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Algarve Barrier Islands: A Noncoastal-Plain System in Portugal

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ABSTRACT

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The small barrier island system of the Algarve (South Portugal) exhibits several unique characteristics that differ from more widely studied systems. The islands exist on a noncoastal-plain coast as a result of a platform on the inner shelf which acted as a cape during the sea level rise. Initial spits became islands as the platform was transgressed, and the islands are transgressive in appearance, although west-to-east lateral processes (inlet migration, spit growth) dominate. The islands exist under moderate to high wave energy and mesotidal conditions. Flood-tidal deltas are dominant and inlet migration is rapid. Aeolian and overwash processes are important to vertical growth of the islands. The largest islands have widened as a result of flood-tidal delta incorporation. After incorporation, aeolian processes modify the delta surface into a dune field before stabilization by vegetation.

Backbarrier dissection by spring tide (4 m.) flooding works in opposition to the constructional effects of delta incorporation, overwash and dune formation. An extensive network of erosional channels has developed on backbarriers as a result of erosion by the ebbing flood. Channel location is controlled by antecedent morphology such as incorporated delta channels, interdune areas, and troughs between incorporated recurved spits. Once established, the channels incise, erode laterally and extend into the island, sometimes joining with overwash passes, and forming important conduits of sediment transport to the lagoon/marsh. The lagoonward sediment transport is partially offset by floating sand and shells carried toward the island interior on the incoming flood tide. Spring tide flooding also results in vegetation kills and groundwater contamination.

Additional Index Words: *Barrier islands, Portugal, flood-tidal deltas, backbarrier erosion, transgressive, mesotidal, spits, floating sand.*

INTRODUCTION

The barrier-island system of the Algarve state, South Portugal (Figure 1), is a group of five barrier islands and two peninsulas extending for a little over 50 km from Ancao to Cacela, located west of the Guadiana River border with Spain. The islands are exceptional in both their physiographic setting, and in the particular combination of environmental parameters responsible for their origin and evolution. Atypical characteristics include: (1) location adjacent to a cliffed coast of moderate relief, rather than the more common "*coastal-plain*" coast occurrence, (2) their occurrence at the upper tidal range limit (3.88 m spring tidal amplitude) for the existence of barrier islands (HAYES, 1979), [and yet by measures of tide versus wave domination, they are wave dominated (DAVIS and HAYES, 1984)], and (3) lagoon sides of the islands are being modified significantly by the erosive effects of spring tides which flood large portions of the islands. As a result, the Algarve barrier-island system provides a model in which the islands exist in equilibrium between island-degrading spring tides and the various processes of island construction.

Earlier studies focused on various aspects of the islands (*e.g.*, GODARD, 1967; GUILLEMOT, 1979; and WEINHOLTZ, 1964), but there

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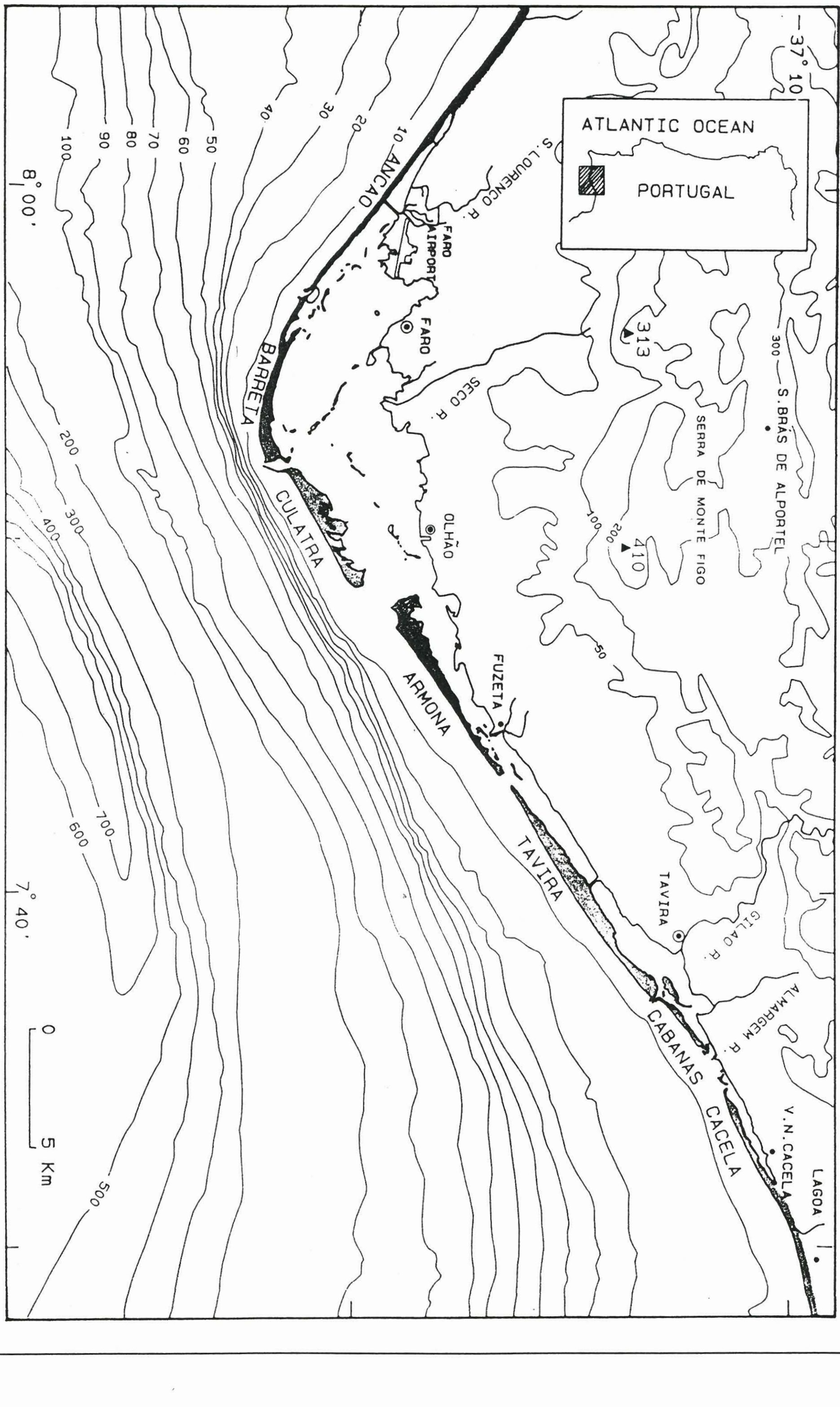
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were no integrated studies of the entire system. Recent interest, however, has been sparked by concern for port facilities, fisheries resources, and development potential of the islands (*e.g.*, BETTENCOURT, 1985; DIAS, 1984; ESAGUY, 1984, 1985; GRANJA, 1984; GRANJA, *et al.*, 1984; JNICT/INSTITUT FRANCO-PORTUGAIS 1985; MONTEIRO, *et al.*, 1984; UNIVERSIDADE DO ALGARVE, 1986). This study is part of an ongoing cooperative project between the Geological Survey of Portugal and the Duke University Program for the Study of Developed Shorelines. Results are based on interpretation of over 10 sets of air photos covering the period from 1949–1984; three sets of air photos taken in September, 1984 during a perigean spring tide (verticals of maximum high and low tides, and oblique photos of the islands) and coincident with a field visit; historic chart summaries; and environmental mapping conducted in 1984–1987, including landforms, sediment types and character, vegetation, and sampling for sediment texture/structure and faunal analysis (*e.g.*, trenches, peels, cores).

OCEANOGRAPHIC FRAMEWORK

Tidal amplitude in the area is 2 m for normal tides and near 4 m for spring tides. Wave energy is high according to the classification of DAVIS and HAYES (1984). Fairweather wave amplitude is typically < 1 m, and storm wave magnitude is 2–4 m. Longshore current direction is dominantly west to east, a response to refracted waves generated over the large fetch of the open Atlantic to the east. Virtually all inlet migration is easterly, and laterally accreting features such as recurved spits clearly have resulted from west to east accretion (Figure 2).

