EVOLUTION OF A RESTRICTED FETCH ENVIRONMENT: THE CASE OF RIA FORMOSA BACKBARRIER, ALGARVE, PORTUGAL

by

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This MSc dissertation is presented in a journal format to be further submitted to the ***Estuarine, Coastal and Shelf Science*** as: CARRASCO, A. R., FERREIRA, Ó., DAVIDSON, M., and DIAS, J. A., *Evolution of a Restricted Fetch Environment: the case of Ria Formosa Backbarrier, Algarve, Portugal.* Instructions for Authors are presented on Appendix I.

Abstract

The shoreline changes along the backbarrier of a barrier system are extremely variable and critically dependent upon geographic location and the inherent interaction with hydrodynamic processes. Main objectives of the present study are related with the definition and adequateness of Backbarrier Development Indexes, and its application to the recent evolution of the Ria Formosa backbarrier.

Backbarrier coastline evaluation is performed based on aerial photographs analysis between 1947 and 2001. Considering it spatial variability, two types of approaches are purposed for the three main dominant morphologies at the backbarrier: cross-shore and longshore evolution. The backbarrier development indexes application recognizes different status of evolution and maturation, taking into account the determined longshore evolution.

Results obtained for the Ria Formosa backbarrier evolution illustrates two distinct periods representative of accretion and erosion trends: for accretion was identified the period between 1947 and 1976, and for erosion or smaller accretional rate was identified the period between 1976 and 2001. Application of the purposed indexes allowed obtaining the classification of a well maturated backbarrier between 1947 and 2001. The central part of the system accomplishes progradational backbarrier behaviour in contrast with a retrograding behaviour at the eastern extreme of the system.

Indexes application reveals to be a good approach in the classification of backbarrier development, and should be discussed within the identification of the main forcing mechanisms acting at the system. Besides the natural forcing mechanisms (complete overwash events), changes at the inlets position are the main factors controlling the backbarrier development and maturation.

Prediction of future changes requires a detailed understanding of the hydrodynamic controls responsible for alteration on restricted fetch areas, like is the Ria Formosa backbarrier.

Key-words: Backbarrier, indexes, maturation, Ria Formosa, overwash, inlets.

1. Introduction

Low energy beaches are located in sheltered and/or fetch-limited environments. Sheltered environments occur in the lee of islands, reefs, or submarine ridges (Hegge et al., 1996 *in* Jackson et al., 2002a), so are protected to varying degrees from higher energy waves generated in larger adjacent bodies of water. Fetch-limited environments occur in lakes (Bauer and Greenwood, 1990 *in* Godfellow, 2005), bays (Ekwurzel, 1990 *in* Goodfellow, 2005), estuaries (Jackson and Nordstrom, 1992, Jackson, 1999), and lagoons (Jackson et al., 2002a), where limited fetch produces small waves that are, however, steep and erosive due to short periods (Battjes, 1974; Jackson et al., 2002b).

The primary agents of erosion on fetch-limited environments are waves generated within the estuaries by local winds, although ocean swell waves that enter the estuaries through inlets, tidal currents, wind drift, and vessel wakes are important on some sites (Nordstrom, 1992). Locally generated waves have usually short periods being principally dependent on wind conditions (speed, direction and duration) and basin dimensions (width, length and depth) (Nordstrom, 1992; Jackson et al., 2002b). The dependence of wave generation on local winds means that fetch-limited beaches experience a highly variable wave climate, with periods of high waves interspersed with periods of calm (Jackson et al., 2002b), while the absence of low-steepness, long-period swell waves from fetch-limited environments restricts the shoreward return of sediment (Wright and Short, 1984).

Tidal range affects the vertical distribution of wave energy profile, determining the width of the beach and the duration that wave break at any elevation (Nordstrom, 1992). Longshore currents are predominantly generated by breaking of local wind-waves but refracted ocean waves, tidal flows and wind drift are important. Tidal currents are especially important where beaches are located near tidal channels, causing important effects on beach change when they operate in conjunction with waves. At these times, resulting currents may be as great as observed on high-energy days on ocean beaches (Nordstrom, 1977 *in* Nordstrom, 1992).

The consequent reduction in significance of wave height increases the importance of surge-related water level fluctuations in explaining profile shape and the location of morphologic features (Hegge et al., 1996 *in* Jackson et al., 2002a). Profile characteristics of low energy sandy beaches include narrow foreshores that are often steep (Jackson, 1999), planar and without a backshore (Nordstrom and Jackson, 1993).

The shorelines occurring along restricted fetch environments, like the backside of barrier islands, are extremely diverse and variable with respect to types and erosion rates. Main controls and shoreline characteristics differ over short distances due to differences in fetch length and exposure to winds (Nordstrom, 1992). These low and narrow islands are periodically dominated by oceanic processes resulting in major sediment input in response to overwash events (Dillon, 1970; Schwartz, 1975; Leatherman, 1976; Andrade, 1990; Dingler et al., 1993; Short; 1999; Morang et al., 2002; Masselink and Hughes, 2003), inlet dynamics, and migrating dune sands (Jackson et al., 2002a). Consequently, many low sediment banks and marsh platforms contain extensive shallow waters with ephemeral strand plain beaches and abundant fringing marsh. These latter processes and responses not only diminish wave energy, but actually build backbarrier platforms critical for barrier island migration processes in response to rising sea level (Nordstrom et al., 1996).

Migration of a barrier is a prime factor to be considered when evaluating lagoon's evolution. Landward migration may reduce size of the tidal prism and generate a series of changes which cause inlet closure and water freshening, and ultimately obliterate the lagoon which if the barrier is joined to the mainland shore (Cooper, 1994). Any change in the hydrodynamics of the inlet and its vicinity are likely to modify the sediment transport pattern; inlet migration and inlet sediment bypassing are processes that can account for dramatic shoreline changes along barrier islands (Salles, 2001).

There are only a few studies evaluating restricted fetch environments, especially in what concerns to backbarrier environments. Further investigation is needed in order to evaluate the generic backbarrier evolution, as a complement of coastal dynamics research. Developing a more objective and quantitative definition of the term low energy requires a better understanding of the occurrence and duration of morphological features, magnitude and frequency of hydrodynamic controls.

In the present analysis it is purpose the definition and application of Backbarrier Development Indexes, in order to classify the evolutionary pattern of backbarrier stretches located in restricted fetch environments. The recent evolution of a backbarrier coastline located at the south of Portugal, Ria Formosa barrier system, is used to support the indexes application. Backbarrier coastline evaluation is accomplish by the determination of cross-shore and longshore evolution, based on aerial photograph analysis between 1947 and 2001.

2. Methods Description

The following description is assumed to be a methodological proposal for backbarrier evolution determination. Taking into account the existence of different issues associated with such methodology, this section is divided in several sub-sections and respective methods of determination in order to clarify each type of analyse.

2.1. Aerial Photograph Analysis: general definitions

Aerial photograph analysis includes a primary step of study period definition, considering the expected behaviour, followed by the georectification process (image processing), and finally the identification and mapping of the backbarrier coastline. The chosen period of analysis should be determined by the period for which quantity and quality of information (vertical aerial photos) are adequate. In attempt to determine the major trends, three sets of photographs, and consequently two period of analysis (representing each period about 25 to 30 years of evolution), are considered of giving a good overview.

During the georectification process it is used a well-distribution set of ground control points over the study coastal stretch, avoiding inherent errors of rectification (Coyne et al., 1999). This process is performed by using the ERMapper programme that allows resample the image into a given coordinate system. The final output is a series of photomosaics for each year, where backbarrier coastline is digitized using the GIS programme Mapinfo.

For the global characterisation, during the backbarrier coastline digitalisation, two approaches are considered: cross-shore and longshore evolution. Both are taken to quantify the evolution of the three main dominant morphologies at the backbarrier: inner beach, salt marsh, and inner beach next to inlet (Table 1, Figure 1).

Table 1. Definition of each morphological unit considered at the backbarrier (see example Figure 1).

Morphology	Definition
Inner Beach (IB)	Sandy beach on the backbarrier sometimes cut by the presence of salt marsh areas, and episodically dominated by the washover fans (Andrade, 1990; Jackson et al., 2002a). Such area smoothly changes to the inner beach next to inlet (Nordstrom et al., 1996). Hydrodynamically is dominated by waves of short period, with restricted fetch, and by low to medium velocity tidal currents.
Salt Marsh (SM)	Backbarrier marsh sites typically exhibit a stratigraphic succession from intertidal muds through alternating salt marsh and brackish peat facies associated with minor variations in magnitude and direction of relative sea-level tendency (Andrade, 1990; French and Spencer, 1993; French 1997). Corresponds to the salt marsh area on the coastline located at the backbarrier, being hydrodynamically dominated by small velocity tidal currents.
Inner Beach next to Inlet (IBI)	Sandy beach on the backbarrier, spatially located next to inlets. Hydrodynamically dominated by strong tidal currents and some oceanic waves that cross the inlet. There is no dune field between these beaches and the oceanic ones.

