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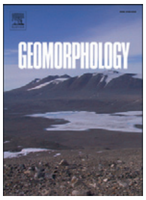

# Natural and human-induced coastal dynamics at a back-barrier beach

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## ABSTRACT

This study contributes to the understanding of very low-energy fetch-limited environments by reporting the evolution of a back-barrier beach (Ancão Peninsula, southern Portugal). It considers two timescales: a large-scale evolution for the past 60 years based on aerial photograph analysis, and a small-scale beach evolution based on monthly topographic surveys performed during three years of monitoring. Each timescale revealed a different rate of evolution, the first reporting a modified beach response-type (from human activities), and the second reporting a natural beach response-type. Human activities caused significant changes in the back-barrier shore, whereas changes under natural forcing were much smaller, were less influential on the area's evolution, and were not sufficient to counteract or mask the consequences of human activities. The findings of the study should contribute to a better understanding about the large- and small- scale changes in other back-barriers characterised by similar very low-energy conditions.

## 1. Introduction

Low-energy estuarine beaches are geographically more extensive than oceanic beaches (Vila-Concejo et al., 2010); however, they have received less scientific attention which has resulted in a poorer understanding of their evolution and morphodynamics. Research efforts on fetch-limited beaches have been focussed not only on identifying the main forcing factors and their relative importance in sediment transport, but also on predicting the beach morphological response over time (Jackson, 1995; Nordstrom et al., 1996; Eliot et al., 2006; Carrasco et al., 2011). Predicting morphological changes in fetch-limited environments, or in other coastal systems, is a non-trivial task due to the complexity of the underlying physical processes involved and because of the sensitivity of system behaviour to natural variability (Karunarathna et al., 2009). Furthermore, there are limits to the predictability of morphological variables, which are related to the issue of scale (Larson and Krauss, 1995; Larson et al., 2002). This requires a better description of the changes occurring over each temporal scale and a better specification for the cross-over between the various scales. The main objective of this work is to quantify the large-scale behaviour (from years to decades) of a low-energy beach and to determine how such behaviour relates to small-scale evolution (months to a few years). Also, local and regional spatial frames are integrated to understand how they interact to explain the evolution of the back-barrier environment.

At the beginning of this study, three research questions were raised: (a) Does a fetch-limited shore segment approach a quasi-equilibrium state over years? (b) Does the beach respond to a seasonal hydrodynamic cycle? and (c) What are the main physical processes responsible for change at different timescales? By answering these questions, we intend to provide a basis for the discussion of controls involved in inter-site variability in net budget trends and to contribute to the overall understanding of back-barrier coastal stretches.

## 2. Field site

The field site is located at Ancão Peninsula back-barrier (Fig. 1), within the Ria Formosa lagoon (southern Portugal). This lagoon is protected by a multi-inlet barrier island system that extends over 56 km in length and includes one peninsula, six islands and seven tidal inlets (Fig. 1a). Tides in the area are semi-diurnal; average ranges are 2.8 m for spring tides and 1.3 m for neap tides. The average offshore significant wave height is 0.92 m (Costa et al., 2001). The field site is sheltered from oceanic waves, and is therefore exposed to a different wave and current regime from other coastal stretches in the region. With the exception of wave regimes generated by exceptionally strong winds, predominant waves are small, of the order of few centimetres in height (Carrasco et al., 2009). The back-barrier beach is bounded by Ancão channel (Fig. 1b), which connects to Ancão Inlet, located about 2250 m to the SE. Ancão Inlet is a small inlet with a cyclic eastward migration pattern (Dias, 1988; Pilkey et al., 1989; Vila-Concejo et al., 2002), exhibiting an ebb-dominated behaviour (Andrade, 1990; Salles, 2001; Pacheco et al., 2010). The field site extends along the shore over ~100 m and includes a low and narrow sandy beach (Fig. 1b). The beach profile is presently