ORIGIN OF THE ISLANDS

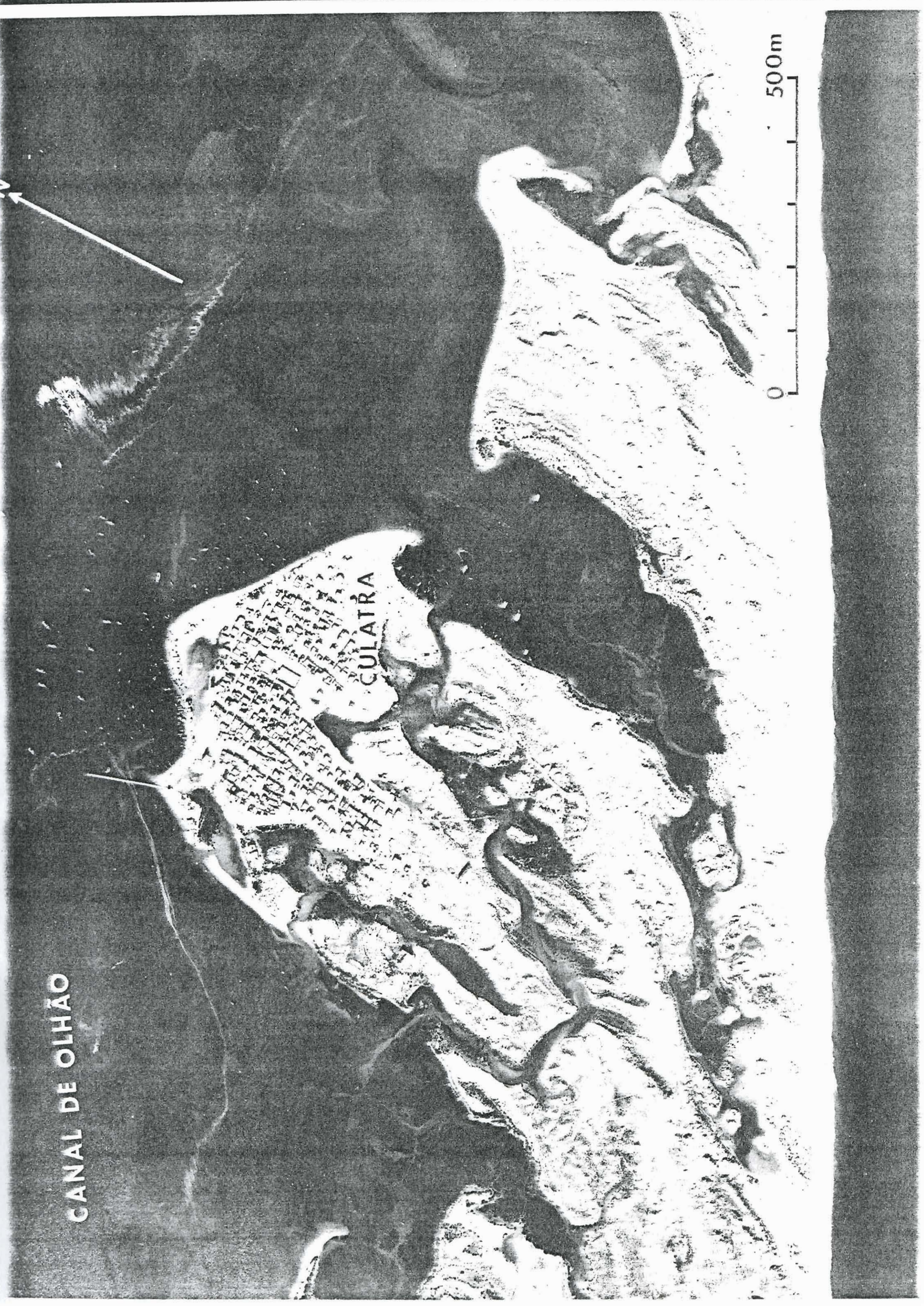
Normally barrier island chains are located at the margins of coastal-plain coasts. In fact, inundation of coastal plains is the 'raison de être' for barrier islands in that the tendency for spit progradation into estuaries or former valleys, from headlands or former ridges, is the common mode of island formation (SWIFT, 1975, 1976). The barrier islands of South Portugal are not found adjacent to a coastal plain, and in fact the mainland shoreline here is most often a Pliocene-Pleistocene shoreline cliff cut into Tertiary sediments. Behind the sea cliff the land slopes up to the Serra do Monte Figo (Figure 1) of the Caldeirâo Mountains of South Portugal.

We propose that the existence of this unusual chain of barrier islands is related to the presence of a shallow platform bounded by a relatively steep scarp or protuberance on the inner continental shelf (Figure 1). The hypothesized sequence of events leading to the formation of the present day chain of barriers is shown in Figure 3. As sea level rose beyond the base of the shelf scarp, the shoreline began to pivot on the escarpment. That is, shoreline retreat on the scarp was less than shoreline retreat in areas to the east and west. As the shelf escarpment became a shoreline cape, a spit began forming to the east. In effect, a baymouth barrier was built across a shoreline indentation in the west-to-east direction of dominant littoral transportation. When the sea level rose over the lip of the continental platform, shoreline retreat was suddenly quite rapid, causing the former spits to begin evolving as barrier islands. At some point in this scenario, a spit from the mainland to the west joined the barrier island chain resulting in the interrelated sediment system of the present barrier-island chain.

If the Algarve chain has migrated landward, it has probably been only across the short distance from the edge of the 10 m deep platform (Figure 1) on which the islands are presently situated. This distance is less than 1 km.

Putting it another way, the Algarve barrier islands probably originated as spits connected to a cape. These spits were detached when the shoreline retreat accelerated in response to the sea level rise over the lip of a platform. The former spits became true barrier islands existing in a dynamic equilibrium between wave and tidal energy, sand supply and sea level. Their existence is a geologically ephemeral one as mainland attachment is a certainty in a future rising sea level.

Figure 1. Index map of the Algarve barrier island system and bathymetry of the adjacent continental shelf (after SCE of Portugal, 1976 edition, 1/25,000). The island chain parallels the edge of a protuberance off the mainland on the inner continental shelf. Contoured depths and land contours are in meters. (Facing Page).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GENERAL ISLAND CHARACTERISTICS

The arcuate form of the island chain (Figure 1) results in variation in island orientation and exposure to a spectrum of wind, wave and current conditions (GRANJA, 1984). The result is a corresponding variety of dominant island processes, environments and morphology.

Following is a brief description of the individual islands and peninsulas making up the Algarve barrier chain.

Ancâo (Faro) Peninsula, extending from the mainland cliffed coast, forms the western extremity of the arc. This barrier is approximately 10 km in length (Table 1), but this dimension varies temporally with the shifting of Ancâo Inlet. The barrier spit is narrow, ranging from 250 m to less than 50 m in width, and it grew from west to east as the inlet migrated. The spine of the barrier is now a single pronounced high dune ridge (> 10 m), that occasionally is overwashed in severe storms. Where the dune has been destroyed in the central urbanized sector, overwash is more frequent. Erosion is affecting both the frontside and backside of the island; between 1945 and 1964 the peninsula narrowed by an average of 34 m (WEINHOLTZ, 1964).

Barreta Island also varies in length according to the position of the Ancâo Inlet. At present the island is 6.8 km in length (Table 1). Of this, the western most 2 km, once part of the Ancâo Peninsula (Figure 4), is narrow, low in elevation, mostly unvegetated and frequently overwashed. The remainder of the island is a complex of several environments including incorporated recurved spits, overwash terraces, beach-dune ridges, swale terraces, and possible incorporated tidal deltas. Faro-Olhâo Inlet at the east end of the island was stabilized by jetties in 1952 resulting in 220 m of updrift beach accretion in the form of low beach ridges by 1964 (Figure 5). An additional 80 m of accretion had occurred by 1980.

Culatra Island is dominantly formed by accreted recurved spits, now expressed as several interior curved dune ridges of 1–3 m in height (Figure 2, Table 1). Overwash and spring tide dissection also are important processes in the evolution of this island. A well-developed dune ridge fronts all of the island except where overwash passes have cut through to the heads of tidal channels or embayments between the incorporated recurved spits in the eastern half of the island.

Armona Island is the only island in the system to show the "drumstick" form (Figure 1). The western tip of the 8.7 km long island has accreted westward as a series of modified recurved spits and welded ebb-tidal swash bars from Armona Inlet (Figure 6). This is virtually the only example of westward accretion in the Algarve island chain. The western half of the island consists of a long continuous frontal dune (8–9 m) behind which are broad backbarrier areas of incorporated tidal deltas. The island's eastern half has formed since the 1930s by the rapid easterly migration of Fuzeta Inlet. Island morphology reflects this migration in the form of short arcuate, low (< 5 m), dune lines that formed on each successive recurved spit, marking old inlet positions. Behind this narrow eastern extension of the island is a complex of bars, small islands, and channelled sand flats that are presumed to be the remnants of former flood tidal deltas. The attachment and incorporation of these delta-related sand bodies into the island results from vertical accretion by overwash, tidal channel fill, and aeolian processes.

Tavira Island is 10.2 km long, and the largest of the barrier islands (Table 1). Historically, the island has been nearly three times its present length, including what is now Cabanas Island and the Cacela Peninsula, as well as eastern Armona Island. Tavira Island is fronted by a single, high (8–10 m), continuous dune ridge backed by a 100–200 m wide overwash apron or terrace. The bulk of the island's area, however, consists of a series of incorporated flood tidal deltas that extend from the overwash terrace well out into the salt marshes. These former deltas, as on Armona Island, are covered by randomly oriented dunes between which are areas flooded by the spring high tides. Flood tide channels between the dunes exhibit varying degrees of incisement.

Cabanas Island, the smallest, is extremely dynamic and its entire 4.8 km length has been affected by inlet migration within very recent times. This post-1961 island is low and completely overwashed in storms. Now in a rebuild-

Figure 2. Eastern Culatra Island at spring high tide (27 September 1984) showing west-to-east recurved spit growth and the pattern of backbarrier flooding (FAP flt. 101, frame 8090). (Facing Page).

Table 1. *Comparison of the dominant processes affecting the frontside and lagoonside of the Algarve barrier island system.*

	Frontside Processes			Lagoonside Processes		
Island	Total Length m.	Overwash %	Single Dune Ridge %	Overwash %	Recurved Spit Incorporation %	Tidal Delta Incorporation %
Ancao	10,000	6	94	100		
Barreta	6,850	48	52	67	33	
Culatra	5,750	65	35		100	
Armona	8,750	40	60		40	60
Tavira	10,250		100	15		85
Cabanas	4,500	100		100		
Cacela	4,400	100		100		

ing phase, it provides a model for the development of the frontal dune line and overwash terrace seen on the other barriers. On the backside, tidal delta sands are buried by lobate masses of overwash sand that merge laterally to form the ramp-like overwash terrace. Vegetation, although sparse, establishes itself quickly in the system, and *Amnophila arenaria* grass traps sand to form a continuous low fore dune. Unless the Cabanas Inlet at the eastern end reforms to the west, the processes of overwash and dune growth will maintain a low, narrow island, similar in form to the Cacela Peninsula.