For the coastline changes determination, a main reference at the bayside (reference line) is need to be established. For the coastal limit of the IB, the dune/inner bluff edge limit is selected to characterise the coastline evolution in the bayside. This limit indicates changes in dune field, like retreat or progradation into the lagoon, and therefore changes at the inner beach position. When vegetation is not present (for example in the reference line used for the IBI) the limit transition of tidal level (colour contrast) is choosen, or in case of being present, the inner bluff edge. The SM limit is defined by the frontal colour contrast caused by different type of vegetation (transition to non vegetated zone) and sediment properties.

The definition of the reference line for each morphological unit allows the individual quantification of IB coastline, SM coastline and IBI coastline.

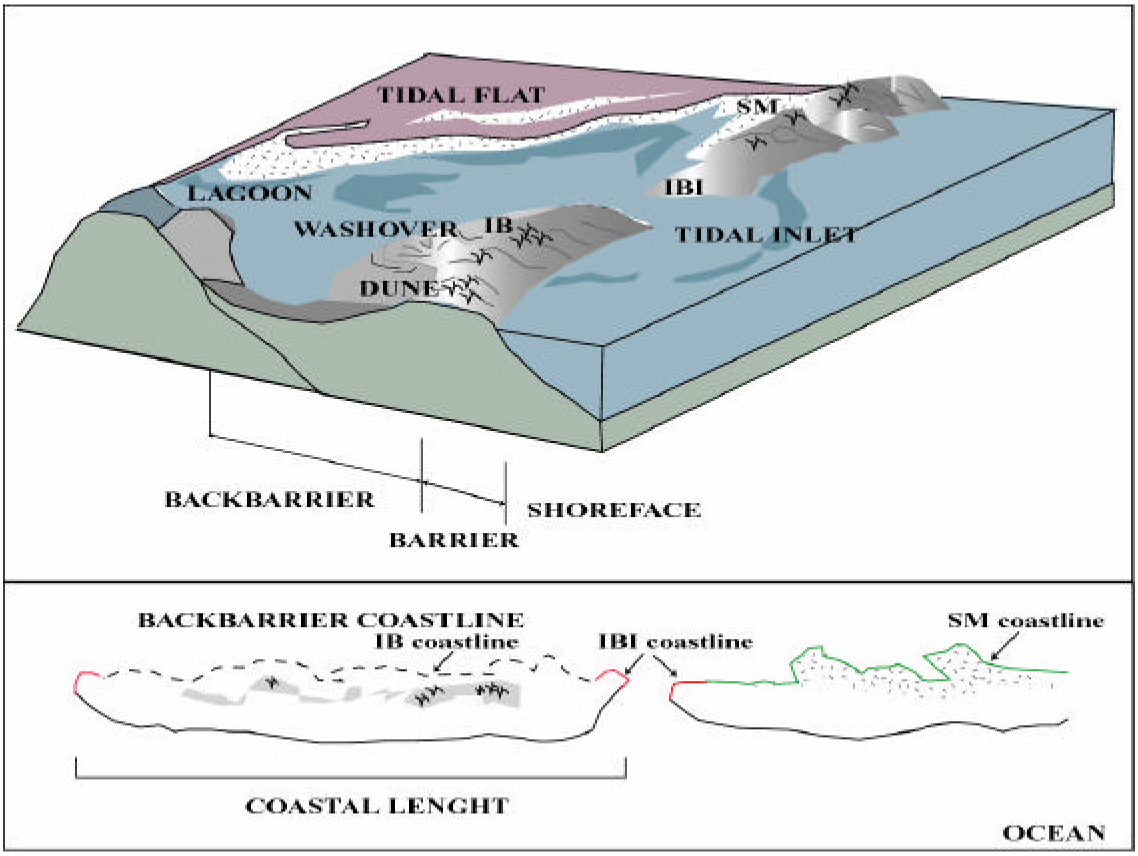

Figure 1. Schematic representation of the main morphologies present at the backbarrier.

2.2. Cross-shore and Longshore evolution: definition and interpretation

Cross-shore (CS) evolution is determined by using cross-shore transects measuring the distance between the transect origin and the reference line limits, previously defined during aerial photograph analysis. Since that it is pretend to compare CS evolution of salt marsh and inner sandy beach, IBI coastline changes are included in the IB coastline CS evaluation.

In general, transects are distributed in order to cover the higher extension as possible. Specific CS transects are also located in washover areas, allowing to identify and quantify backbarrier coastline alterations (progradation/retreat) due to the complete overwash occurrence. The first appearance is identified, as well as its maintenance and recovery (using additional years of analysis), however, only the first appearance accounts to estimate the total number of occurrences during each study period. Backbarrier coastline interruption is used as the inner limit of the washover. Longshore interruptions are measured (in meters) to obtain a total value for the entire system (Figure 2).

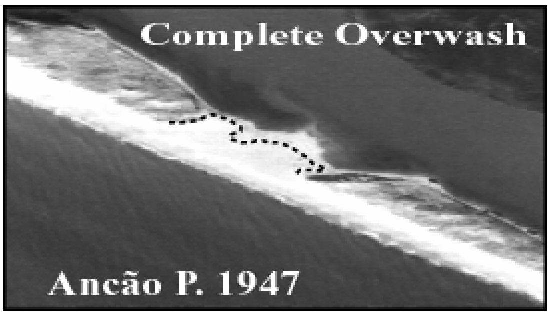

Figure 2. Example of a complete overwash occurrence.

Besides the complete overwash occurrence, other alterations on the system with relevant influence to the backbarrier evolution should be consider, and therefore request local CS determination. That is the case of backside areas that had suffered dredge disposal operations, and where should be also located CS transects.

Longshore (LS) evaluation takes into account the determination of IB, SM, and IBI coastline extends for each set (IBC, SMC, and IBIC respectively). The total backbarrier coastline extend (BC) represents the sum of these last three morphological coastline extends for each coastal stretch, in each year of analysis; longshore evolution is determined in m/yr and expressed as a percentage.

3. Backbarrier Development Classification

Based upon the performed LS measurements, a Backbarrier Development Classification is purposed in order to recognize different status of evolution/maturation. Main objective is related with the definition of indexes of backbarrier development to be applied to each coastal stretch, for a giving period:

?BC (%) = (BC in the last year of analysis -BC in the first year of analysis)*100/(BC in the first year of analysis) *(1)*

?L (%) = (L in the last year of analysis -L in the first year of analysis)*100/(L in the first year of analysis) *(2)*

?SMC:TIBC = [(SMC in the last year of analysis/TIBC in the last year of analysis) – (SMC the first year of analysis/TIBC in the first year of analysis)] *(3)*

The BC corresponds the backbarrier coastline extend; **?** BC represents the backbarrier coastline extend variation expressed in percentage; L the rectilinear coastal length of each island/peninsula; **?** L the coastal length variation expressed in percentage; SMC the salt marsh coastline extend; TIBC represents the sum of IBC and IBIC coastlines extend; and **?** SMC:TIBC the variation between the ratio SMC coastline and TIBC coastline extends in the chosen years of analysis (see Figure 1).

Different status of backbarrier development are obtained after comparing the distribution of the indexes: **?** BC *vs* ?L for backbarrier evolution, and ?SMC:TIBC *vs* ?L for backbarrier maturation level When relating the first two indexes, a positive backbarrier evolution is giving by positive BC variations due to accretion of L (Table 2).

Table 2. Possible scenarios of backbarrier development classification.

Possible indexes relationshiop	**Backbarrier Development Classification**
Backbarrier evolution	
Increase of BC and increase of L	Progradating backbarrier
Increase of BC and decrease of L	Ramified backbarrier
Decrease of BC and increase of L	Rectilinear backbarrier
Decrease of BC and increase of L	Retrograding backbarrier
Backbarrier maturation level	
Positive ?SMC:TIBC; SMC growth	Well maturated

?SMC:TIBC =0	Relative stable
Negative ?SMC:TIBC; TIBC growth	Not maturated

The SMC:TIBC ratio is determined for each year, in attempt to perform a temporal classification of the level of maturation of the backbarrier: higher levels of backbarrier maturation are obtain by higher values of SMC:TIBC (higher extension of SMC in relation to TIBC). Therefore, a well maturated backbarrier admit a positive **?** SMC:TIBC variation within accretion of L, between the distinct years of analysis (Table 2).

Intermediate status of development (ramified and rectilinear backbarriers) are achieved when indexes exhibit contrary evolution (Table 2).

4. Case study

4.1. The Ria Formosa backbarrier system

The Ria Formosa is a multi-inlet barrier island system located in southern Portugal (Figure 3). Its present configuration consists of two peninsulas and five islands that extend over 56 km. The cuspate shape of the Ria Formosa system produces 2 different areas in terms of exposure to wave action. The west flank is more energetic, being under the direct influence of the dominant wave conditions, while the east flank is only directly exposed to the "Levante" conditions (SE Mediterranean wind); the west flank presents two inlets, while the east flank has five inlets.

Tides in the area are semi-diurnal, average ranges are 2.8 m for spring tides and 1.3 m during neap tides, however, maximum ranges of 3.5 m can be reached. Wave climate in the area is moderate to high (Ciavola et al., 1997). Incident waves are normally from the W-SW, representing 68% of the total (Costa, 1994), although "Levante" occurs often in the area producing the E-SE waves, which represent 29% of the total (Costa, 1994). Storms have been defined for this area as events where significant wave height is greater than 3 m (Pessanha and Pires, 1981). Pires (1998) established the return periods for the main incident wave directions and concluded that for the same return period, SW storms are more energetic than SE storms. The occurrence of periods of high energy wave in winter leads to severe erosion problems, with frequent overwash of the barrier islands (Martins et al., 1996).