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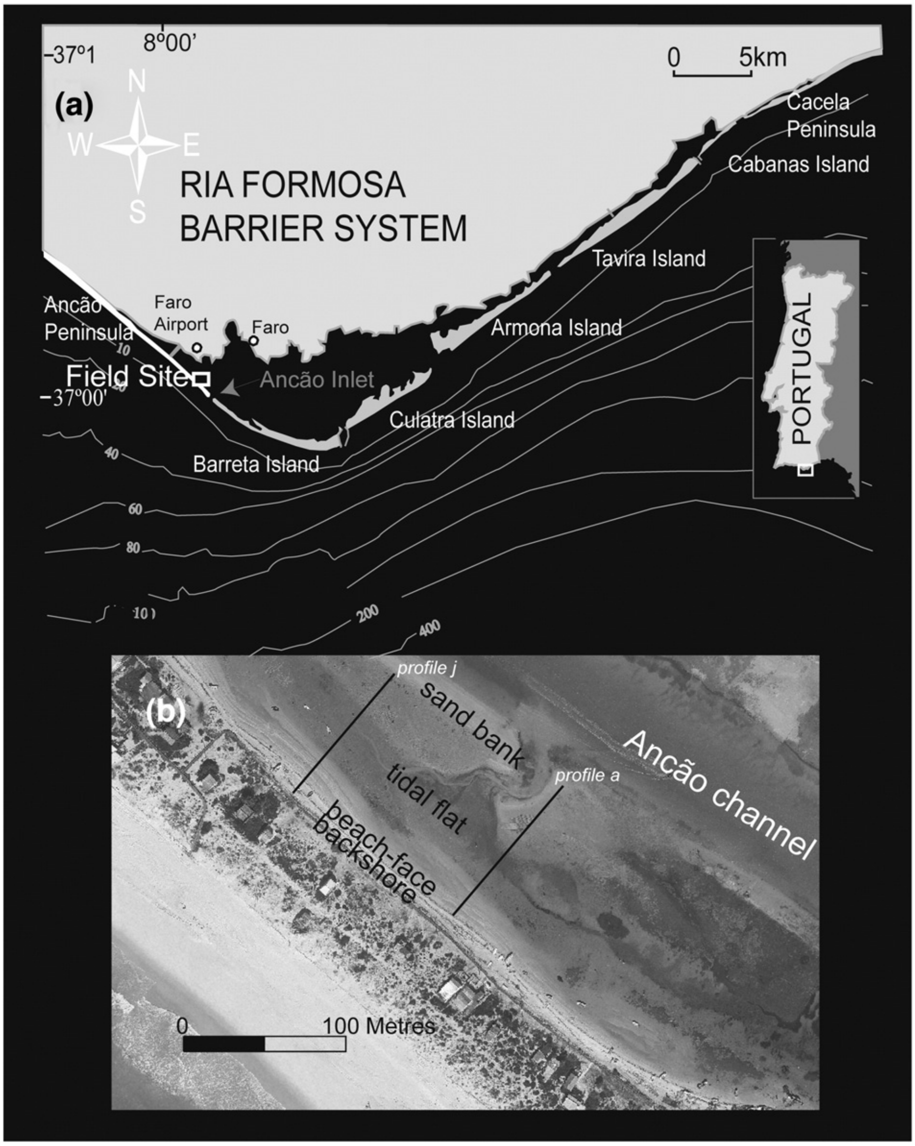

**Fig. 1.** (a) Field site location, showing Ancão Peninsula back-barrier; and (b) a vertical aerial photograph (taken in 2007) showing the main beach morphologies, profile *a* and profile *j*.

composed of four different morphologies: backshore; beach face; tidal flat; and a detached sand bank. The intermediate-steep beach face (~39 m wide) presents a very narrow swash zone during high tide. In contact with the beach face, a tidal flat with a gentle slope is present (~44 m wide), ending in a small sand bank (~30 m wide) parallel to Ancão tidal channel. Both the tidal flat and the sand bank show no bedforms and are cut-off by a small oblique secondary tidal channel.

Human occupation at the field site dates from the 1940s. Currently, the site hosts a small number of dwellings (for local fishermen) in the backshore area and an alongshore elevated footpath (Fig. 1b). Besides human occupation, other human activities included dredging operations and the relocation of the inlet during the 1990s. The Ria Formosa system has undergone an extensive environmental rehabilitation programme to recover the natural dynamic equilibrium while decreasing natural hazards (Ramos and Dias, 2000; Dias et al., 2003). This programme included soft engineering techniques such as tidal channel dredging, beach and dune nourishment, and the relocation of two inlets, including Ancão Inlet. Sand renourishment operations close to Ancão Peninsula occurred in 1990, and between 1999 and 2000. In 1990, about 300,000 $m^3$ were dredged from Ancão tidal channel and deposited along Ancão Peninsula. Ancão Inlet was relocated in 1997 to a more westerly position, improving its hydrodynamic efficiency and reducing navigational difficulties (see inlet positions through time in Vila-Concejo et al., 2006). This relocation effectively brought the inlet closer to the study area, from the former position of 5600 m (1996) to 1740 m (2001). Between 1999 and 2000, about 570,000 $m^3$ were dredged from the entire Ancão tidal channel and placed in the vicinity of the oceanic beach of Ancão Peninsula (Ramos and Dias, 2000). Dredging operations were responsible for the Ancão tidal channel deepening and channel axis shift.