Cacela Peninsula is similar to Cabanas Island, except it is higher (6 m dune ridge) and well-vegetated (*e.g, Retana monogyna*). Overwash is less frequent than on Cabanas, however, large storms do breach the dune allowing overwash to build the island's elevation, and accrete on the backside. The latter may ultimately close the narrow lagoon and shorten the length of the barrier chain by moving the existing mainland attachment to the west.

PROCESSES OF ISLAND EVOLUTION

The major processes of island evolution are: (1) shoreline retreat, (2) longshore drift, (3) overwash, (4) vegetated dune formation, (5) tidal delta incorporation, (6) inlet migration and (7) erosion of backbarrier regions of the islands by spring tides. The latter process seems to be uniquely important to the Algarve islands as its importance has not been documented elsewhere.

Figure 3. Proposed sequence of origin and initial migration of the Algarve barrier island system. The dashed reference line represents 50 m below present sea level. (A) As sea level rose to the edge of the cape-like protuberance, (B) a spit formed and began growing to the east. A similar spit grew from the west. (C) Continued sea level rise isolated the spits and strand as a series of barrier islands. (D) West-to-east longshore drift maintained the chain as sea level rose, and some landward transgression of the system occurred. With the decline in the rate of sea level rise, lateral processes have dominated, resulting in mainland attachment at the eastern end, and lagoonal infilling. (Facing Page).

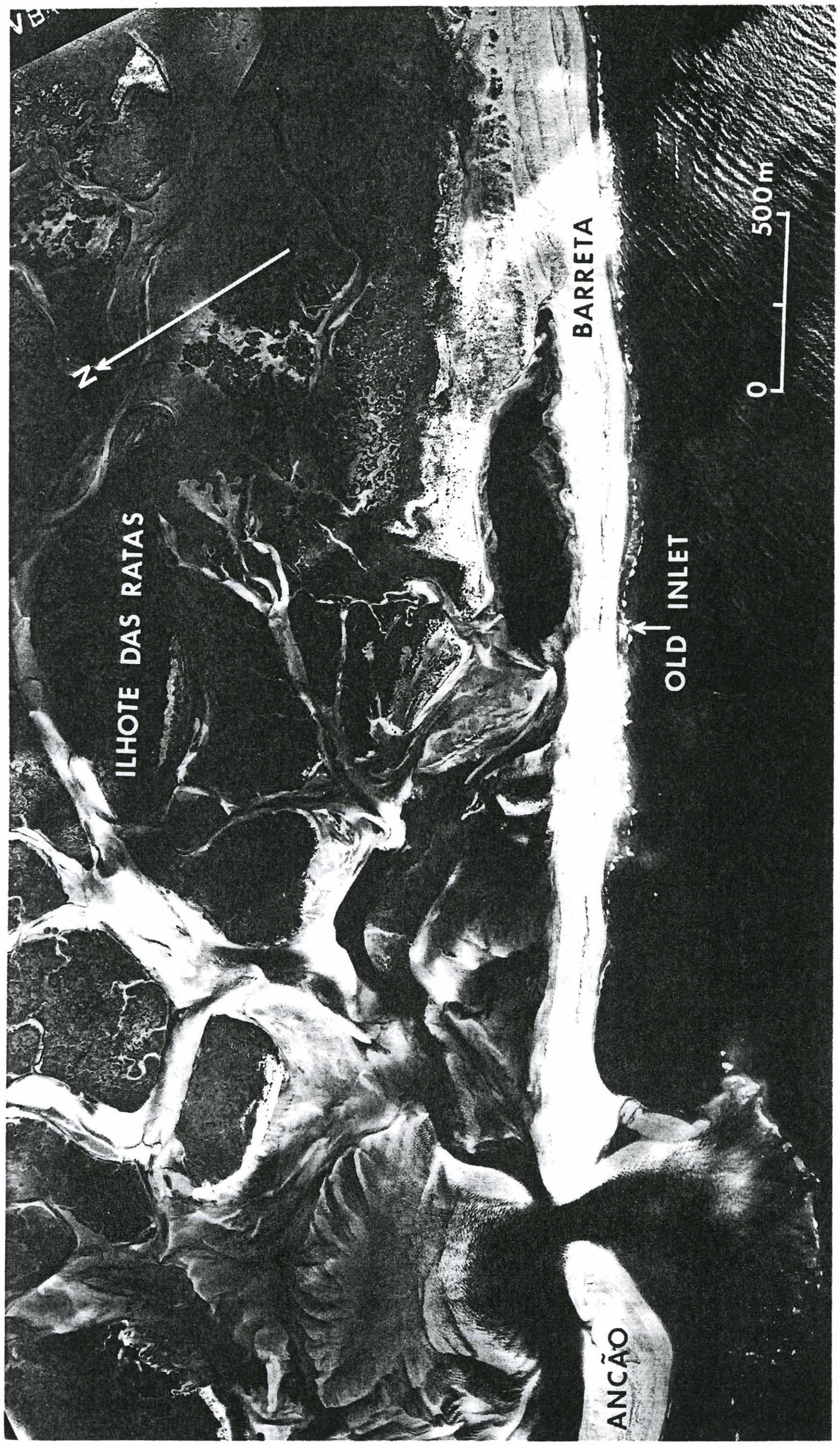
Table 1 shows the various dominant processes on an island by island basis, and separates front-side and lagoon-side processes. The lateral variation in importance of island processes is assumed to be due primarily to variations in island orientation relative to both wind and wave energy. Secondary factors include shelf morphology, island shape/elevation control on the vulnerability to erosion by spring tides, sediment grain size, proximity to inlets, and the impact of man due to channel dredging and jetty construction.

The lagoon behind the island chain (Figure 1) is largely filled with an accumulation of fine sediment in salt marshes and flood-tidal-delta sands. Essentially, flood tidal deltas have expanded to fill the available open lagoon behind the islands. Lagoon filling appears, on the basis of old chart notations, to be an ongoing process, but some areas of marsh are being eroded due to natural and man-made channel migration.

Salt marsh fringing the islands usually consists of clearly defined zones of high and low marsh. The principal plant species of the low marsh is *Spartina maritima*. Over a dozen plant species make up the high marsh and include the genera *Arthrocnemum, Halimione, Limonium,* and *Suaeda*.

Shoreline Retreat

Sand supply is the critical factor affecting rates of island retreat everywhere. In the Algarve, sand supply is large, judging from island volumes and widths, rates of lateral growth (*e.g.,* Culatra Island), and seaward pro-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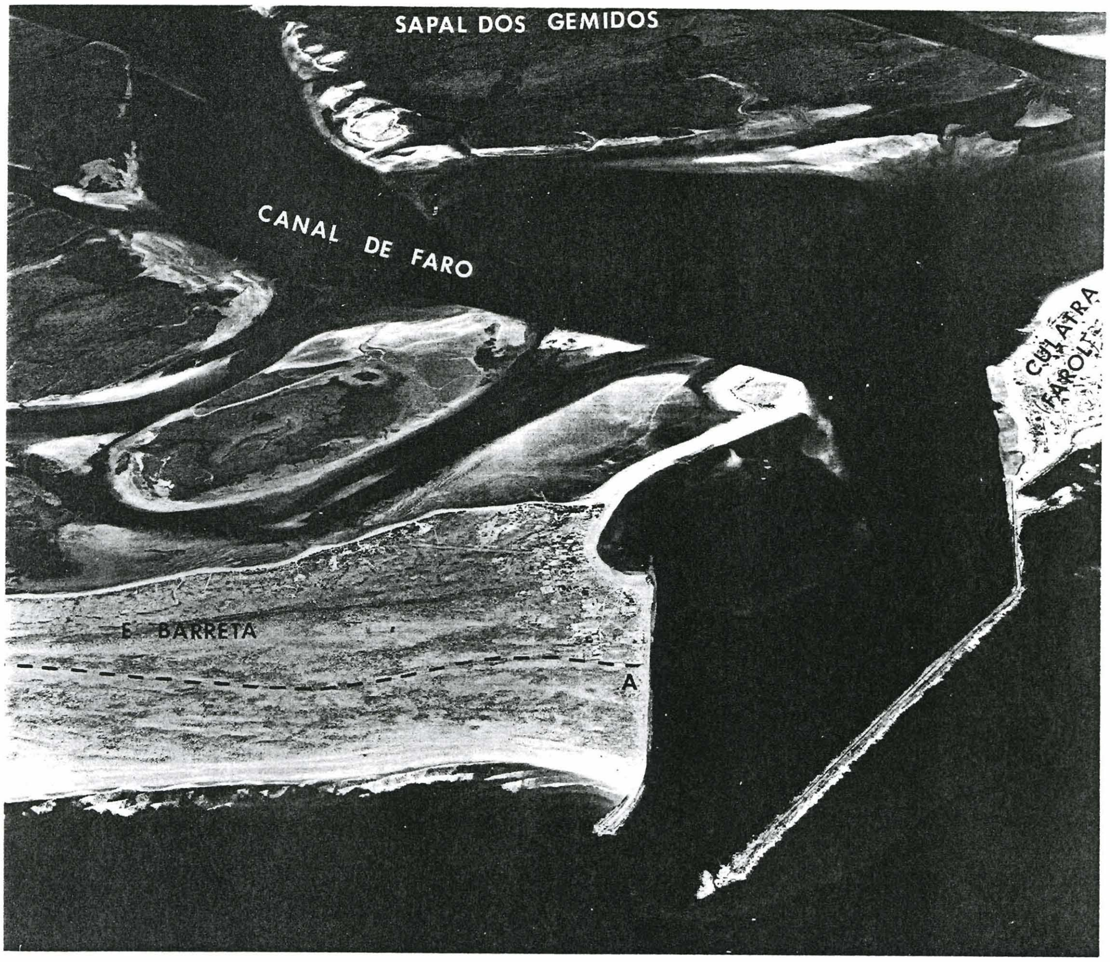