The backbarrier cover an area of $8.4x10^7$ m^2, being characterised by: i) large salt marsh areas with a high density of shallow meanders, largely composed by silt and fine sand (Bettencourt, 1984); ii) large sand flats partially flooded and reworked during spring tides (Pilkey et al., 1989); and iii) by a complex net of natural and partially-dredge channels thought the lagoon, which narrow and shoal in upper regions of the system (Salles, 2001).

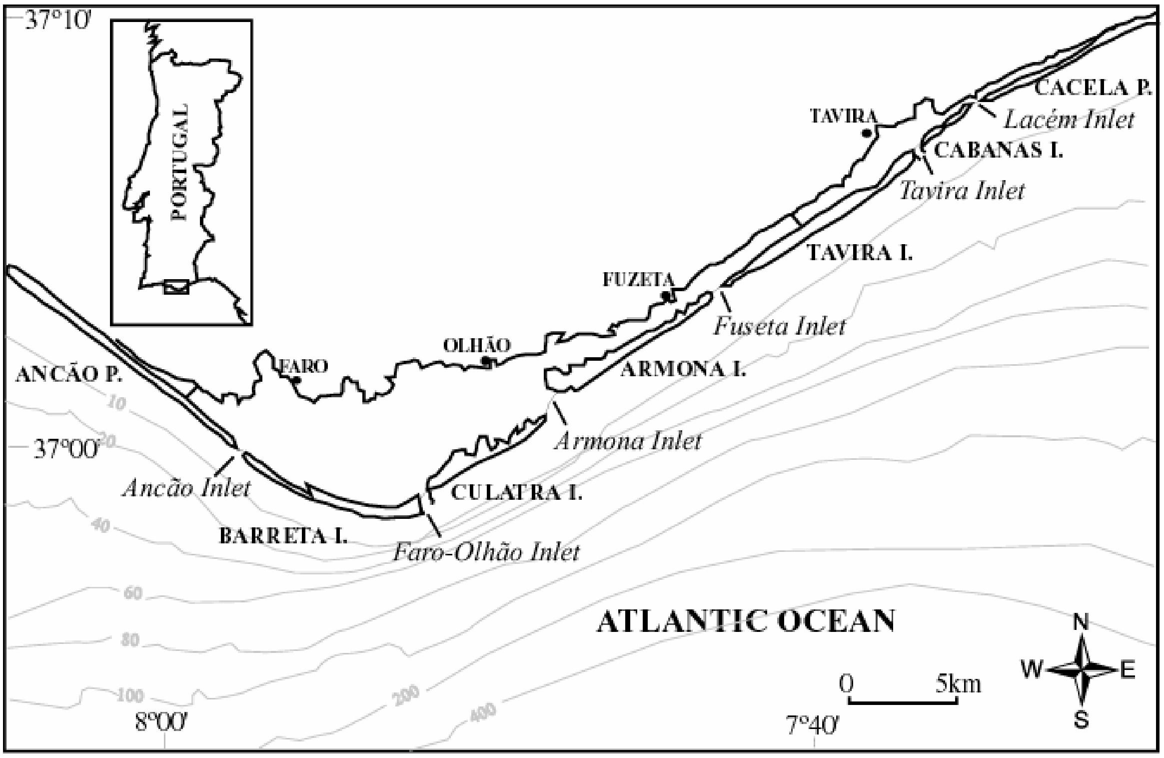

Figure 3. Study area.

The shoreline along the portion of the backbarrier is characterized by low, narrow sandy beach alternating with portions of salt marsh, and overwash platform formed by oceanic overwash (Andrade, 1998). The salt marshes are located in intertidal zone representing a surface area of $4x10^7$ m, corresponding to half of the lagoon area, where distribution decreases with the increase of the slope bottom (Andrade, 1990).

Recent evolution of Ria Formosa barrier system is strongly dominate by physical alterations conduced by inlets position displacement (see inlets location at Figure 3). Ancão Inlet is a small migrating inlet that has an average width of 300 m (Vila-Concejo et al., 1999), being located in one of the most dynamic areas of the system, and presenting a constant shift in its morphology and position (Andrade, 1990; Bettencourt, 1994). Migration of this inlet occurs from West to East until a limiting location, with directly interference with the Barreta I. coastal length (Pilkey et al., 1989; Vila-Concejo 1999, 2000, 2004). In the eastern part of this island, the opening and stabilization (1927-1955) of Faro-Olhão Inlet had provided the interruption and diversion of the littoral drift, resulting in a significant shoreline retreat in the barrier immediately downdrift (western part of Culatra I.). However, even admitting the drift trapping, a persistent accretion was observed at the eastern part of the Culatra I. resulting in an island growth of 32 m/yr of between 1945 and 1958 (Garcia et al., 2002). At downdrift, the narrowing of Armona Inlet is directly attributed to changes in the lagoon hydrodynamic due to the increasingly larger Faro-Olhão Inlet cross-sectional area that captured a significant fraction of Armona Inlet tidal prism. This inlet is considered to be the only naturally stable inlet of the system (Weinholtz, 1964; Pilkey et al., 2001).

In the eastern extreme of Ria Formosa system, Lacém Inlet eastward migration, as well as inlet narrowing, controls the dominance of processes of accretion/erosion at Cabanas I. (accretion at East) and Cacela P. (significant decreases of coastal length) (Dias, 1988; Pilkey et al., 1989; Vila-Concejo et al., 1999; Matias, 2000).

Besides the tidal inlets stabilisation (Faro-Olhão Inlet and Tavira Inlet) and tidal inlets relocation (Ancão Inlet and Fuseta Inlet), another anthropogenic intervention with relevant influence to the backbarrier system is related with the dredge disposal operations, in the beach shore and/or dune field of Armona Island (Armona Inlet and Fuzeta Inlet), and Cacela P. These interventions were performed in order to consolidate these islands presenting sedimentary deficiencies extremely exposed to storm conditions.

4.2. Methods Application

4.2.1. Aerial Photograph analysis

The period of analysis is comprised between 1947 and 2001 including two distinct periods for each island/peninsula (Table 3) (Aerial photograph coverage and scale are presented on Table

AII-1, Appendix II). Some islands presents it analysis conditioned by their appearance and/or development (*e.g.* 1st appearance of Cabanas I. on 1969); and for some years the complete morphological identification is not possible. In particular, IBI coastline is only determined for the 4 inlets non stabilised at the system. Such restrictions turned difficult to establish similar periods of analysis for each island/peninsula.

Table 3. Periods of analysis considered for each island/peninsula

Island/Peninsula	Periods of analysis	
Ancão P.	1947-1976	1976-2001
Barreta I.	1947-1976	1976-2001
Culatra I.	1947-1972	1972-2001
Armona I.	1969-1989	1989-2001
Tavira I.	1947-1976	1976-2001
Cabanas I.	1989-1996	1996-2001
Cacela P.	1976-1989	1989-2001

The processes of georectification allowed resample the image into the Portuguese Coordinate System UTM/MELRICA/TMPORT_SHG73. The estimated errors in the georectification process for each period of analysis resulted in most cases closer to 8 m, being mostly representative when dealing with CS changes (Figure AII.1, Appendix II).

An example of CS transects distribution and BC coastline mapping in the final obtained photomosaics are giving by Figures 4 and 5.

4.2.2. General evolution

Shorelines occurring along the backside of barrier islands are extremely diverse and variable with respect to accretion/erosion rates. Figure 6 presents the average CS changes determined for the total study period (1947-2001), while Table AII-2 at Appendix II presents the CS values obtained in the two distinct periods of analysis chosen for each island/peninsula.

Results suggest the existence of a common backbarrier landward displacement in all the islands/peninsulas with the exception of Tavira I., showing low values of backbarrier coastline accretion. In general, the IB coastline suffered particular CS accretion at Cacela P. and Armona I., while SM coastline only exhibited significant CS accretion at Barreta I and Cacela P.