## 3. Methods

### 3.1. Large-scale data collection

Shoreline evolution over the last 60 years was calculated by analysing a time-series of georeferenced aerial photographs (1947, 1976, 1989, 1996, 2001, 2005, and 2007). For the overall back-barrier shoreline analysis, Ancão back-barrier was sub-divided into two sectors, with the field site being located in sector 1. Digital Shoreline Analysis System from the USGS (DSAS; Thieler et al., 2005) was applied to infer shoreline displacements (for details see Thieler and Danforth, 1994; Thieler et al., 2005). Shoreline change was determined based on the endpoint rate (EPR), according to Dolan et al. (1991). In the present study the uncertainty in data and methods used for long-term data collection is related to the accuracy of photographic interpretation of the shoreline. Errors associated with long-term rate-of-change statistics include the inherent aerial photo georeferencing error, which is more significant in areas where changes in shoreline positions are small, as occurs in the case of this study. The RMS error associated with aerial photo georeferencing is reported in Table 1. The statistical uncertainty for the long-term evolution rate at each transect was reported at the 99% confidence interval. The determined mean least square estimate (LSE), which includes the above errors using the EPR method, was 5 m for the overall Ancão Peninsula and 2 m for the field site. The obtained results represent best estimates and can be used to assess general tendencies.

The long-term evolution of the beach profile was assessed by the comparison of recent profiles (2008) with topographic data measured around 1944–1945 (source, Instituto Portuário Transportes Marítimos).

### 3.2. Small-scale data collection

The small-scale analysis reports the main beach volumetric tendencies with respect to wind (wave driver) conditions. Wind data, and topographic data were collected from April 2005 to March 2008. Prevailing wind directions and maximum and mean wind speeds were accessed every 30 min from Faro airport, 2 km north of the study area with no obstacles in between (Fig. 1; Weather Underground, 2008). Ten cross-shore profiles (from *a*, in the east, to *j*, in the west, see Fig. 1) with 10 m spacing were measured during each survey. Volumes were determined for the main morphologies, in relation to mean sea level (MSL). Errors associated with topographic maps and with volume computations resulted from equipment error (maximum vertical error of ±0.003 m, quoted by the manufacturer), fieldwork operational errors (mean horizontal error of 0.01±0.07 m, and mean vertical error of 0.00±0.002 m, based on test surveys) and surface interpolation method errors (maximum difference between interpolations with different methods of 0.39%).

## 4. Results

### 4.1. Large-scale evolution and morphological changes

The mean shoreline-change rate for the overall Ancão Peninsula back-barrier between 1947 and 2007 was 0.1 m yr$^{-1}$. Sector 1 (containing the field site) presented a mean and a maximum back-barrier shoreline-change rate of 0.05 and 0.69 m yr$^{-1}$, respectively (Fig. 2a). Sector 2, in the eastern part of Ancão Peninsula, presented the most dynamic evolution, with a mean and a maximum back-barrier shoreline-change rate of 0.22 and 4.04 m yr$^{-1}$, respectively (Fig. 2a). Back-barrier shoreline-change rates at the field site were relatively small, of about 0.09 m yr$^{-1}$ between 1947 and 2007, and direct towards the mainland (dune field advance towards Ancão tidal channel; Fig. 2b). Maximum accretion values were recorded between 2001 and 2005 (1.22 m yr$^{-1}$, Table 2). The beach, the nearshore, and Ancão tidal channel evolved in separate ways, on which basis five main periods of evolution were distinguished (aerial photos, Fig. 3; Table 2): (a) between 1947 and 1976, with no major shoreline changes; (b) between 1976 and 1989, and (c) between 1989 and 2001, both characterised by important changes occurring in the nearshore and at Ancão tidal channel; (d) between 2001 and 2005, characterised by changes occurring in the beach and nearshore; and (e) between 2005 and 2007, characterised by beach and nearshore stability (see evolution and morphological description in Table 2).