Figure 5. Faro-Olhâo Jetties (Barra Nova). The jetty at the east end of Barreta Island has blocked the easterly movement of sand resulting in 300 m of beach accretion. The dashed line 'A' marks the position of the 1951 shoreline (oblique view North; FAP flt. 87, frame 766, 13 September 1984). The artificial inlet has produced a very small flood-tidal delta.

gradation adjacent to jetties (Figure 5). Volumes of sand added to islands and tidal deltas within historic time are large relative to known rates of "upstream" cliff recession (> 2 m/year) west of the barrier island chain. Hence, the continental shelf is assumed to be an additional major source of sand. Comparative study of sands from the islands, the cliffs and adjacent continental shelf, based on the modes and grain-size populations, support the importance of the shelf as a major source of sand (DIAS, 1986: DIAS and MOITA, 1986). Local small rivers dump their load in the lagoon or within their lower estuaries and are not an important factor in present-day barrier island sand supply. The sand supply apparently diminishes somewhat to the east as indicated by the low elevation and small size of the easternmost barriers.

Armona Inlet (Figure 6) represents an exception to the general rule of abundant sand supply. With a width of 1.5 km it is the widest inlet

Figure 4. Western Barreta Island. The false-spit appearance resulted from the attachment of the east end of the Ancâo Peninsula to Barreta Island when the old Ancâo Inlet closed, and the new inlet breached the Ancâo Peninsula to the west (FAP flt. 101, frame 8008, 27 September 1984). The new inlet is migrating to the west. Ilhote das Ratas is a marsh island marking a former inlet position. (Facing Page).

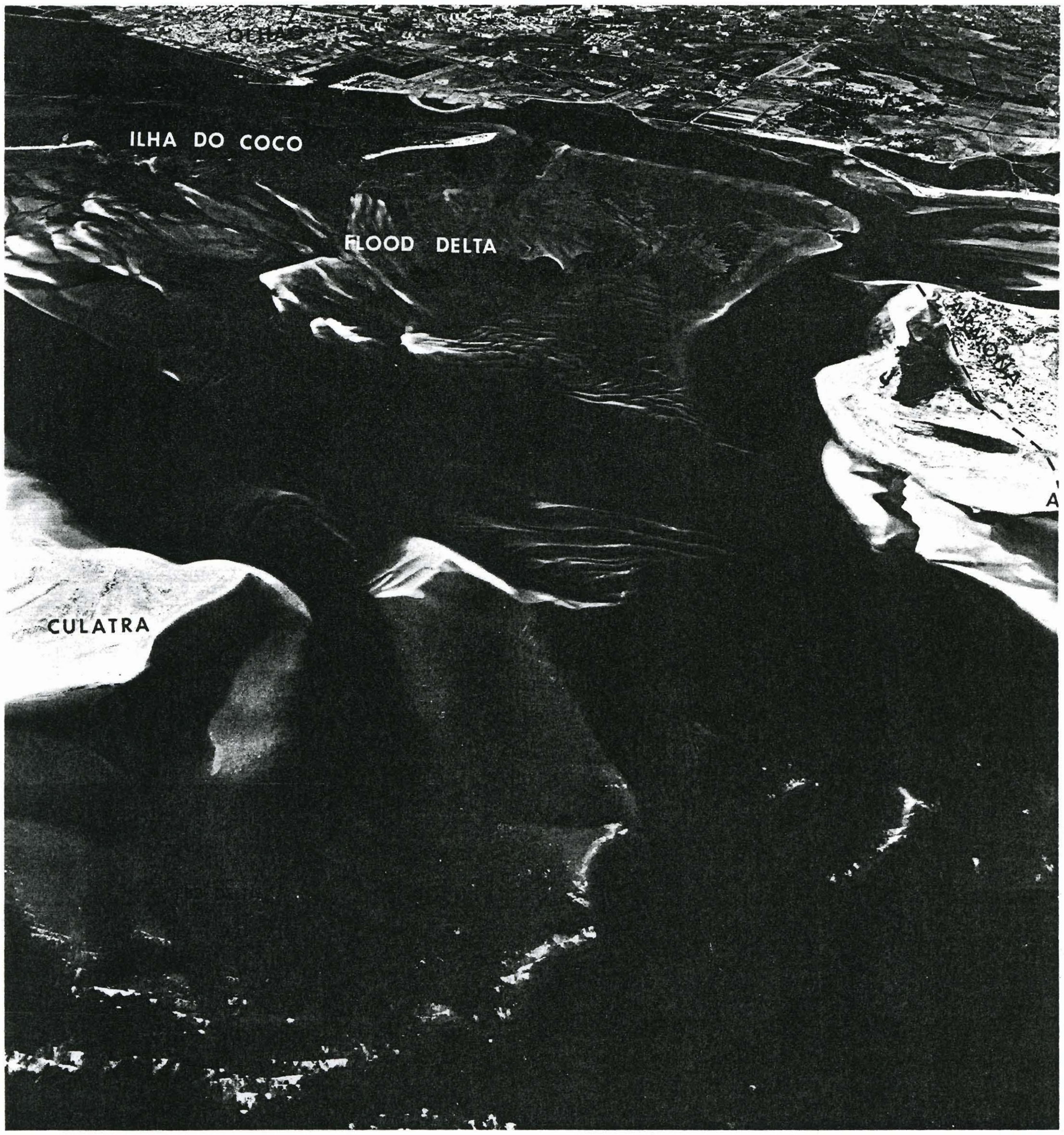

Figure 6. Armona Inlet (oblique view North, FAP flt. 87, frame 777, 13 September 1984). This inlet has been the only historically stable inlet in the system. The inlet has narrowed significantly since 1951. Note the accreted area of western Armona Island on the east side of the inlet. This reversal of the easterly transport pattern is due to wave refraction around the ebb tidal delta (Granja, 1984). Ilha do Coco is a large marsh island complex that formed at the back of the flood tidal delta. The dashed line 'A' represents the 1951 shoreline position.

in the island chain. Very wide inlets may exist due to a lack of sand supply and their cross sectional area is not a measure of the size of the tidal prism (OERTEL, 1985).

Grain size of the Algarve island sands is variable, but typically in the medium sand range. Most sands are negatively skewed, and the presence of coarse pebbles is not uncommon.

Shell content also is variable, averaging perhaps 10%. Wind-winnowed shell lags are commonly present on backbarrier flat environments and tidal-current produced shell lags are sometimes present in springtide channel deposits.

At the present time, almost the entire shoreline is retreating at an annual rate of less than 1 m/year. However, during a February 1987 storm the shoreline, as measured by frontal dune scarp position, retreated as much as 5 m to 10 m in some locations.

Longshore Drift

Transgressive features (NUMMEDAL, 1983) dominate the island system, however, lateral processes related to the longshore current system may be of greater importance here than in most barrier island systems reported in the literature. For example, judging from areal observations, significant portions of the island chain owe their existence and much of their sand volume to inlet migration and channel filling processes. Seaward progradation is relatively unimportant.

Overwash

Overwash is the dominant process bringing material to the lagoon shoreline of the narrow barriers including eastern Ancâo, western Barreta, eastern Culatra, eastern Armona, all of Cabanas and parts of Cacela. On these reaches, because of the large spring tidal amplitude, even minor storm events, occuring during a spring high tide, can produce overwash. On most other stretches of the Algarve islands, overwash is an infrequent event due to the high continuous frontal dune. However, even the Ancâo Peninsula is overwashed during storms with SW to SSW waves forming passes with widths to 35 m (Figure 7). During a February 20/21, 1966 storm the Ancâo dune line was overwashed forming eleven such passes (GUILLEMOT, 1979). Table 1 lists the percentages of island lengths along which overwash is an important process.

On some overwash-prone stretches, such as on the Cacela Peninsula as well as on eastern Culatra and eastern Armona Islands, the overwash occurs repeatedly through long-lived, distinct overwash passes. Alternatively, overwash may occur across a broad front and not through discrete overwash passes as on the west end of Barreta Island, and over most of Cabanas Island. In many instances, overwash passes are caused by access footpaths/tractor paths to the beach in continuous use by fishermen and tourists for many years.

Vegetated Dune Formation

Vegetated dunes are the dominant topographic feature of the Algarve islands. Along much of the oceanside of these barriers is a continuous frontal dune; 5 to 10 m high with no significant gaps (Figure 8). Table 1 lists the percentages of island lengths characterized by such a frontal dune ridge. Generally there is only one continuous, well-developed dune, except where man-induced progradation occurs such as west of the Barreta jetty (Figure 5), and where low dune lines (< 3 m) mark the positions of former recurved spit growth and inlet migration.

Behind the frontal dune, smaller dunes dot the surface of former overwash terraces and incorporated tidal deltas in more or less random distribution (Figure 8). Some of these mound-like domal features may have inherited their location from the initially higher, subaerial portions of delta and recurved spit sand bodies, while others may owe their form and position to former blowouts through the frontal dune or adjacent tidal channel sand sources as noted above. The dunes are vegetated except where some reactivation is taking place such as along the backbeach scarp, and exposed areas due to overwashing or tidal channel incisement.