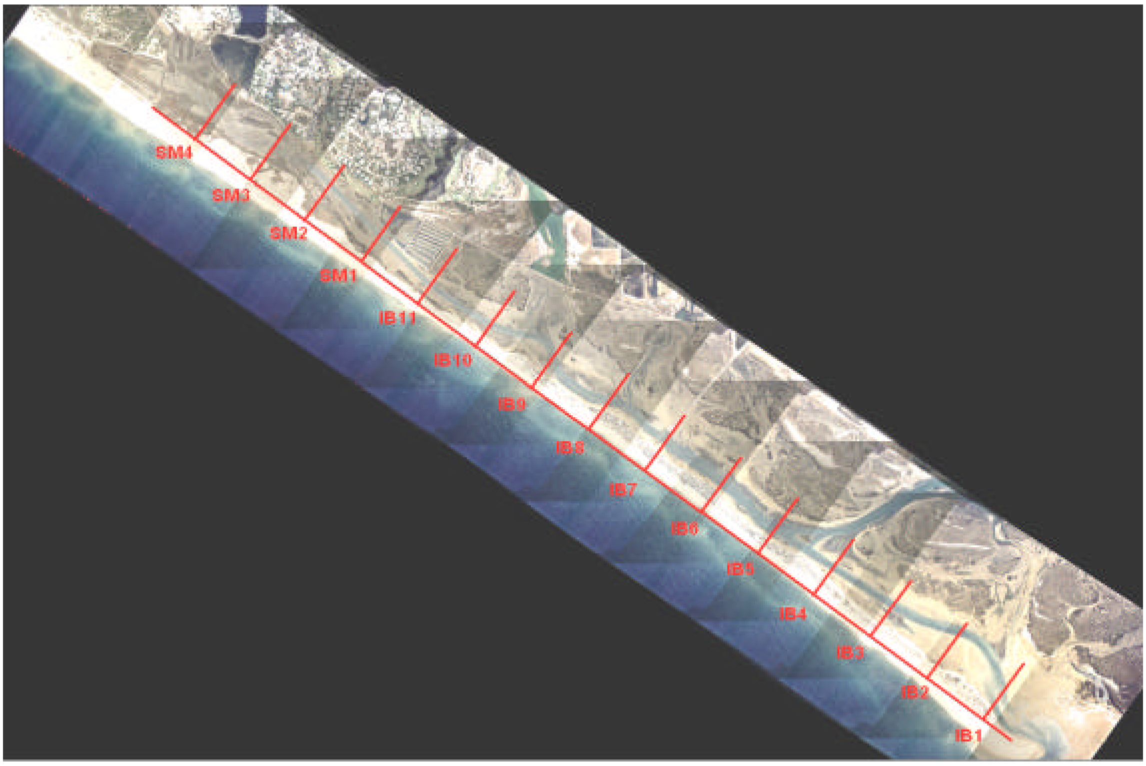

Figure 4. Distribution of the CS transects along the Ancão P. (photomosaic from 2001).

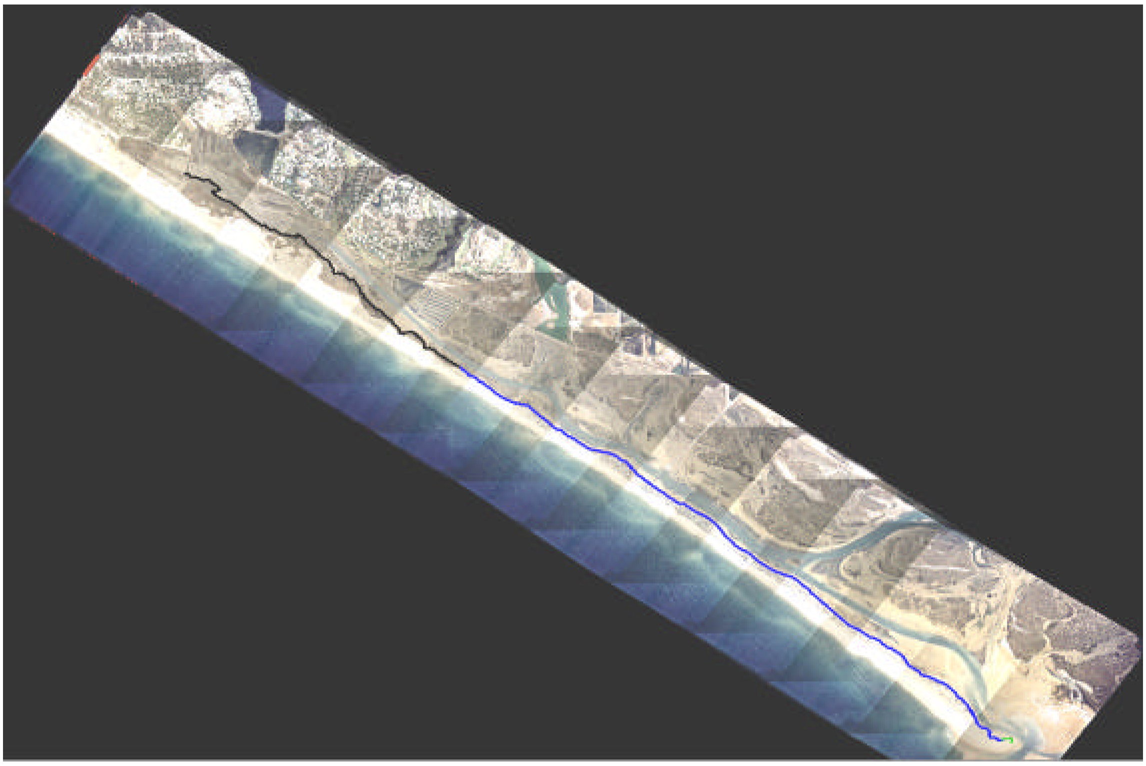

Figure 5. Backbarrier coastline mapping along the Ancão P. (photomosaic from 2001).

Backbarrier areas located at places where dredge dispose operations occurred between 1996 and 2001 (Fuzeta Inlet and Cacela P.), shown particular CS increases of about 4.6 and 3.3 m/yr, respectively (Table AII-3, Appendix II).

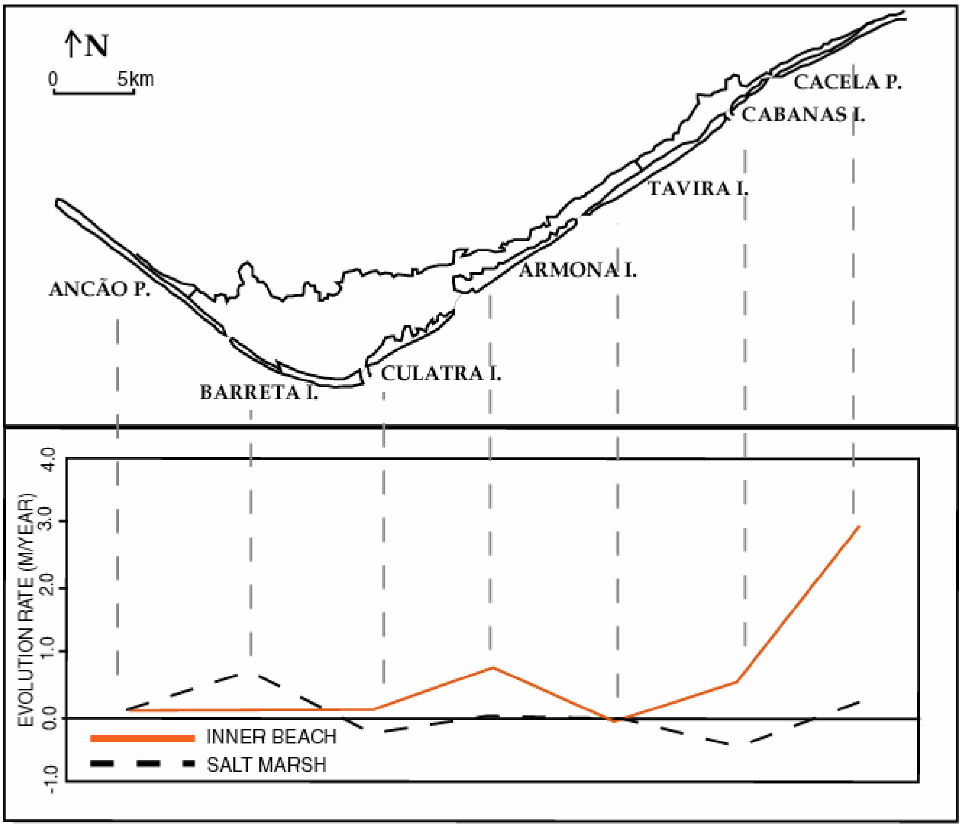

Figure 6. Cross-shore evolution of the backbarrier coastline between 1947 and 2001. The average rate presented is determined for the total period of analysis considered in each island/peninsula. Positive values represent landward displacement, and negative values represent shoreward displacement.

Relative LS changes determined for the entire system and for each morphological unit are presented on Table 4. Even admitting individual accretion at some islands, total LS results suggests a negative trend, representing a generic retreat of the system backbarrier coastline (of about -5124 m). Only at Barreta and Culatra islands was observed important LS increases with values close to 50% of accretion. In general, SM evolution comprises the changes of higher magnitude followed by IB and IBI coastlines.

Considering the global behaviour, four islands are representative of higher magnitude variations: Barreta I., Culatra I., Tavira I. and Cacela P. The eastern sector is the one representative of major alterations; changes on the extreme of the system, Ancão and Cacela peninsulas act in the same direction, retreat.

Table 4. Longshore variations for the three main morphologies evaluated (m). Negative values represent coastline retreat, and positive values represent coastline accretion.