**Table 1**
Total RMS error associated with georeferenced aerial photographs (in metres).

| Date | RMS |
|---|---|
| 1947 | 3.11 |
| 1976 | 1.73 |
| 1989 | 1.46 |
| 1996 | 1.13 |
| 2001 | 0.49 |
| 2005* | - |
| 2007 | 1.39 |

* Orthophoto.

The morphological changes since 1947, as described, are also visible in profile view (Fig. 3, bottom right diagram). Around 1944–1945, in the absence of nearshore morphologies (tidal flat and sand bank), the beach face dipped directly into the Ancão tidal channel. The sandy beach was very narrow when compared with the 2008 topography. Over the ensuing decades since 1944–1945, substantial sediment accumulation occurred in the nearshore, which led to the development of both the tidal flat and sand bank, and subsequent shoreline displacement towards the tidal channel. The Ancão tidal channel migrated towards the mainland (i.e., to the northeast).

### 4.2. Small-scale evolution, wind, grain-size, and volumetric changes

Between 2005 and 2008, W–NW winds prevailed with a mean direction of 210° during summer and 181° during winter (with higher percentage of NE winds), and with a few episodes of easterly winds (mostly at the end of 2007 and beginning of 2008). Maximum monthly intensities occurred associated with S–SE winds. Wind velocity was generally low to moderate with a mean wind velocity of ~4 m s$^{-1}$. Maximum wind velocity in 2005 was 15 m s$^{-1}$ (from the SW), in 2006 was 14 m s$^{-1}$ (from the SW to the W), in 2007 was 17 m s$^{-1}$ (from the SW), and in 2008 was 15 m s$^{-1}$ (from the SE).

Beach volume variations were small, with a maximum variation between surveys of 47 m$^3$ (Fig. 4). Slope gradients did not change over the study period. Maximum volumetric variation for the backshore and beach face between 2005 and 2008 was $+0.18$ m$^3$ m$^{-1}$ and $+4.88$ m$^3$ m$^{-1}$, respectively, whereas maximum volumetric variation on the tidal flat and the sand bank between 2005 and 2008 was $+4.50$ m$^3$ m$^{-1}$ and $-3.45$ m$^3$ m$^{-1}$, respectively (Fig. 4). The backshore has a minimal variation, while the beach face shows considerable variation, indicating no similarity in trend between them (Fig. 4a and b). The nearshore evolved as an independent sub-system, with analogous volumetric variations within it, indicating the absence of cross-shore transport between the tidal flat and the sand bank (Fig. 4c and d). There was no marked seasonality in beach evolution (Fig. 4e), nor any significant correlation between volume and prevailing wind conditions. The results reveal that the influence of wind (and wind-driven waves) on the beach was almost non-existent.

## 5. Discussion and conclusions

### 5.1. Linking timescales

The studied back-barrier beach is itself a channel margin, and consequently vulnerable to changes in the respective tidal channel and surrounding areas. Two timescales were articulated to provide a broad overview of changes over the past 60 years. Each timescale described a different rate of evolution, the first (large-scale) reporting a modified beach response-type, and the second (small-scale) reporting a natural beach response-type. Differences between them are described later. Besides operating at different time-steps, the timescales are complementary since information can be transferred from one to the other.

At the large-scale the beach recorded advance towards Ancão tidal channel, partly from natural beach accretion but mostly human imposed (Section 4.1). Two major periods of change occurred: between