Tidal Delta Incorporation

The wide portions of Tavira and Armona Islands owe their origin to the incorporation of flood-tidal deltas after inlet migration or closure. Such an origin explains the great width of the backbarrier areas for these islands in spite of the prevention or reduction of overwash by the continuous frontal dune ridges. In addition, the complex pattern of spring tide channels on the backbarriers resembles the channels and major bedform network of a flood tidal delta. Figure 8 compares the present-day flood tidal delta of Ancâo Inlet with a backbarrier region

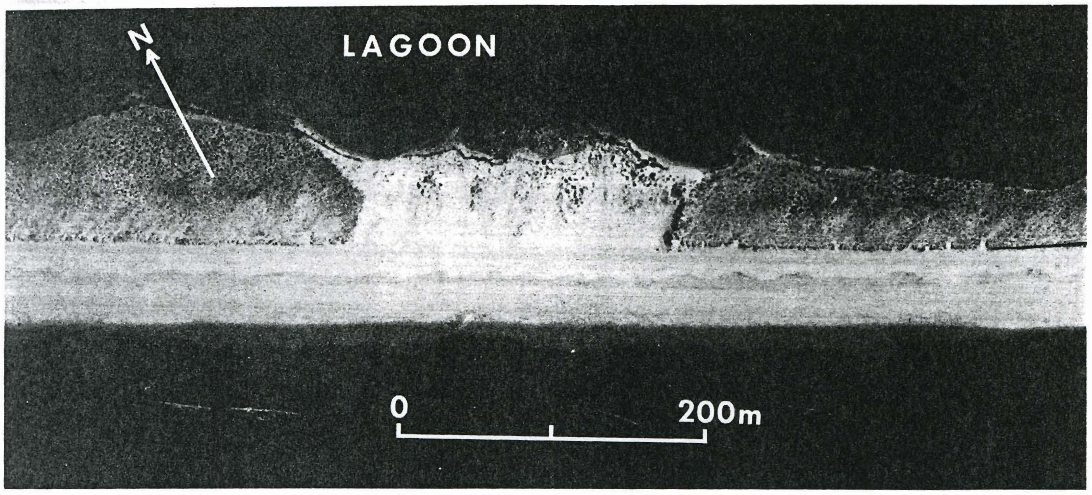

Figure 7. Overwash breach in the high dune line of the Ancâo Peninsula. By 1984 this 1960s pass was nearly sealed by reformation of the vegetated dune (FAP flt. 90, vertical frame 8311, 28 August 1980).

of Tavira Island, presumed to have formed by tidal delta incorporation.

Because of the spring tide amplitudes, flood-tidal deltas often are built well above normal high tide levels. As a result, when such a delta is abandoned it can immediately become part of the island. Incorporated flood tidal deltas are well known for other barrier island systems (*e.g.* HERON, *et al.*, 1984), but usually as subaqueous platforms on which salt marshes must first flourish and trap sediment or be buried by overwash and dunes to form a subaerial portion of the barrier island.

Because the Algarve deltas are initially subaerial at normal tides, it is thought that delta features such as the tidal delta channels and large sandy bedforms strongly influence the location of the later spring tide channels (Figure 8). As the welded or incorporated tidal delta evolves, dunes in interchannel areas should grow via sand supplied from adjacent channels as well as from the beach.

On the basis of air photos and field observations we interpret the backbarrier patterns of Tavira Island and parts of Armona Island to indicate that the island widened through the welding of several tidal deltas, none of which can be associated with historic inlets (15th century or younger). The degree of spring-tide tidal channel development appears to vary from one delta form to the next. Some have channels that are very broad with only small interchannel areas that remain unflooded by the highest tides. Others have less distinct channels, marked only by vegetation differences and lines of drift, and broader areas not affected by flooding. These differences in the degree of dissection may provide a means of evaluating the relative ages of the deltas; that is the older deltas may be the most dissected, the younger the least. This hypothesis is complicated by the fact that the original deltas probably were of somewhat different sizes, shapes, elevations, and sand volumes (Figures 6, 8A, and 9).

Inlet Behavior

This dynamic barrier island system is characterized by high rates of inlet migration and four patterns or modes of inlet behavior. From west to east these are: (1) progressive easterly migration in a continuous mode followed by a new inlet opening in a former western position and repeating the migration pattern (Ancâo Inlet), (2) a stable inlet position that widens and narrows (Armona Inlet), (3) easterly migration in a series of "jumps" as a new inlet opens during a storm a short distance east of the former position, usually occupying the next overwash pass adjacent to the former inlet (Fuzeta Inlet), and (4) inlet reformation after a storm

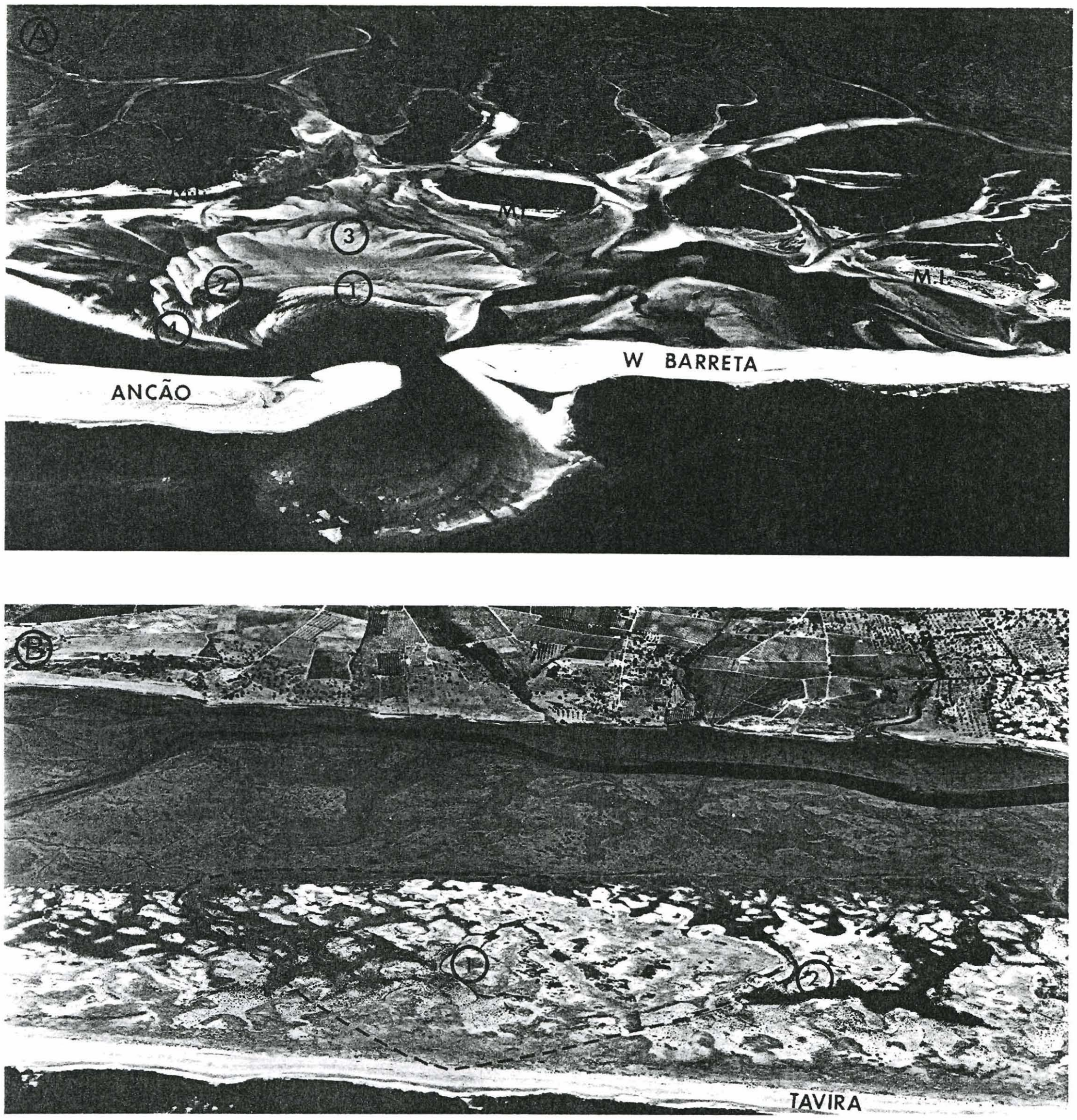

Figure 8. Aerial views of (A) the Ancão Inlet flood-tidal delta (FAP flt. 87, oblique frame 751, 13 September 1984); flood-tidal delta components are labeled: (1) flood ramp, (2) flood channel, (3) ebb shield, and (4) ebb spit; M.I. marks marsh islands; and (B) Tavira Island showing (1) an incorporated tidal delta complex, and (2) a relict ebb channel, behind the frontal dune and overwash terrace (FAP flt. 87, oblique frame 797, 13 September 1984). Note the similarity of scale and form. Such incorporated delta complexes have been modified into random dune fields and are being dissected by ebbing spring tide floods.

event in which an island or island segment is totally overwashed and inundated followed by shoaling, reemergence, and the formation of inlet-like channels, one of which remains open as an inlet as the island reforms (Cabanas Inlet). This change in behavior pattern appears to be related to differences in the orientation of the barrier island system. Inlets (usually one, but sometimes two) on the southwest-facing arm of the Algarve barrier island chain migrate by distinctly different modes than those on the southeast facing arm, east of the center of Barreta Island (WEINHOLTZ, 1964).