Morphologies	**Ancão P.**		**Barreta I.**		**Culatra I.**	
(m)	**1947-1976**	**1976-2001**	**1947-1976**	**1976-2001**	**1947-1972**	**1972-2001**
Inner beach	-744	-1876	2009	1591	4219	-3000
Salt marsh	212	480	1608	179	1363	545
Inner beach next to inlet	-109	13	*[1]	*[2]	429	-525
Total	-641	-1383	3783	1770	6010	-2980
	Armona I.		**Tavira I.**		**Cabanas I.**	
	1969-1989	**1989-2001**	**1947-1976**	**1976-2001**	**1989-1996**	**1996-2001**
Inner beach	2581	-2921	-1539	206	-1211	-43
Salt marsh	1152	-1509	-8096	-955	1261	1174
Inner beach next to inlet	-179*[3]	130*[3]	-125	-4	65	-6
Total	3554	-4300	-9625	-753	393	1126
	Cacela P.		**Total (1947-2001)**			
	1976-1989	**1989-2001**				
Inner beach	-492	-389	-833			
Salt marsh	-101	-1395	-4081			
Inner beach next to inlet	-7	106	-210			
Total	-600	-900	-5124			

*[1] Aerial photograph from 1947 does not cover the inlet area
*[2] IBI does not corresponds to the definition performed on Table 1, Section 2.1
*[3] Relative to the total IBI coastline of Armona and Fuzeta inlets

Table 5 compares the major obtained CS and LS trends between 1947 and 2001. According with the results integration, two periods representative of erosion and accretion trends are defined: for erosion or smaller accretional rate was identified the period between 1976 and 2001; and, for accretion was identified the period between 1947 and 1976 (with exception to Tavira I. and Cacela P.), and in some islands like Cabanas I., the period between 1989 and 2001.

In general, accretion (CS and LS) is more dominant at the central part of Ria Formosa system, while at the extremes of the system LS retreat takes special importance in the IB coastline.

Table 5. Summary of the main cross-shore and longshore trends observed between 1947 and 2001.

Island/Peninsula	Observed Trends (1947-2001)	
	IB	SM
Ancão P.	CS development of the inner beach	LS development of salt marsh areas
Barreta I.	CS+LS development of inner beach	CS+LS development of salt marsh areas (longshore and cross-shore)
Culatra I.	CS+LS development of the inner beach	CS+LS development of salt marsh areas
Armona I.	CS+LS development of the inner beach	CS+LS development of salt marsh areas
Tavira I.	Global erosion of the inner beach	CS+LS development of salt marsh areas
Cabanas I.	CS development of the inner beach	LS development of salt marsh areas
Cacela P.	CS development of the inner beach	CS+LS development of salt marsh areas

Individual behaviour allows the identification of 3 groups of evolution.

- **Group A:** Barreta and Armona islands with accretion at backbarrier;
- **Group B:** Ancão P., Culatra I., Cabanas I. and Cacela P., with CS accretion of inner beach; Culatra I. presents CS and LS development of salt marsh, while the rest of them present CS accretion of salt marsh areas; and
- **Group C:** Tavira I., with global erosion in the inner beach, but CS and LS accretion of salt marsh areas.

The occurrence of complete overwashed areas in Ria Formosa from 1947 to 2001 was also quantified in order to measure its importance to the backbarrier coastline evolution. Figure 7 presents the total number of complete overwashes and the percentage of backbarrier coastline interrupted between 1947 and 2001. Identification and distribution of these overwashes at the system are considered on Table AII-4, Appendix II. The sets of 1969, 1972, 1985, and 1989 represent the additional years used just to notice the maintenance of the previous identified overwashes.

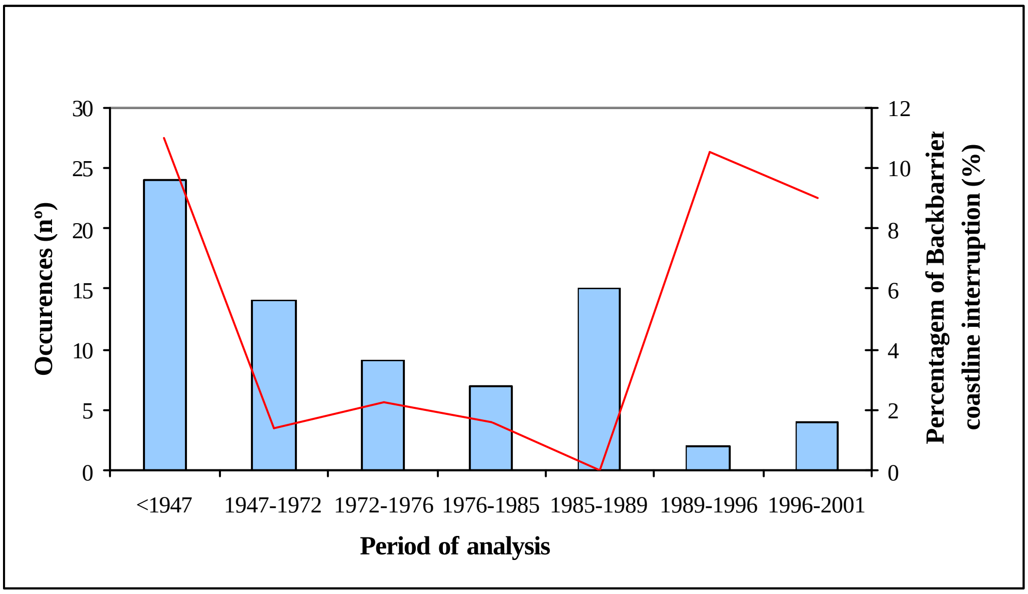

Figure 7. Occurrence of complete overwash at Ria Formosa between 1947 and 2001. The number of occurrences is represented by the columns and percentage of backbarrier interruption by the line.

Results illustrate the occurrence of 68 complete overwashes between 1947 and 2001. These overwashes represented an interruption higher than 4003 m of the total backbarrier coastline of the Ria Formosa system, being 3616 m in the west flank, and 388 m in the east flank. Two main periods of overwash occurrence were identified: before 1947, with 25 occurrences, and between 1985 and 1989, with 15 occurrences. Cabanas I. had the higher frequency, 26 complete overwashes, with major occurrences between 1985 and 1989. The percentage of interrupted backbarrier coastline is more significant between 1989 and 2001, even considering a lower number of complete overwash occurrences.

Aerial photograph adequateness only allowed determining CS variations at washover areas located at Ancão P. between 1947 and 1976, at Barreta I. between 1947 and 1976, and at Cacela P. between 1976 and 1989. In such areas, CS results had shown a landward displacement of 1m/yr and 2 m/yr at Ancão P. and Cacela P., while the western sector at Barreta I. backbarrier coastline shown a shoreward displacement of 4 m/yr.

Even representing a small fraction, it should be notice that some of the registered overwashes could be related with the human occupation, which is the particular case of the central part of Ancão P. and Fuseta village located at Armona I.

4.2.3. Backbarrier Development: Indexes Application

Backbarrier development indexes were applied to Ria Formosa system for the period between 1947 and 2001 (Figure 8 and 9). On Table AII-5, Appendix II is presented the obtained values for each index.

With exception of the extremes of the system (Ancão and Cacela peninsulas) and Tavira I. it is common to observe a positive variation of BC, even considering the dominance of L retreat in more than a half of the evaluated islands/peninsulas. Global distribution of ?SMC:TIBC distribution suggests the presence of a high level of backbarrier maturation in the most part of the system. A status of well maturated and progradating backbarrier (increase of BC, L and ?SMC:TIBC) is accomplished by Culatra, Armona and Cabanas islands, while a retrogradational backbarrier behaviour was only observed at the eastern extreme of the system, Cacela P.; higher levels of maturation are mostly significant at Ancão P. and Cabanas I.

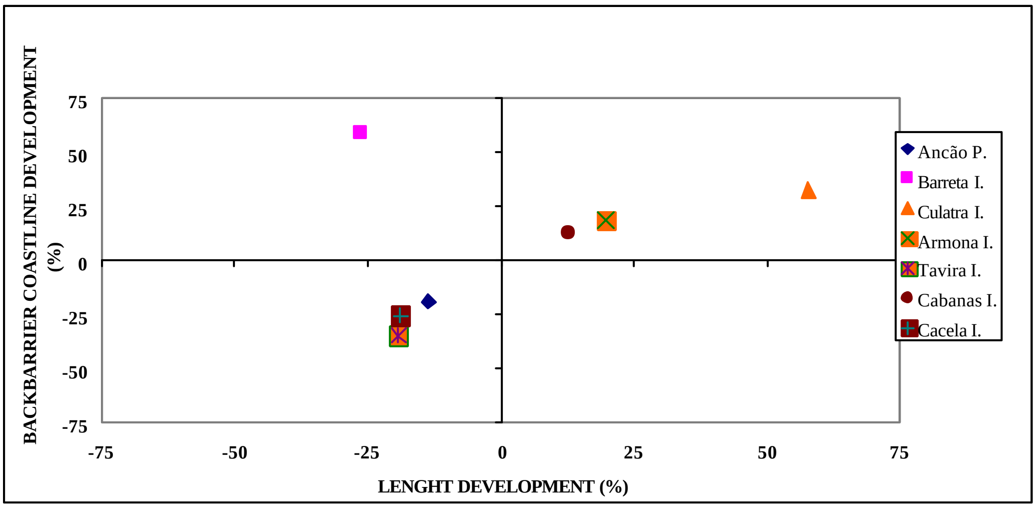

Figure 8. Classification of the backbarrier evolution considering the obtained variations for the backbarrier coastline and coastal length, between 1947 and 2001.

