAL CHARACTERISTICS

The Ria Formosa barrier island system (Figure 3.1) is extremely dynamic (Dias, 1988). Inlet processes are of great importance in the system dynamics inducing historic dramatic changes in the number and morphology of the barrier islands. The Ria Formosa tidal inlets have been studied by several authors, e.g. Weinholtz, 1964; Esaguy, 1984, 1985, 1987; Andrade, 1990; Salles, 2001; Vila-Concejo, 2003. Other major processes affecting recent island evolution have also been studied: shoreline retreat (e.g. Ferreira *et al., in press*), longshore drift (e.g. Ciavola *et al.*, 1997), overwash processes (e.g. Andrade *et al.*, 1998), dune formation (e.g. Gomes *et al.*, 1994), and backbarrier processes (e.g. Pilkey *et al.*, 1989).

3.3.1.1. Tidal Inlets

The western flank typically has only one tidal inlet, *Ancão Inlet* (Figure 3.1), which is a small migrating inlet. The eastern flank presently has five inlets (Figure 3.1) although the number of inlets has varied over time. Two of the inlets were artificially opened and stabilised with jetties, *Faro-Olhão Inlet* in 1929-1955 (Esaguy, 1986a) and *Tavira Inlet* in 1927-1985 (Esaguy, 1987). *Armona Inlet* is considered to be the only naturally stable inlet of the system (Weinholtz, 1964; Pilkey *et al.*, 1989) that has been getting narrower since at least 1873

(Esaguy, 1984). *Fuzeta Inlet* shows a clear pattern of cyclic easterly migration (Weinholtz, 1967; Esaguy, 1985; Dias, 1988; Pilkey *et al.*, 1989; Andrade, 1990; Salles, 2001; Vila-Concejo *et al.*, 2002). *Lacém Inlet* typically opens over a wide area during storms, and subsequently narrows and migrates eastwards (Dias, 1988; Pilkey *et al.*, 1989; Andrade, 1990, Vila-Concejo *et al.*, 2002).

Vila-Concejo *et al.* (2002) distinguished two typical migration patterns within the Ria Formosa system, the high-energy migration pattern (HEMP, represented by Ancão Inlet) and the low-energy migration pattern (LEMP, best represented by Lacém Inlet). According to Vila-Concejo *et al.* (2002), the typical HEMP is characterised by an initial stage of readjustment, with low migration rates, followed by a stage of high eastwards migration rates, until a limiting position is reached where inlet infilling occurs. A new migrating cycle starts with the opening of a new inlet in a position close to the initial one and the subsequent closure of the inlet that migrated to the limiting position. During the migration the updrift margin, the inlet is built at approximately the same rate as the downdrift margin is eroded; therefore, inlet width remains reasonably constant during the entire migration cycle. Inlets with LEMP are typically formed by barrier breaching during major storms which produces very wide inlets. The typical LEMP implies that the eastward migration is accompanied by strong constructional processes on the updrift barrier leading to inlet width reduction (Vila-Concejo *et al.*, 2002).

3.3.1.2. Barrier islands

The western end of *Ancão Peninsula* is particularly stable and it constitutes the attachment of the barrier islands to the mainland coast. The length of Ancão Peninsula is highly variable (from 8,500 m to 12,800 m, between 1947 and 2001) because its eastern end depends on Ancão Inlet position. The barrier is narrow (between 50 m and 200 m) and the dunes are generally single crested and high (5.5 m MSL; Andrade, 1990). The western part is characterised by stable foredune with blowouts (Dias, 1988) and dune bluffs, but at the eastern part is more dynamic with lower incipient foredunes. The central sector is urbanised (locally called Praia de Faro) and therefore sediment dynamics are conditioned by human actions.

The length of *Barreta Island* varied between 5,000 m and 9,200 m (between 1947 and 2001) in relation to the position of the Ancão Inlet. The western part of the barrier is dominated by inlet processes and therefore is narrow, low in elevation, mostly unvegetated and frequently overwashed (Pilkey *et al.*, 1989). The eastern end of the barrier is stabilised by the Faro-Olhão western jetty that has induced an intense coastline advance (about 220 m in the 12 years after its construction, Bettencourt, 1985).