Ancâo Inlet (Figure 8), for example, migrates in a relatively simple and repetitive pattern from west to east; maintaining a more or less constant shape and cross section. The inlet typically migrates at rates exceeding 30 m/year, and the flood tidal delta is continually constructed as the inlet moves. In this case, the former delta is destroyed by channel migration and currents in the lagoon, although remnant sand bodies remain. Ancâo Inlet has been near its present position since 1968. During the 1950s and early 1960s, the inlet migrated to the east, extending the spit which attached to, and became the western end of Barreta Island. During this interval, approximately 1.3 km of the former western portion of Barreta Island were removed (GRANJA, 1984) as the inlet migrated and the Ancâo spit grew in front of the former island. For awhile, two inlets existed when the present inlet formed, and before the former inlet closed to weld the spit onto the western end of Barreta Island (Figure 4). Thus the western tip of Barreta Island, which gives the appearance of a spit built by westward moving longshore currents, is actually a feature formed by eastward moving longshore currents as Ancâo Inlet migrated.

Armona Inlet (Figure 6) is the only stable inlet, occupying approximately the same position through recent centuries (WEINHOLTZ, 1964). During this century the inlet has progressively narrowed, primarily due to the eastward growth of Culatra Island. Between 1877 and 1983 the inlet width narrowed by 2.45 km. (ESAGUY, 1984), and much of this narrowing has taken place since the first aerial photographic records of 1942. Both Culatra and Armona Islands have extended into the mouth of the former inlet position, but, as noted above, narrowing is mostly due to the eastward extension of the Culatra Island spit. Between 1977 and 1983 the inlet narrowed by 150 m to its present width of approximately 1.8 km. The accretion of the SW end of Armona Island (the east side of the inlet) added 400 m between 1951 and 1976, and another 50 m between 1976 and 1980. This inlet, accreting on both the upstream and downstream sides, closely follows the drumstick island evolution model outlined by HAYES and KANA (1976).

The eastern end of Armona Island clearly owes its origin to spit growth associated with the migration of Fuzeta Inlet (Figure 9). This inlet has a history of rapid easterly change in position, followed by inlet closure when a new inlet opens to the west. The rapidity of the migration is illustrated by the ruins of a SNSN (Portuguese Rescue Service) house on the eastern-most end of Armona Island in the inlet. The house originally stood on the western-most part of Tavira Island. The house "moved" from Tavira Island to Armona Island during a storm in which the inlet "jumped" past the house to its new position. The present inlet migrated 2.9 km between 1944 and 1984, a mean rate of 72 m/year, and has also narrowed from 750 m in 1944 to 400 m in 1984 (ESAGUY, 1985). The small flood tidal delta shifts with the inlet, and remnant sand bodies in the lagoon, as well as marsh islands (CLEARY, *et al.*, 1979), mark the positions of the former deltas and associated inlets (Figure 9).

In contrast, Cochicho Inlet (former) and Cabanas Inlet (present), between Cabanas Island and the Cacela Peninsula, forms over a wide area during storms as Cabanas Island, in particular, is easily inundated. The broad connection between sea and lagoon quickly shoals, chokes with sand bars, and portions of Cabanas Island reemerge, until a more well-defined narrow inlet forms. For a time the inlet may have two channels, but the western channel closes and the pronounced eastern channel causes the inlet to migrate rapidly from west to east. The spit-like growth associated with the inlet migration builds a feature from west to east, ultimately attaching to the mainland, so that when the inlet reforms to the west the resulting Cacela Peninsula, like the west end of Barreta Island, gives the false appearance of east-to-west spit growth. The known history of the inlet migration and the trends of small incorporated recurved spits on Cacela demonstrate the easterly direction of island construction. As recently as 1928, the now-closed Cochicho Inlet was close to the junction of the Cacela Penin-

Figure 9. Vertical aerial photo of Fuzeta Inlet (B.F.) at low spring tide (FAP flt. 101, frame 8024, 27 September 1984). Incorporated recurved sits, marsh islands (M.I.) and remnants of flood tidal deltas mark the former positions of the rapidly migrating inlet. Dredge spoil (D.S.) from the early 1980s covers a former marsh island. (Facing Page).

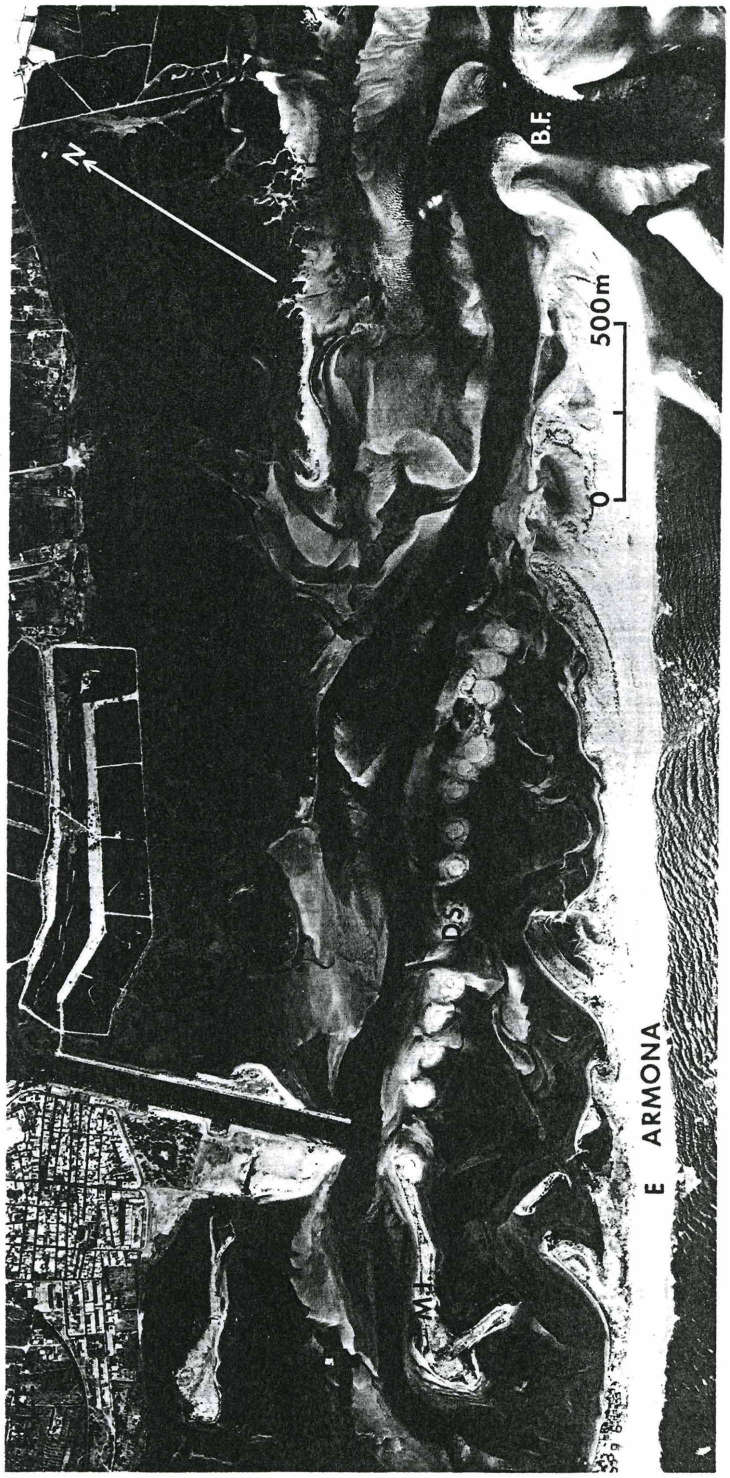
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Table 2. *Reduction in island area due to spring-tide flooding.*

	SPRING FLOOD TIDE	
ISLAND	PRECENT REDUCTION IN AREA BETWEEN SPRING LOW & HIGH	PERCENT REDUCTION IN AREA BETWEEN SPRING MIDTIDE & HIGH
ANCAO	67	48
BARRETA	69	52
CULATRA	66	44
ARMONA	78	63
TAVIRA	69	64
CABANAS	84	64
CACELA	69	56

sula with the mainland. Cacela's Fort was built atop of the mainland cliff in the eighteenth century to guard the inlet that once existed in this extreme eastern location. The cycle of wide inlet formation, shoaling, and then migration is rapid. Between 1979 and 1984 one such cycle occurred, and the inlet is now migrating to the east.

Spring Tide Flooding and Erosion

Because of the large difference in amplitude of spring versus normal tides (4 m vs 2 m), low elevation portions of the Algarve islands are regularly and significantly inundated by spring tides. The flow of this water both on and off the island causes significant flooding and results in channelization and sediment transport.

Table 2 compares areas of each of the barriers at midtide level and at a maximum spring tide. Figure 10 illustrates the variability in the shape of Armona Island at different tide levels based on September 1984 air photos during a spring tide. Control of the location of spring tide flooding is largely dependent upon antecedent topography and is discussed further under island evolution. The ebb flow from the flooded area is responsible for widespread erosion and channel formation on the backbarriers.

Spring tide channels take a wide variety of forms and shapes depending upon (1) the antecedent topography and (2) the relative age of the island segment being affected. Control of tidal channel location by antecedent topography is particularly apparent on Culatra Island where the channels follow courses between successive recurved spits which once formed the island terminus (Figure 2). The tidal channels approximately parallel the low dune ridges of the spits in the axes of former inlet channels. On Tavira and Armona Islands, the tidal channels form complex patterns controlled by the distribution of vegetated dunes which in turn are probably inherited from complex channel and large bedform patterns on old tidal deltas incorporated into the barrier island (discussed below). In fact, the main tidal channels appear to be the ebb channels (HAYES and KANA, 1976) of old flood tidal deltas which originally connected to the throat of the associated inlet (Figure 8).