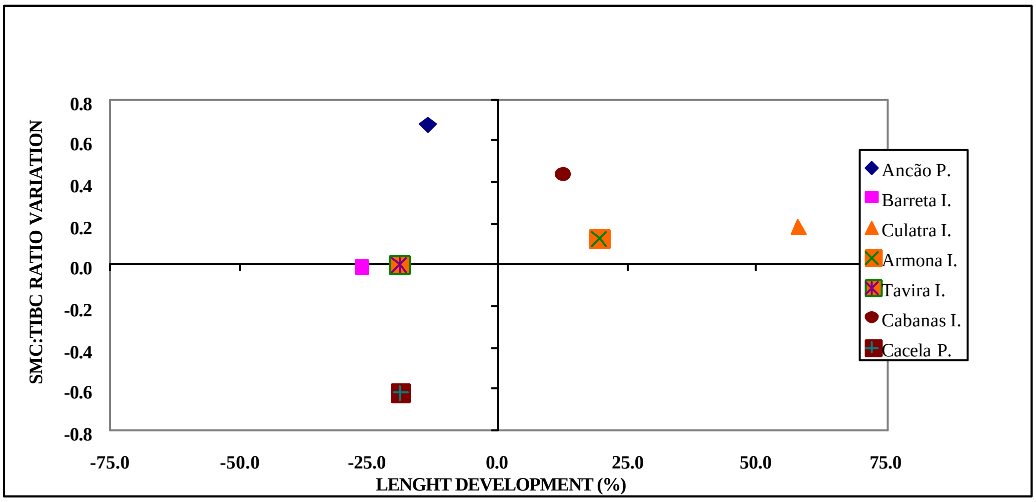

Figure 9. Classification of the backbarrier maturation level considering the obtained variations for SMC:TIBC ratio and coastal length, between 1947 and 2001.

In particular, at Barreta I., the assumed L retreat occurs in opposition to a significant BC accretion, suggesting the existence of an intermediate development stage traduced by a ramified backbarrier coastline that, however, does not exhibit variation at SMC:TIBC ratio. In this case, BC progradation is only related landward displacement of inner sandy beach (TIBC).

Opposite situation, rectilinear backbarrier, could be only achieved when is observed accretion at the coastal length but with negative variations of the backbarrier coastline. This status was not obtained for the study system.

5. Discussion

5.1. Indexes application and accuracy

Application of backbarrier development indexes allowed classifying the system as a well maturated backbarrier. In general, the central part of the system accomplishes a progradational backbarrier behaviour (positive variations of BC and L), in contrast with a retrograding behaviour at the western extreme of the system, Cacela P. (Table AII-5, Appendix II). Even admitting the generic presence of a quite developed backbarrier, it seems to be common the occurrence of L retreat between 1947 and 2001. System evolution is thus dominated by a frequent salt marsh progradation into the lagoon, but with loss of the total coastal length.

Besides the progradational and retrograding behaviours, it is also possible to observe an intermediate status of development at Barreta I., ramified backbarrier coastline (the backbarrier includes a positive variation of BC, but with retreat of L).

Indexes application reveals to be a good approach in the classification of Ria Formosa backbarrier development between 1947 and 2001, that should not be dissociate from the inherent system's evolution. Therefore, indexes relationships are not linear in what concerns to the expected behaviour, being only object of future evolutionary predictions when integrating all the main forcing mechanisms acting at the system. The geographic location and the interaction with the adjacent littoral processes are assumed to explain the rework of the backbarrier of each island/peninsula, and the respective obtained indexes; differences between the indexes are likely of being related with differences in the hydrodynamic controls.

A conceptual scheme of backbarrier development classification is purposed in order to integrate and summarize the different status of evolution/maturation (Figure 10). Indexes range classification is also purpose based on indexes determined for Ria Formosa backbarrier system (Table 6).

The benefits of the presented scheme are that it enables simple discrimination of four main expected classes of development/maturation of backbarrier environments for a given period of analysis. In what concerns to indexes application, issues of uncertainly remain and must be address to the indexes application:

i) data-resolution and accuracy. This includes the aerial photographs availability and resolution, and factors such as inaccuracies in the georectification process, caused by the number/distribution of the existent ground control points;

ii) the definition of parameters values, such as the backbarrier limits dependent on local conditions;

iii) the validity of the purposed indexes, as they are highly generalised approximations and representations of real situations.

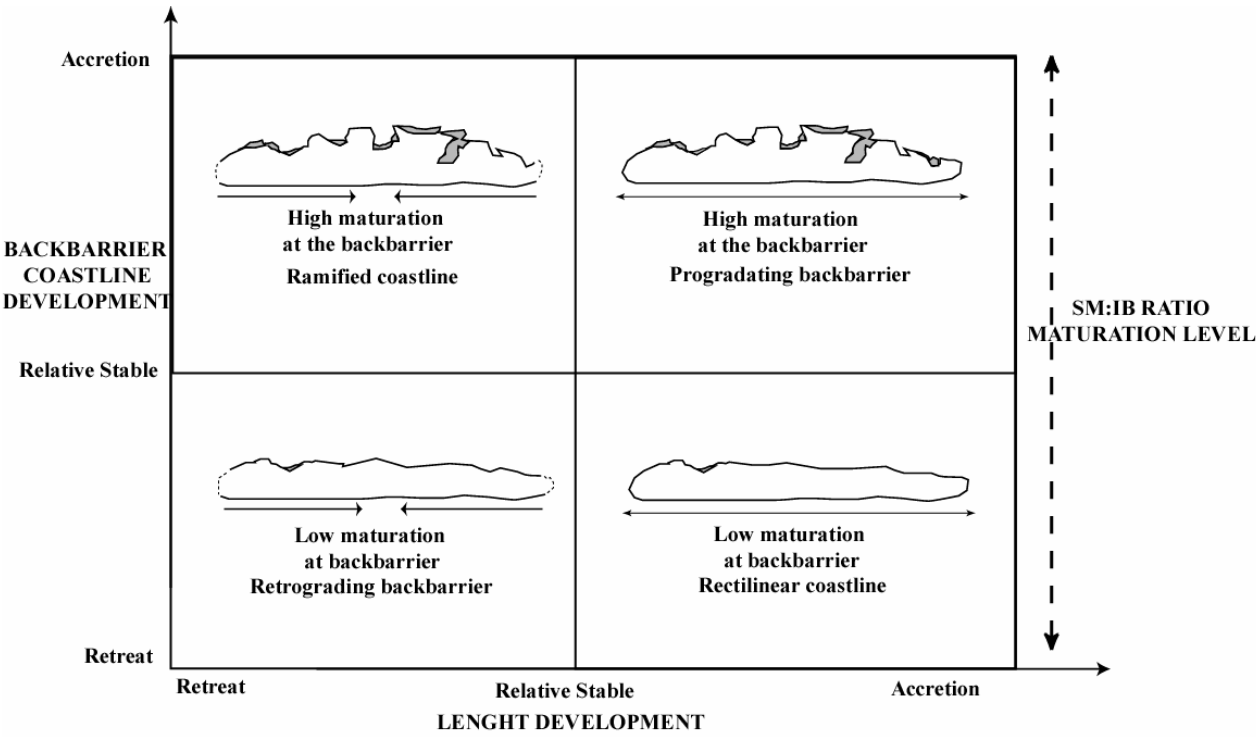

Figure 10. Conceptual Scheme defining the different status of backbarrier development taking into account backbarrier coastline evolution, length variations and SM:IB ratio variations.

Accuracy of the analyses such as the undertaken is required to be making suitable for application, being enhance through study of additional parameters of development. Additional factors constraining sediment supply in the complexity of the system are likely to be significant (*e.g*. hydrodynamic controls). It is almost certain that each type of restricted fetch environment will have different process signature and morphodynamic behaviour.

Table 6. Limits and respective scenarios of backbarrier development, defined by backbarrier coastline evolution, length evolution and variations at SM:IB ratio.

Backbarrier coastline Evolution (%)	Length Evolution (%)	? SM:IB ratio
< -50 % (very high retreat)	< -50 % (very high retreat)	? SM/IB<0 (not maturated)
-50% to -10% (retreat)	-50% to -10% (retreat)	? SM/IB=0 (relative stable)
-10% to 10% (relative stable)	-10% to 10% (relative stable)	? SM/IB>0 (well maturated)
10% to 50% (accretion)	10% to 50% (accretion)	
> 50% (very high accretion)	> 50% (very high accretion)	

5.2. General Evolution

The obtained rates of landward/shoreward displacement along the backbarrier are extremely variable and critically dependent upon geographic location and the interaction with oceanic processes. Results suggest the existence of a general backbarrier landward displacement (CS) in most of the islands/peninsulas. Accretion (CS and LS) is more dominant in the central part of Ria Formosa (Group A and B) system, while at the extremes of the system LS retreat takes special importance in the BC (Group C). Even admitting some individual BC accretion, it is observed a negative trend of BC and L evolution, suggesting a generic retreat of the system extend.