Culatra Island grew from less than 3,000 m in 1947 to about 6,300 m in 2001. The western part of the island was greatly affected by the updrift construction of Faro-Olhão Inlet jetties that promoted severe sediment starvation and shoreline retreat (up to 5.8 m/year between 1958 and 1976, Garcia *et al.*, 2002). The eastern part is dominated by the accretion of recurved spits (Dias, 1988) encompassing Armona Inlet width reduction. Dune formation in this part of the island started as scattered incipient foredunes were overwashes were recurrent, that ultimately evolved to established foredunes cut by heads of tidal channels or embayments (Pilkey *et al.*, 1989).

Armona Island length varied between 6,200 m and 8,800 m, depending on the position of Fuzeta Inlet. The western part of Armona Island, downdrift of Armona Inlet, has a high continuous foredune (average 4.5 m MSL, Andrade, 1990) and broad backbarrier areas. The eastern part of the barrier developed as Fuzeta Inlet rapidly migrated eastwards, which resulted in a narrow and low-lying barrier, where washovers and embryonic dunes alternate.

Tavira Island length varied between 11,100 m and 13,700 m (between 1947 and 2001), depending on the position of Fuzeta Inlet. The island has a single continuous foredune (average 4 m MSL, Andrade, 1990), backed by an extensive backbarrier area where dunes, marshes and tidal channels form a complex three-dimensional pattern. The western end of Tavira Island is undergoing shoreline retreat due to the sediment starvation induced by the updrift Fuzeta Inlet, while the eastern end is accreting due to the construction of Tavira Inlet jetties.

Cabanas Island was entirely eroded by a major storm in 1961 and has been reconstructed since then (Weinholtz, 1964; Esaguy, 1986b) until reaching a length of 5,100 m, in 2001. The island extraordinary growth was closely related to Lacém Inlet migration pattern (LEMP) that promotes eastward migration (average rates of 97m/year, Vila-Concejo *et al.*, 2002) accompanied by inlet narrowing (from 2,800 m in 1962, Esaguy, 1986b to 200 m in 1996, Matias, 2000). The foredune is low (2.5 m MSL, Andrade, 1990) and formed by pioneer plant communities developing over washovers bare sand. The backbarrier is also low; consequently lagoon intrusion is greater than on other barriers and washouts occurs occasionally.

The eastern end of *Cacela Peninsula* is the barrier system attachment to the mainland coast. The peninsula length has varied between 7,400 m to 2,900 m (in the period 1947-2001), depending on the width and position of Lacém Inlet. The western part of the barrier had a single crested stable foredune with an average elevation of 3.4 m MSL, that was completely eroded by Lacém Inlet migration and barrier breaching (Matias, 2000). The eastern barrier dunes developed mostly after the closure of an inlet in the 1930’s (Weinholtz, 1964). The former inlet morphologies evolved to a low-elevation denuded sandy surface, where extensive overwashes were frequent; the overwashes were later confined to the depressions between recurved foredune ridges.

3.3.2. BARRETA ISLAND

Barreta Island is part of both the western and eastern flanks of the Ria Formosa barrier island system (Figure 3.1), including the southernmost point of the Ria Formosa (Cape Santa Maria). The western part, starting at Ancão Inlet has a reflective beach face and a narrow or inexistent dune ridge. The part to the east of Cape Santa Maria is a wide prograding dune field with several densely vegetated ridges. The progradation is related to downdrift Faro-Olhão inlet jetties.

The western part of Barreta Island is on the downdrift margin of Ancão Inlet (Figure 3.2). This inlet undergoes eastwards migration cycles, and the study area is located inside the inlet migration path. Between 1947 and 1996 Ancão Inlet underwent two eastward migration cycles, at average migration rates close to 40 m/year for the first migration cycle and 100 m/year for the second migration cycle (Vila-Concejo *et al.*, 2002). In June 1997 the Ancão Inlet was artificially opened, and since then the inlet has been migrating towards the study area (for detailed location of the study area see sections 4.2.1, 5.2.2, and 6.2.1). The inlet had reached its dynamic equilibrium as a “mature migrating inlet” in May-July 1999 (Vila-Concejo *et al.*, 2003).

While Ancão Inlet was evolving towards dynamic equilibrium, it was acting as a sediment trap, therefore Barreta Island was undergoing sediment starvation that caused dune erosion and shoreline retreat. The evolution of Ancão Inlet and Barreta Island was strongly related, with island low-volume states associated with sediment starvation due to the updrift trap effect of the inlet; high-volume states at Barreta Island were related to the arrival of swash bars from the inlet ebb-delta (Vila-Concejo *et al., in press a*). Due to the erosion of the dunes of Barreta Island, overwash processes occurred frequently (for example Figure 3.3) forming washover lobes on the western part of Barreta Island. The washover plain of the study area (Figure 3.2) was initially formed by overwash of the low-lying barrier. Continuous overwash led to the coalescence of the washover lobes with the washover plain to the east.