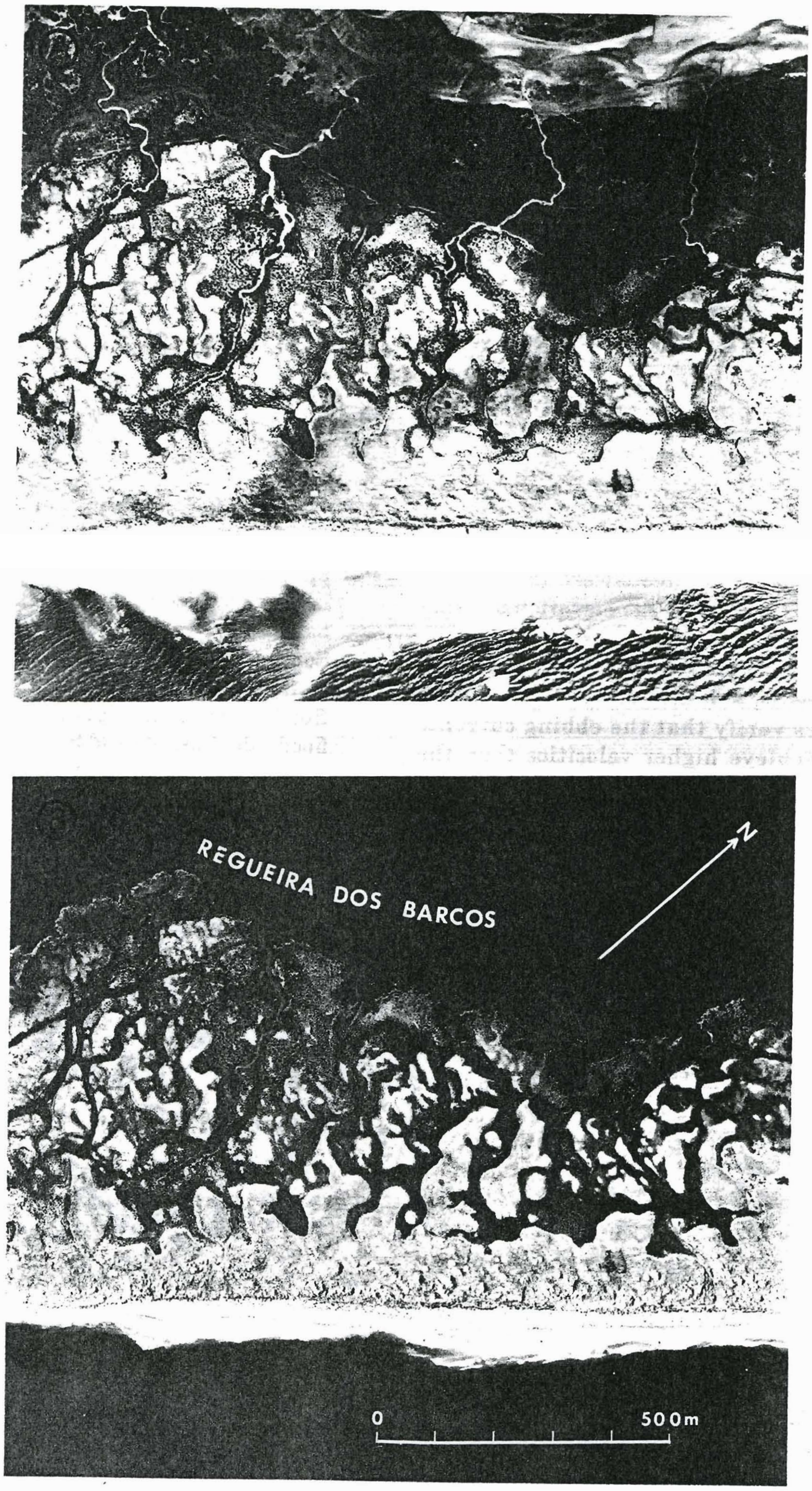
Spring tide channels vary widely in appearance from the inherited features noted above to incised dendritic patterns in flat areas such as the backbarrier sand flats. Many of the meandering channels are incised through scarping of vegetated dunes. Examples of such channels are common on portions of Culatra, Armona and Tavira Islands, where channels have the appearance of intermittent streams in regions of arid climates (Figure 11).

Less spectacular, but more widespread evidence shows that the effect of the spring tide flooding extends well beyond the main channels. Driftwood rack lines, fresh kills of non-salt-tolerant plant stands, changes in the vegetation patterns between salt-tolerant and non-salt-tolerant species, and sparsely-vegetated rippled surfaces in topographic lows between dunes and dissected terraces interconnect with the main tidal channels.

On Culatra Island, spring tidal channels extend from the lagoon across the entire island and merge with overwash fans. The potential for such connections exists on most of the other islands. When the frontal dune is breached as occurred on Cacela in February 1987, overwash fans spill into the heads of the tidal channels. As a consequence, overwashed sediment is eventually removed by the spring tides to the backbarrier environment. Obviously, such locations, where spring tide channels and overwash passes meet, have a high potential for new inlet formation.

Erosion of the backbarrier portions of the barrier islands redistributes sediment to the island in two ways: (1) unvegetated erosion surfaces

Figure 10. Aerial views of western Armona Island during a perigean spring tide of September 1984 comparing the island's area at (A) low tide and (B) high tide (FAP flt. 101, frames 8021 and 8084, 27 September 1984). See also Figure 2. (Facing Page).


REGUEIRA DOS BARCOS
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500m

Figure 11. Ground view of flooding spring tidal channel complex on Culatra Island (28 September 1984). Most of the time the upper channels have an arid-region appearance; dry and bare of vegetation. Adjacent vegetation kill lines and rack lines indicate the highest levels of salt-water flooding. Small pool is covered with floating sand.

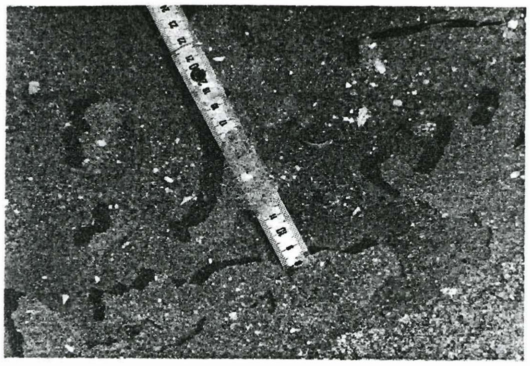

Figure 12. Floating sand and shells in spring-flood tidal channel. Significant amounts of sand are moved from the islands back sides into the island interior by this process.

furnish sand to adjacent dunes, and (2) the material transported lagoonward in channels by tidal currents adds to the elevation of fringing marshes.

Bedform orientation reflects the dominance of ebbing currents, and field observations during spring tides verify that the ebbing currents generally achieve higher velocities than the incoming tides. Net sediment transport by tidal flow is "off" island. Observed bed forms in well-developed channels include plane beds, ripples, ripples on dunes, and dunes. In general, bedforms indicate flow conditions throughout the range of lower flow regime conditions.

Flood tidal currents flush sediment up the channels in some cases. A significant mode of on-island transport is by floatation of sand and shells (Figure 12). In some instances the surfaces of the incoming tide water flooding a dry channel are observed to be almost entirely covered with floating sand and scattered shells in a concave-upward orientation. Floatation of sediment on the flood tide appears to be an important mechanism for transport of material toward the island interiors as well as within the vegetative cover of the salt marsh where floating sand is common on the rising tide. Floating sand is insignificant on the ebbing tides.

The more important geologic impacts of the spring tides on the barrier islands can be summarized as follows:

(1) Erosional incisement and extension of tidal channels are dissecting low-lying backbarrier areas; gradually lowering average island elevations.
(2) Sand-sized material eroded from the island is being carried to the fringing marshes and backbarrier lagoon.
(3) Some offsetting transport of sand and shells to the interior of the islands results from flood currents and grain flotation on the flood tide. Loss of sand from the island, however, significantly exceeds this gain.
(4) The heads of tidal channels form potential sites for new inlet formation during major storms.
(5) Widespread and repeated saltwater flooding in and adjacent to the channels reduces the variety, number and density of terrestrial plants, increasing low open sand areas that are further deflated by wind action. Correspondingly, dune growth potential is enhanced.
(6) Contamination of the fresh water aquifer on the islands adds to the environmental harshness for the biota.

COMPARISON WITH OTHER BARRIER ISLANDS

The Algarve barrier-island system owes its origin to the now-submerged topographic features on the inner continental shelf. The islands of this system differ markedly from most barrier islands around the world in that their loss by welding onto the mainland is virtually assured in the case of a continued sea level rise. Mainland welding is a certainty because of the steepness of the adjacent mainland. In fact, the attachment point appears to be migrating to the west as the island chain is shortened. Old maps (16th and 17th centuries) show the barrier system as continuous to near the mouth of the Guadiana River, including the area in front of the village of "Lagoa" (lagoon). This area of Manta Rota, east of Cacela, is now a wide mainland strand. Currently, Cabanas Island is attaching to the mainland, and, if undisturbed by major storms, could produce a morphology like that of Manta Rota. The question is: is the attachment part of the system's natural evolution, or the result of human impact? The Guadiana jetties caused 150 m of accretion in front of Manta Rota between 1951 and 1976.