Distinct trends are associated with the distinct periods of analysis: for erosion or smaller accretional rate was identified the period between 1976 and 2001; and, for accretion was identified the period between 1947 and 1976. To these same periods are associated the occurrence of different physiographic and hydrodynamic alterations at the Ria Formosa barrier system, mainly related with changes at the tidal inlets pattern (previously focused on Section 4.1). Induced changes at the sediment transport pattern, in result of inlets displacement and/or relocation, are likely of being responsible for the observed results at the backbarrier coastline (especially in what concerns to IBI coastline extend); different stages/rates of inlets displacement (position/width) seems to determine different rates of accretion/recession, and consequently different levels of development/maturation at the backbarrier (indexes determination) (Esaguy, 1984, 1985, 1986; Andrade 1990; Vila-Concejo et al., 1999, 2002, 2003, 2004; Salles, 2001). For instance, the relocation of Ancão Inlet at the western position in 1997 was responsible for reduction of L and BC in Ancão P., with consequent increase of BC at Barreta I. between 1996 and 2001 (Table 4, Section 4.2.2) (Vila-Concejo et al., 1999, 2002, 2003, 2004). Even admitting a ramified backbarrier coastline, Barreta I. have been subject to permanent L alterations, and thus consequent hydrodynamic changes, turning difficult the achievement of higher levels of backbarrier maturation (SM development).

Similarly, the decreasing of Tavira I. IB and IBI coastlines between 1947 and 1976 are also associated with the relocation of another inlet: Fuzeta Inlet (Esaguy, 1985; Vila-Concejo et al., 2002, 2004). This inlet had verified significant width increments between 1962 and 1969 (of about 550 m/yr), causing the destruction of the western part of island (significant decrease of IBC observed in the period 1947-1976) (Vila-Concejo et al., 2002). Nevertheless, the induced alterations between 1947 and 2001 did not interfere with salt marsh and inner sandy beach proportion leading to a negligible SMC:TIBC variation (same level of maturation).

Alterations at Cacela P. BC were caused, not only by the landward displacement of the peninsula, but also by changes at Lacém Inlet position (Dias et al., 1999; Matias, 2000; Vila-Concejo, 1999, 2003). According with Vila-Concejo et al. (2002), the eastward migration rate of this inlet had an average value of 97 m/yr, showing several decreases of the inlet width between 1976 and 1996, and consequent accretion of Cacela P. IBC (Section 4.1). After 1996 the relative landward displacement is only related with the dredge disposal operations took at the peninsula (Table AII-3, Appendix II). However, these increments of IBC were not significant, since that the global BC retreat (especially of SMC) resulted in a retrograding behaviour of the backbarrier peninsula's (Table AII-5, Appendix II).

Besides the mentioned inlets relocation, the stabilisation of the Faro-Olhão Inlet had also lead to the most important changes to the system. The major effect was the drastic reduction of the downdrift sediment budget, making barriers more vulnerable to erosion and decreasing the sediment supply to the eastern inlets (Salles, 2001). Particular CS erosion took place at the East flank of Barreta I. (Table AII-2, Appendix II), while Culatra I. had shown a natural eastward elongation within significant increase of BC, especially between 1947 and 1972 (Table 5, Section 4.2.2) (Andrade, 1990; Garcia et al., 2002). In result of abundant sediment conditions, a landward displacement of SMC was observed at Culatra I., indicating a progradational behaviour and consequent increase of the maturation level (Godfrey and Godfrey, 1974 in Leatherman, 1979; Frey and Basan 1985; French, 1993; Pethick, 1998).

Whether overwash plays a significant role in a backbarrier evolution depends on numerous factors such as elevation of island, presence of vegetation, sediment supply to the beach, and frequency and strength of storms (Morton and Sallenger, 2003 *in* Donnelly et al., 2004). The complete overwashes observed at Ria Formosa between 1947 and 2001 had major expression at the western flank of the system, due to differences in exposure to wave action and morphological characteristics (Andrade, 2004). In general, washover areas are representative of higher vulnerability, related with a narrow barrier with gentle slopes, a fragile dune field, and/or next to inlets location, like is the case of Ancão P., Barreta I. and Cacela P. (Table AII-4, Appendix II) (Andrade et al., 1998).

Even admitting the CS retreat observed at the Barreta I. backbarrier, it seems to exist some relation with overwash occurrence and progradation of backbarrier. Barreta I. landward displacement is only justified by the Ancão Inlet migration (Andrade, 1990; Vila-Concejo, 1999, 2002, 2003), where overwash events plays a secondary role (Section 4.2.2). The period where the higher number of overwash events was identified (1947-1976) was also coincident with the period of predominant landward displacement at the Ria Formosa (Section 4.2.2). Overwash occurrence brought landward displacement of the BC (CS positive variations), facilitating the achievement of higher levels of maturation. They can be considered a sink in the littoral system, where the resulting washover is a source to the barrier island sediment budget contributing to the vertical accretion of the backside (Leatherman, 1981; P. S. Roy et al., 1994). Such assumption has been cited before by several authors as a primary mechanism of landward barrier migration (Fisher et al., 1974; Leatherman, 1976; Dingler and Reiss; 1990; Eiser and Birkemeier, 1991 *in* Donnelly et al. 2004; Bray and Carter, 1992; Bartholdy et al., 2004). Although, it should be noticed that the formation of the flood-tidal deltas, often associated with breaching, can also contribute to the island's migration (Leatherman 1979; Andrade, 2004), which can be the particular case of Cacela P.

Migration of a barrier is one of the major influences in lagoon evolution, by reducing the size of the tidal prism and generating a series of changes in inlets pattern (Cooper, 1994). In a cyclic way, such alterations are likely to affect the hydrodynamics pattern of the system, and consequently the backbarrier evolution.

Besides the natural forcing mechanisms identified at the system (complete overwash events), the displacement/relocation of natural inlets, are the main factors controlling the backbarrier evolution/maturation (Figure 11); the determined influence of dredge disposal operations to this system is not enough representative to evaluate its importance in the backbarrier rework.

High levels of development are thus associated with particular stable hydrodynamic conditions and/or increase of sediment availability at the lagoon, while low maturation levels are especially related with inlets relocation/displacement.

BACKBARRIER DEVELOPMENT CLASSIFICATION		ASSOCIATED FORCING MECHANISMS
High maturation at the backbarrier Ramified coastline	ΔBC>10% ΔL<-10% ΔSMC:IBC> 0	Cross-shore and longshore development of the backbarrier Alteration of the hydrodynamic conditions at the lagoon
High maturation at the backbarrier Progradating backbarrier	ΔBC>10% ΔL>10% ΔSMC:IBC> 0	Complete overwash occurence Anthropogenic interventions (dredge disposal operations)
Low maturation at the backbarrier Retrograding backbarrier	ΔBC<-10% ΔL<-10% ΔSMC:IBC< 0	Inlets relocation/displacement Cross-shore and longshore retreat of the backbarrier
Low maturation at the backbarrier Rectilinear coastline	ΔBC<-10% ΔL>10% ΔSMC:IBC< 0	Infilling of secundary channels/embaymentas at the backbarrier Inlets relocation/displacement

Figure 11. Integration of the purposed backbarrier development classification and the main factors controlling the Ria Formosa backbarrier system.

Even not being part of the main objective of the present study, additional factors like sediment exchange between beach, backshore and dunes are admit to be other important source of sediment to the lagoon, and consequent induced alterations to the backbarrier development (Jackson, 1999; Short, 1999).

6. Conclusions

Shorelines along the backside barrier of overwash-dominated islands are extremely different from mainland shorelines. These low and narrow islands are periodically dominated by oceanic processes resulting in major sediment input in response to overwash events, inlet dynamics, and migrating dune sands (Short, 1999).

There are only a few studies evaluating restricted fetch environments, especially in what concerns to backbarrier environments. Main objectives of the present study were related with the adequateness of Backbarrier Development Indexes (evolution and maturation), and its application to the recent evolution of a Ria Formosa backbarrier coastline, between 1947 and 2001. Different status of evolution are obtain by relating the backbarrier coastline and the coastal length variations, while the level of maturation is concern with the temporal distribution of the salt marsh coastline *vs* inner sandy beach in relation to the obtained coastal length variation.

Results obtained for the Ria Formosa backbarrier coastline system suggests two periods representative of accretion and erosion trends of backbarrier: for accretion was identified the period between 1947 and 1976, and for erosion or smaller accretional rate was identified the period between 1976 and 2001. Application of the purposed indexes allowed classifying it as a well maturated backbarrier between 1947 and 2001. The central part of the system accomplishes a progradating backbarrier (positive variations of backbarrier coastline and coastal length, and a high level of maturation), in contrast with a retrograding behaviour at the eastern extreme. Indexes application reveals to be a good approach in the classification of backbarrier development between 1947 and 2001.

Besides the natural forcing mechanisms identified at the system (complete overwash events), changes at the inlets position are the main factors controlling the backbarrier development. Changes at the sediment transport pattern, in result of inlets displacement/relocation, are likely to being responsible for the observed results at the backbarrier coastline; different stages/rates of inlets displacement (position/width) seems to determine different rates of accretion/recession, and consequent different levels of development/maturation at the backbarrier (indexes determination).

It is suggesting the existence of a relationship between complete overwash occurrences and progradation of backbarrier, possible associated to local landward migration. Lagoon alterations in result of migration are likely to affect the hydrodynamics pattern of the system, and consequently affect the backbarrier evolution.