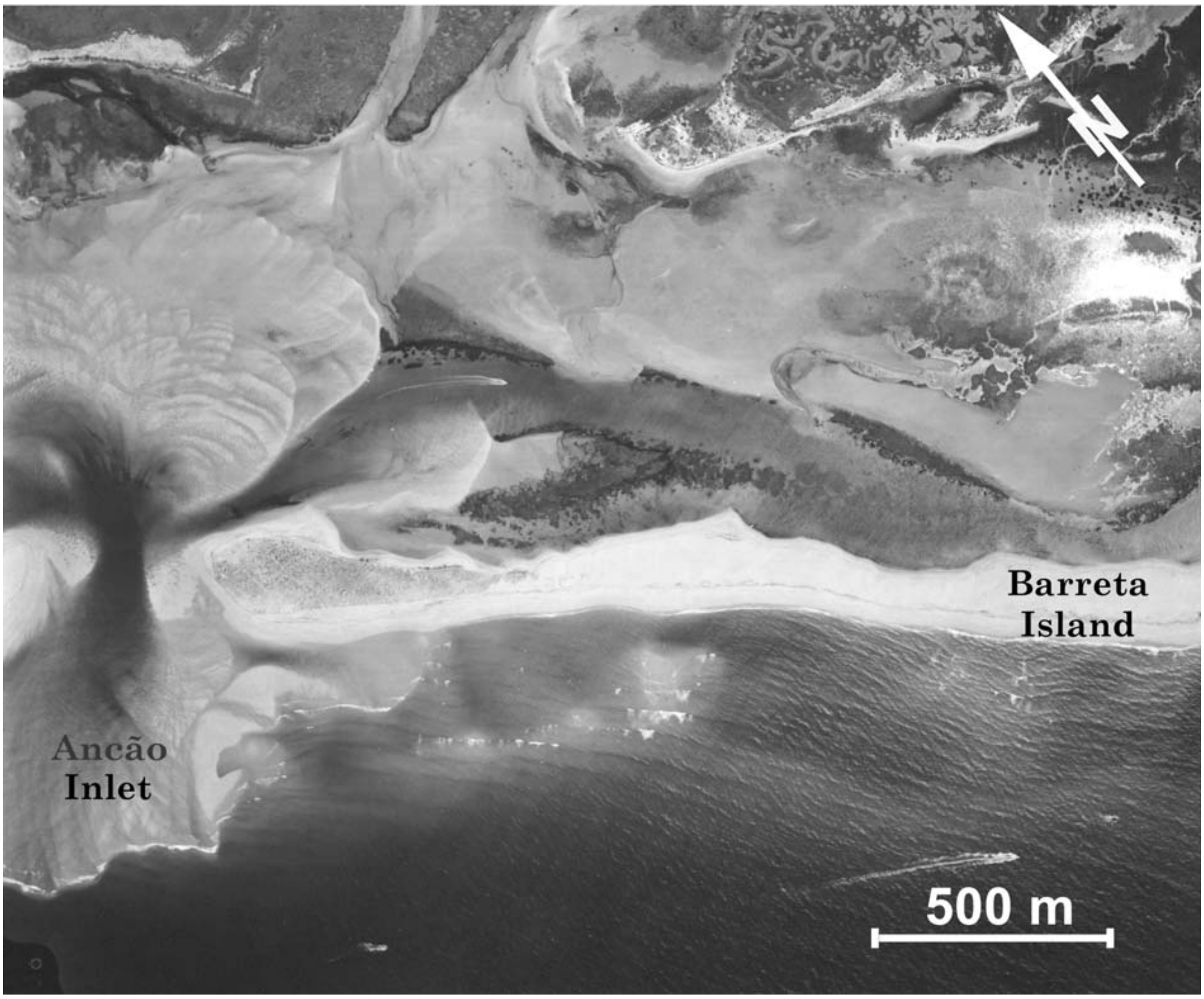

Figure 3.2. Location of the washover plain on the western part of Barreta Island, and Ancão Inlet channel and eastern deltas. Vertical aerial photograph date: August 2001.

Figure 3.3. Overwash on the washover lobes and washover plain, on western Barreta Island (date: September, 2001).