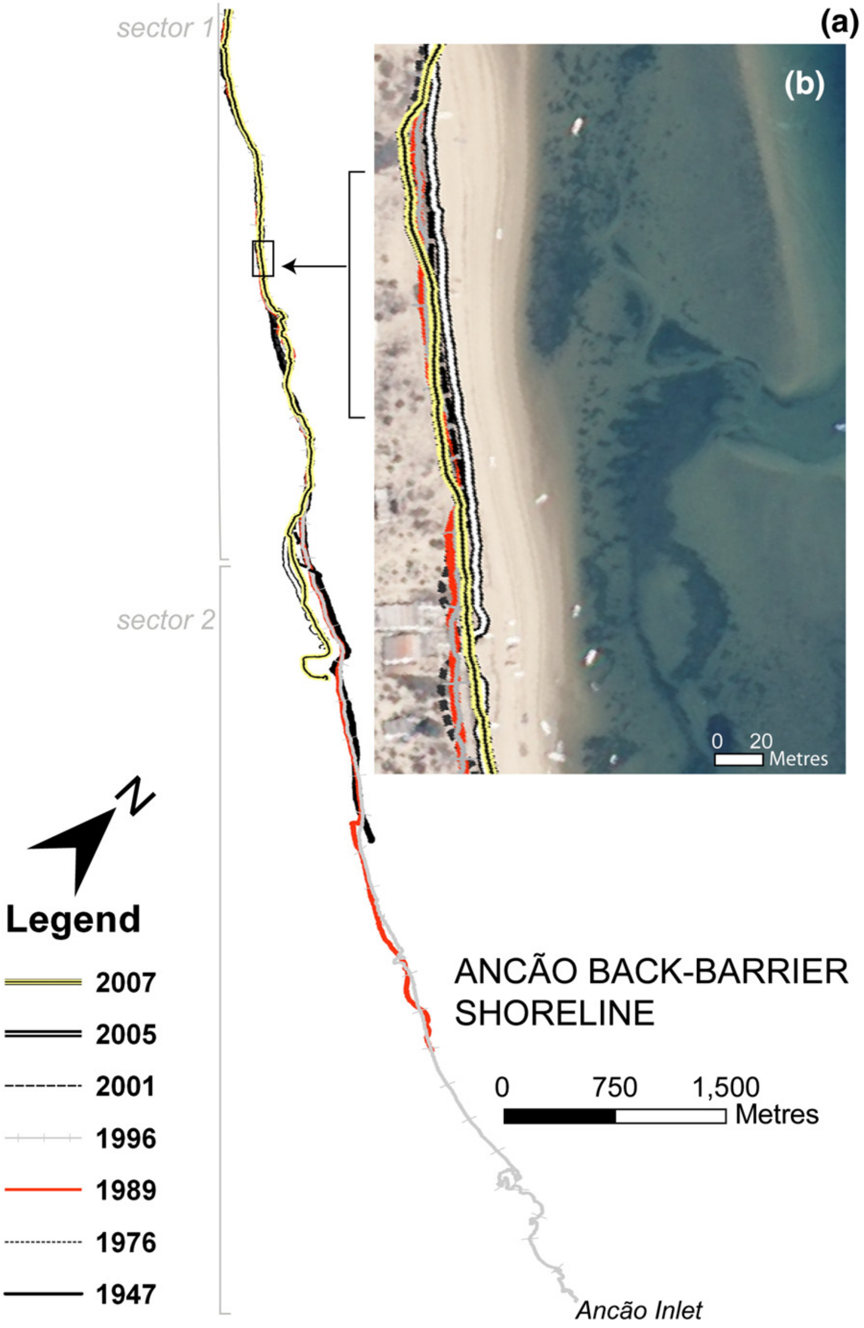

**Fig. 2.** (a) Ancão back-barrier shoreline evolution between 1947 and 2007; and (b) shoreline displacements between 1947 and 2007 at the study area (aerial photo from 2007).

1947 and 1996 (before human interventions) with minor changes observed for the beach profile, and after 1996 (prior to human interventions) with deep changes observed for the beach profile (nearshore development) and surrounding tidal channel. Human activities leading to change comprised dredging and inlet relocation. Before human interventions the natural back-barrier beach was originally composed of backshore, beach face, and various sand spits forming the tidal flat (between 1947 and 1996, Fig. 3). The back-barrier, as a channel margin, was relatively stable, but Ancão tidal channel was suffering an intense infilling, like in other parts of the lagoon (Carrasco et al., 2008). The area was affected by a few sand spits and small tidal channels (photo 1989, Fig. 3), probably relics of a former position of the Ancão Inlet flood delta (as observed in other case studies by Godfrey and Godfrey, 1974; Kraft et al., 1979).

Dredging took place far from the back-barrier shoreline, and the Ancão channel axis was transposed towards the mainland (with profound profile changes between ~1944–1945 and 2005, Fig. 3). Channel axis transposition promoted morphological changes at the nearshore, namely sand bank development (Table 2). After 1996, both beach face and nearshore evolved at different rates. The newly detached sand bank operated as a natural protection to the beach, resulting in nearshore displacement towards Ancão tidal channel (between 2001 and 2005, Table 2). Since its artificial construction between 1996 and 2001, the sand bank has evolved by adjusting its shape to the time-varying forcing mechanisms (Fig. 3). Besides dredging, with Ancão Inlet relocation in 1997, current velocities at the field site increased in intensity as a result of the decreasing distance to the inlet.