Prediction of future changes requires a detailed understanding of the hydrodynamic controls responsible for alteration on restricted fetch areas, like is the Ria Formosa backbarrier.

Accuracy of the purposed indexes classification required to be enhancing through study of additional parameters of development like wave climate, tidal range, sediment supply and sediment transport and adequateness to any individual morphodynamic behaviour.

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APPENDICES

APPENDIX I - INSTRUCTION FOR AUTHORS

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Gooday, A.J., Bett, B.J., Shires, R., Lambshead, P.J.D., 1998. Deep-sea benthic foraminiferal species diversity in the NE Atlantic and NW Arabian sea: a synthesis. Deep Sea Research Part II 45, 165-201.

References to a book:

Names and initials of all authors, year. Title of the book. Publisher, location of publisher, total number of pages.

Fennel, W. and Neumann, T., 2004. Introduction to the Modelling of Marine Ecosystems. Elsevier, Amsterdam, 297 pp.

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Names and initials of all authors, year. Title of paper. Names and initials of the volume editors, title of the edited volume. Publisher, location of publisher, first and last page numbers of the paper.

Thomas, E., 1992. Middle Eocene-late Oligocene bathyal benthic foraminifera (Weddell Sea): faunal changes and implications for ocean circulation. In: Prothero, D.R., Berggren, W.A. (Eds.), Eocene Oligo-cene Climatic and Biotic Evolution. Princeton Univ. Press, Princeton, NJ, pp. 245-271.

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Smith, F., Peabody, A.N., 1997. Hydrographic data for the Sargasso Sea, July-September 1993, SarSea mission. (Deep-Sea Data Centre, Hull, UK), online, dataset, 740 MB, http://www.dcdc.gov.

Green, A., 1991. Deformations in Acanthaster planci from the Coral Sea, observed during UEA Special Project 7, July 1978. Journal of Pollution Research 14 (7) suppl., CD-ROM, photographic images, 240 MB.

James, Z., 1997. Ecological effects of sea wall construction during 1994 at Bridlington, UK. List server Message, Eco-list, 20 October 1995.

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APPENDIX II

Table AII-1. Coverage and scale of the vertical aerial photos used for this study.

Year	Ancão P.	Barreta I.	Culatra I.	Armona I.	Tavira I.	Cabanas I.	Cacela P.	Scale (approximate)
1947	X	X	X	Photo not available	X		Photo not available	1/ 20 000
1969				X		1st appearance of island	Photo not available	1/ 25 000
1972			X			in development	Bad quality photo	1/ 7 000
1976	X	X			X	in development	X	1/25 000
1989				X		X	X	1/ 8 000
1996	X	X	X	X	X	X	X	1/ 8 000
2001	X	X	X	X	X	X	X	1/ 8 000

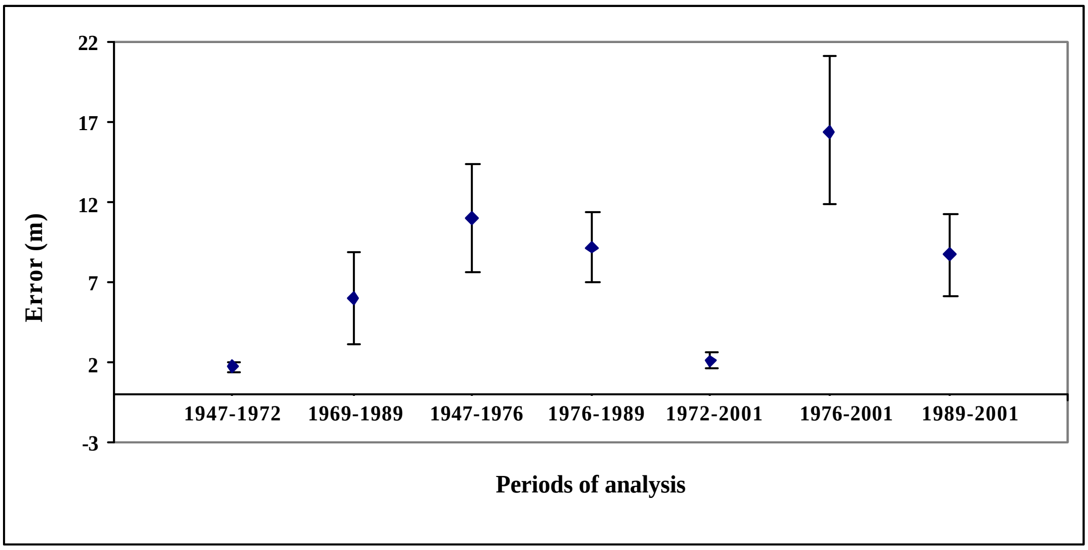

Figure AII.1. Maximum errors determined for the analysed periods and respective standard deviation

Table AII-2. Cross-shore evolution of the three main morphological units analyse (m/yr). Negative values represent coastline retreat, and positive values represent coastline accretion.

Morphologies	Ancão P.		Barreta I.		Culatra I.	
(m)	1947-1976	1976-2001	1947-1976	1976-2001	1947-1972	1972-2001
Inner beach	0.2	0.1	0.2	-1.0	0.2	0.0
Salt marsh	0.2	0.1	1.1	0.3	0.0	0.3
	Armona I.		Tavira I.			
	1969-1989	1947-1976	1947-1976	1976-2001		
Inner beach	1.1	0.9	0.5	-0.6		
Salt marsh	-0.3	1.3	0.0	0.1		
	Cabanas I.		Cacela P.			
	1989-1996	1996-2001	1976-1989	1976-2001		
Inner beach	1.0	1.2	0.9	5.0		
Salt marsh	1.7	0.1	0.6	0.3		

Table AII-3. Cross-shore evolution at the dredge disposal areas (m/yr) between 1996 and 2001. Positive values represent coastline accretion.

Island/Peninsula	Cross-shore variation (m/yr)
Armona I. (Fuseta Inlet)	3.3
Cacela P.	4.6

Table AII-4. Complete overwash occurrence at Ria Formosa barrier system between 1947 and 2001. Denomination of each overwash is related with the island/peninsula where occurred. Maintenance and reappearance of overwashes between different years is also presented.

Year	Ancão P.	Barreta I.	Culatra I.	Armona I.
1947	A1,A2,A3,A4	B1,B2,B3,B4		Ar1,Ar2,Ar3,Ar4,Ar5,Ar6,Ar7,Ar8
1969	A3,A4,A5,A6,A7	B1,B2,B3,B4		Ar9
1972	A4,A5,A6,A7,A8,A9,A10	B5,B6	Cu1, Cu2	
1976	A5,A6,A7,A8	B3,B5,B6	Cu1	Ar9, Ar10,Ar11,Ar12,Ar13
1985	A5,A6,A7,A8,A9,A10	B3,B5,B6		
1989		B3		
1996		B3,B7		
2001		B8,B9,B10,B11		

Year	Tavira I.	Cabanas I.	Cacela P.
1947			Ca1,Ca2,Ca3
1969		Cb1	Ca1,Ca2
1972		Cb1	
1976		Cb1,Cb2,Cb3,Cb4,Cb5	
1985		Cb6,Cb7,Cb8,Cb9,Cb10,Cb11,Cb12,Cb13	
1989		Cb7,Cb8,Cb9,Cb10,Cb11,Cb12,Cb13,Cb14,Cb15,Cb16,Cb17, Cb18,Cb20,Cb22	Ca1,Ca4,Ca5
1996		Cb23	
2001			

Table AII-5. Backbarrier development indexes determined for the Ria Formosa between 1947 and 2001.

Island/Peninsula	? BC (%)	? L (%)	? SMC:TIBC
Ancão P.	-18,8	-13,5	0.7
Barreta I.	58,3	-26,3	0.0
Culatra I.	32,1	57,9	0.2
Armona I.	18,3	19,6	0.1
Tavira I.	-34,8	-19,1	0.0
Cabanas I.	12,6	12,8	0.4
Cacela P.	-25,7	-18,8	-0.6

FIGURE CAPTIONS

Figure 1. Schematic representation of the main morphologies present at the backbarrier.

Figure 2. Example of a complete overwash occurrence.

Figure 3. Study area.

Figure 4. Distribution of the CS transects along the Ancão P. (photomosaic from 2001).

Figure 5. Backbarrier coastline mapping along the Ancão P. (photomosaic from 2001).

Figure 6. Cross-shore evolution of the backbarrier coastline between 1947 and 2001. The average rate presented is determined for the total period of analysis considered in each island/peninsula. Positive values represent landward displacement, and negative values represent shoreward displacement.

Figure 7. Occurrence of complete overwash at Ria Formosa between 1947 and 2001. The number of occurrences is represented by the columns and percentage of backbarrier interruption by the line.

Figure 8. Classification of the backbarrier evolution considering the obtained variations for the backbarrier coastline and coastal length, between 1947 and 2001.

Figure 9. Classification of the backbarrier maturation level considering the obtained variations for SMC:TIBC ratio and coastal length, between 1947 and 2001.

Figure 10. Conceptual Scheme defining the different status of backbarrier development taking into account backbarrier coastline evolution, length variations and SM:IB ratio variations.

Figure 11. Integration of the purposed backbarrier development classification and the main factors controlling the Ria Formosa backbarrier system.