The typical progression of sedimentary environments was: at the seaward limit a very reflective beach face; a beach berm was only present during high-volume stages (Vila-Concejo *et al.*, *in press a*); a washover crest in the case of plains (Figure 3.4a) or a washover mouth in the case of washover lobes; an extensive terrace surface (Figure 3.4b) or the channel (Figure 3.4c) of the washover lobe; and at the landward limit the washover terminus or the washover fan (Figure 3.4d). During storms or high spring tides with winter waves, overwash was frequent in the study area. During fair-weather conditions, the washover surface was normally reworked by the wind, with occasional development of embryonic dunes where the barrier was wider. Some vegetation colonization occurred in these backfan areas (Figure 3.4b), but normally they were either eroded or buried during subsequent overwash.

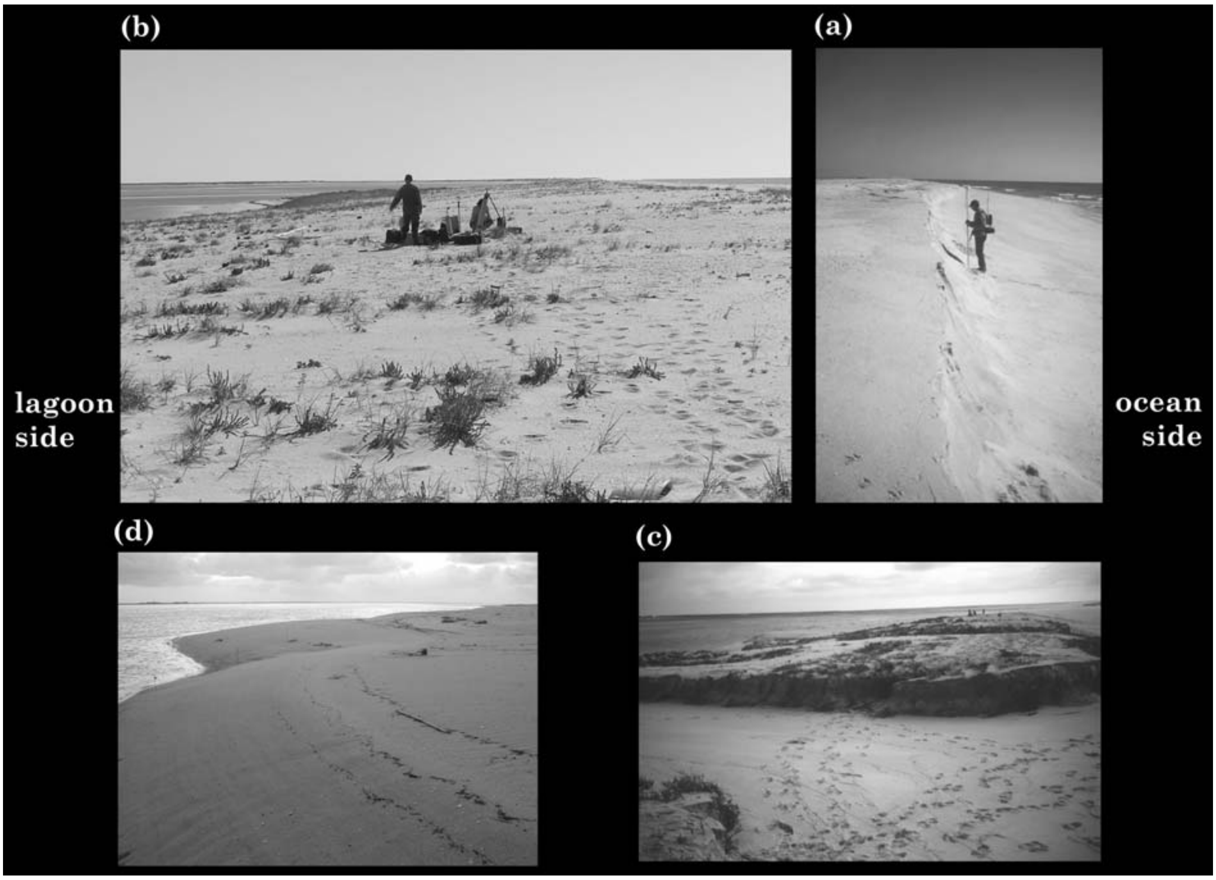

Figure 3.4. Examples of washover morphologies on Barreta Island. (a) Washover crest with an erosional bluff (date: February 2002); (b) washover terrace with pioneer vegetation communities (date: February 2005); (c) washover channel (date: February 2001); and (d) washover fan (date: February 2003).