The small-scale analysis is critical for understanding the period between 2005 and 2007, and illustrates a natural beach response-type (without human interventions). Rates of evolution between 2005 and 2008 (Section 4.2) should be in agreement with the

**Table 2**
Shoreline displacements between 1947 and 2007 (positive values indicate displacement towards the Ancão tidal channel), back-barrier morphologies and related changes.

| Period | Mean displacement ($m\ yr^{-1}$) | Back-barrier morphologies | Major morphological changes |
|---|---|---|---|
| 1947–1976 | 0.05 | *backshore, beach face* | • Beach face and nearshore stability<br>The beach profile was short and the foreshore contacted directly with Ancão tidal channel. Human occupation was limited to small and traditional settlements associated with the fishing industry. |
| 1976–1989 | −0.05 | *backshore, beach face, tidal flat* | • sand spit development<br>• channel infilling<br>The beach was narrow, and the beach face was the major compartment, with no evidence of a prominent nearshore. A few sand spits were observed at Ancão tidal channel. These spits had limited width and were split by several tidal channels (see photo 1989, Fig. 3). The channels in between the sand spits merged to form the tidal flat. |
| 1989–1996 | 0.08 | *backshore, beach face, tidal flat* | • sand spit development<br>• dredging<br>After 1989, there was a reduction in human occupation in the dune field. Sand was dredged from Ancão tidal channel (1990), and was used to replenish the ocean shore. |
| 1996–2001 | −0.22 | *backshore, beach face, tidal flat, sand bank* | • dredging<br>• sand bank development<br>• tidal channel axis migration with changes in the channel margins<br>Sand spits were again modified by dredge operations in Ancão tidal channel during the late 1990s (Section 2; see dredge channel in photo 1996, Fig. 3). Simultaneously, the back-barrier beach became wider and another detached compartment (the sand bank) started to form close to Ancão tidal channel (after 1996, Fig. 3). The sand bank was an impact of dredging. Besides changes in the density of human occupation, between 1996 and 2001 an elevated footpath was also constructed across the dune field. |
| 2001–2005 | 1.22 | *backshore, beach face, tidal flat, sand bank* | • sand bank evolving<br>• changes in tidal channel margins<br>By 2001, the back-barrier profile was exhibiting the four well-developed compartments/morphologies: backshore, beach face, tidal flat, and sand bank. High shoreline displacements occurred (towards the tidal channel) as a consequence of the incorporation of the sand bank into the beach. |
| 2005–2007 | 0.15 | *backshore, beach face, tidal flat, sand bank* | • nearshore stability<br>There were no major shoreline displacements or morphological changes. In 2005, both the sand bank and secondary tidal channel were established as important features for the evolution of the upper beach profile. |

morphological changes observed in aerial photographs between 2005 and 2007 (Section 4.1). Over a monthly timescale beach evolution was small and continuous (Fig. 4), similar to the very sheltered meso-tidal beaches described in Short (2006); (tide-dominated beach and tidal flat, Section 4.2). Beach face and nearshore were independent sub-systems operating in different ways. The only relationship between them is that the nearshore offers protection to wind-induced waves that impact on the beach. There was no demarcation of

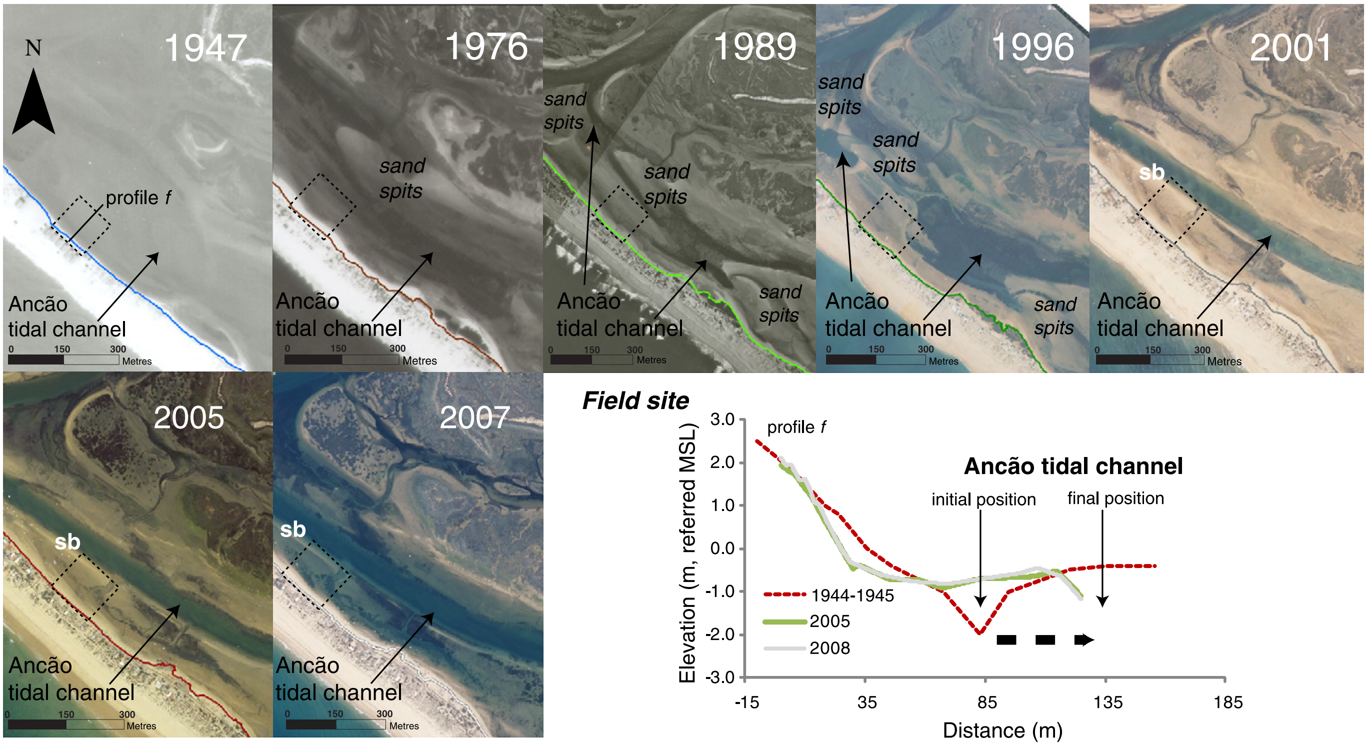

**Fig. 3.** Field site evolution between 1947 and 2007; beach profile evolution between 1944–1945 and 2008. The dotted box in aerial photographs represents the field site with profile *f* located at a middle position; sb corresponds to the sand bank.

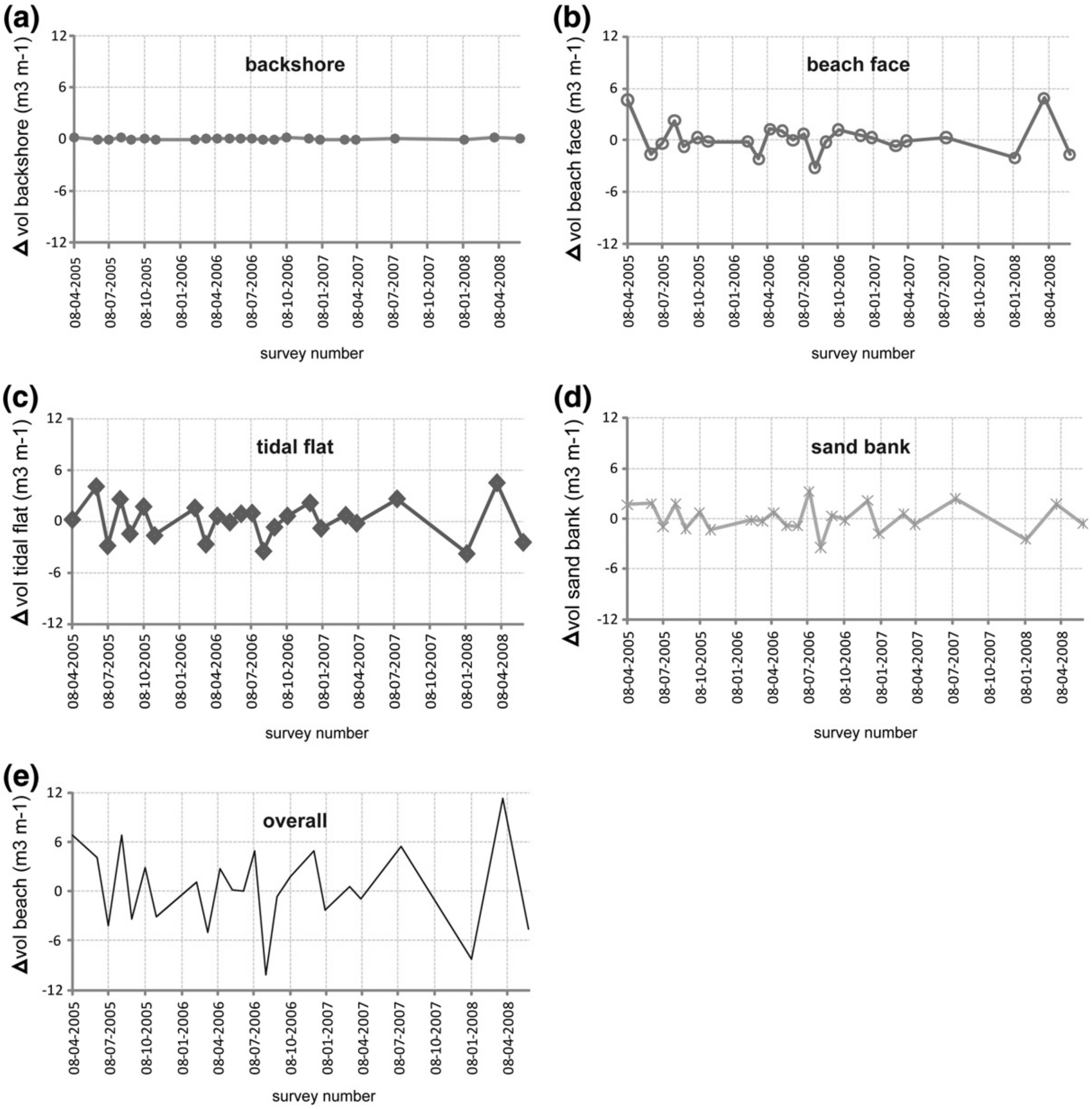

**Fig. 4.** Volumetric variations at (a) backshore; (b) beach face; (c) tidal flat; (d) sand bank; and (e) overall area.

seasonal beach behaviour (Fig. 4e), in contrast to the behaviour described for other low-energy beaches (e.g., Nordstrom, 1980; Travers, 2007), and the beach underwent less conspicuous changes in response to relatively energetic (wind- and wave-driven) events than is the case for high-energy fetch-limited beaches. Contrary to most oceanic beaches (e.g., Wright and Short, 1984; Dubois, 1988), the studied back-barrier showed a reluctance for cyclic changes (Fig. 4); the small monthly shift between erosion and accretion around the mean volume suggests a slow response to forcing (rate of reaction; Fig. 4e). Volumetric changes were small because of the low to moderate prevailing wind intensities, and consequently because of the low breaking wave energy.

### 5.2. Beach inheritance

Human activities left a strong imprint and consequent inheritance in the system, instilling morphological changes that were neither erased nor counteracted by the cumulative back-barrier evolution trends (Section 4.1; Table 2). It was demonstrated that a back-barrier coastal stretch can remain relatively unchanged for a long period due to low-energy conditions, revealing a beach lagging behind prevailing conditions, and a small chance of reaching a full morphological response before the same conditions change; the outcome is that it appears to change little over time (e.g., Fig. 4e). The capacity of the beach to exhibit major morphological changes is small and the response time is not necessarily immediate. Therefore, the momentary beach state on the back-barrier beach is not a contemporary response to prevailing hydrodynamics but reveals the system memory and evolution associated with continuously acting processes (Section 4.2). In the absence of human interventions, the field site would experience much smaller shoreline advance rates than those observed after such activities, and the natural beach profile would look very similar to the one observed in ~1944–1945 (with a natural propensity to channel infilling; Fig. 3).

Although back-barrier resources may not be immediately appealing, they have value because of their uniqueness, and because they are sometimes close to human populations, as is the case of Ancão back-barrier. The low perceived value of back-barrier beaches often results in loss of beach habitats as the shoreline is modified to accommodate human uses or shore protection methods (Nordstrom, 1992). The findings of this study provide reasonable approximations for the beach changes involving both natural and human dynamics (e.g., volumetric variability or shoreline displacement rates) and indicate the slow adjustment magnitude of these very low-energy systems. Therefore, any human action (even "working with nature" approaches such as dredging, dune fencing or nourishment) should be regarded as having a "permanent" (decades) imprint, disruptive of the past conditions and generating new conditions that will take long time to be changed.

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