The islands are true barrier islands in that they contain the "six required elements needed to impose the distinction 'barrier island' to a littoral sand body" (OERTEL, 1985). These elements are the (1) mainland, (2) backbarrier lagoon, (3) inlet and inlet deltas, (4) barrier island, (5) barrier platform (substructure), and (6) shoreface. In addition, the processes of barrier island evolution are basically the same as for other barrier island chains, although differing in their relative importance and intensity.

The Algarve islands are neither transgressive or regressive according to the definition of KRAFT and JOHN (1979). The core of the islands is formed principally as the result of inlet migration, and whatever barrier stratigraphy that was once present has been replaced by inlet fill. Inlet fill islands are a common type of island worldwide (*e.g.*, MORTON, 1979; HERON, *et al.*, 1984). Because progradation is not an important process, and because the islands are migrating, the system more closely resembles transgressive barriers. However, the standard field evidence of a transgressive system, such as marsh outcrops and backbarrier-bay shell fauna on the beach, is generally missing.

According to HAYES' (1975) classification of coasts, the Algarve islands are subjected to moderate wave energy and are mesotidal. A moderate wave energy coast under mesotidal conditions is typically characterized by short islands, *i.e.*, frequent inlets and well-developed ebb-tidal deltas (HAYES, 1979). The Algarve coast is typified by the former characteristic, but not the latter. Ebb tidal deltas are considerably smaller than the associated flood tidal deltas and none extend seaward more than one-half kilometer.

The mean wave height in the study area is believed to be about 1.0 m and the mean tidal range about 2.5 m. According to modifications of HAYES' (1975) island classification (NUMMEDAL and FISHER, 1978; HAYES, 1979; DAVIS and HAYES, 1984) these conditions should put the Algarve islands into a mixed-energy, tidal dominated category.

The lack of large ebb-tidal deltas, typical of tide-dominated islands, is difficult to explain, but may be an effect of very rapid rates of inlet migration. The 4 m spring tide would seem to be an additional factor encouraging construction of large ebb tidal deltas. One explanation could be that the sand supply is too small for large delta constructions, but that seems unlikely because large flood tidal deltas are constructed (Figure 6).

In many barrier island chains, island shape is greatly affected by the nature of inlet processes. The best known example is the drumstick island model characteristic of mixed energy shorelines (HAYES and KANA, 1976). FITZGERALD, *et al.*, (1984) demonstrated that in the East Frisian Islands off the German North Sea coast, inlet bypassing processes control island shape. Such is the case for Armona Inlet. The "downstream" island (Armona) is the "drumstick" type with the bulbous end built up by the addition of swash bars and other features from the tidal delta. The "upstream" island (Culatra) is lengthening through spit progradation.

The remaining natural inlets of the Algarve islands suggest that present inlet processes are not determining present day island morphology, although they are temporal process models. Except for sand bars associated with tidal deltas exposed only at low tides, the inlets give the appearance of having formed very recently. Stated otherwise, except for Armona Inlet, the inlets appear to have moved to or developed in their present positions in the last few decades.

A comparison with islands of the Southeastern U.S. is useful to visualize important characteristics of the Algarve islands which affect island evolution processes. One important difference is the relatively low abundance of shell material in sediments. Typical island sands range in CO_3 content from 5% to 10%. One important ramification of this is that shell lags seem to be less important on the Algarve islands. Shell lags do form, but only on long-exposed surfaces. In the Southeastern U.S. shell lags probably play a role in stabilizing overwash sand and holding it in place until it is revegetated (GODFREY, 1976; 1970). On the Algarve islands fresh overwash sand may be a major source of dune sand because it remains unstabilized.

On most barrier islands in the Southeastern U.S. beach ridges or frontal dunes have gaps through which overwash enters the island. Where the frontal dunes exist overwash gaps are rare on the Algarve islands, although Cacela Peninsula appears to be an exception. Overwash is not a common event except on low-lying portions of the islands (*e.g.*, western Barreta Island, eastern Culatra Island, eastern Armona Island, and all of Cabanas Island) where it tends to occur across broad fronts. Localized overwash passes do breach the dune lines on Ancâo and Cacela Peninsulas, and overwash is common where dunes have been removed as in the urbanized sector of Ancâo.

Other differences relative to the norm of Southeastern U.S. barrier islands are the relatively coarse grain size, unusually active inlets, the general lack of any natural forest or dense woody shrub cover in the vegetative assemblage, and, most significantly, the previously mentioned impact of the spring tide flooding on Algarve island interiors.

SUMMARY AND CONCLUSIONS

The Algarve barrier system is a 50 km arcuate chain of five islands and two peninsulas. These barrier islands are unusual in that they exist on a non-coastal plain coast. Located on a 10 km wide, flat platform extending across the inner shelf from the mainland shore to 10 m depth, the islands are considered to have originated form spits that extended from a now-submerged cape. These spits were left stranded as barrier islands by rapid shoreline retreat across the platform. Once formed, the islands evolved by processes of overwash, tidal delta incorporation, inlet migration, and dune formation. The islands are geologically ephemeral, and rapid welding to the mainland shoreline should occur with continued rise in sea level.

These islands are subjected to average wave heights of around 1 m and a normal tidal amplitude of 2 m (mesotidal). Spring tides are 3.9 m, an important factor in island development. The islands fall into the mixed energy zone of HAYES' (1979) classification. The limited ebb tidal delta development is characteristic of wave-dominated systems, however, closely spaced inlets point to tidal domination. Sand transportation is dominantly in a west-to-east direction, and a substantial sand supply is indicated by island volumes and flood tidal delta sizes. Sand supply decreases to the east. Sand is derived from both eroding cliffs "upstream" to the west and the continental shelf.

Inlets are very active, tending to migrate from west to east, maintaining general form and then closing when a new inlet occupies the initial position, or forming over a wider zone and then narrowing as the western margin accretes. Armona Inlet, the largest, has been historically stable, but has narrowed in width in recent years from 4.5 to 1.5 km. Because of the highly active nature of the inlets and their migration, the bulk of the island volume is likely to be inlet fill.

Flood tidal deltas are large, but ebb tidal deltas in this high wave energy system extend less than 0.5 km seaward. Islands are widened by a combination of addition of recurved spits, flood tidal deltas, and overwash. In one unusual case, the west end of Barreta Island prograded seaward when inlet migration resulted in construction of a new island in front of, but separated from, the old one. The 4 m spring tides cause flooding of low areas on the barriers resulting in incisement of erosional channels over large areas. As a consequence these islands exist in a dynamic equilibrium between island degrading spring tide floods and the various island construction processes.

The most important conclusions are the following:

(1) These geologically ephemeral barrier islands on a non-coastal plain coast owe their existence to an anomalous continental shelf platform.

(2) The islands exist in an equilibrium between the destructive action of spring tide channel erosion and the processes of island construction.

(3) As a consequence of the high spring tides, tidal deltas sometimes stand emergent above normal tides, permitting ready attachment of the delta after inlet closure, and aeolian build up of sand from island interiors.

(4) As a consequence of high rates of inlet migration, the core of the islands is believed to consist of inlet fill.

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□ RESUMEN □

El sistema de islas barrera del Algarve (Sur de Portugal) muestra algunas caracteristicas únicas que difieren de las de otros sistemas más extensamente estudiados. Las islas se encuentran sobre una llanura costera como resultados de una plataforma en el interior que actuó como un cabo durante la elevación del nivel del mar. Las flechas de arena iniciales se convirtieron en islas al producrisene la transgresión de la plataforma, y las islas son aparenntemente transgresivas, sin embargo los procesos laterales (oscilación e las desembocaduras, crecimiento de flechas) son dominates. Las islas se encuentran bajo energia de oleaje de moderada a alta y condiciones mesomareales. Los deltas con corrientes mareales son dominantes y las oscilaciones en las desembocaduras son rápidas. Los procesos eólicos y de rebase son los más importantes en el crecimiento vertical de las islas. Las islas más grandes deben su gran desarrollo al resultado de la incorporación de deltas de corriente mareal. Después de la incorporación, los procesos eólicos modifican la superficie del delta hasta convertirla en campos de dunas antes de producirse la estabilización por la vegetación. La disección de barras por la marea viva trabaja en oposición a los efectos constructivos del delta, a los procesos de rebase y a la formación de dunas. Como resultado de la erosión producida por la pleamar se ha formado en las barras una extensa red de canales de erosión. La localización de los canales está controlada por la morfologia anterior como por ejemplo canales deltaicos y áreas interdunales. La presentación de los canales, erosiona lateralmente y se extiende hacia el interior de la isla, algunas veces conjuntamente con rebase y formando importantes conductos para el transporte de sedimentos hacia el lago/pantano. El transporte de sedimentos en dirección al lago se compensa con la arena suspendida y conchas transportadas hacia el interior de la isla con la entrada de la corriente mareal. La muerte de la vegetación y la contaminación de las aguas subterráneas son también consecuencia de la corriente producida por las mareas vivas.—*Department of Water Sciences, University of Cantabria, Santanda, Spain.*

□ RÉSUMÉ □

Le système d'îles barrières de L'Algarve (Sud de Portugal) présente des caractères très différents de ceux habituellement étudiés. Les îles s'étendent sur une côte d'un type particulier résultant de la présence sur le plateau continental d'une plateform qui a agi comme un cap pendant la durée de la transgression marine. Les flèches originelles sont alors devenues des îles qui ont l'apparence d'îles transgressives, malgré la dominance des processus dynamiques d'ouest en est (migration de goulet, croissance de la flèche). Ces îles existent sous des conditions d'énergie de la houle modérée à forte et en régime mésotidal. Les deltas de marée dominent et la migration des goulets est rapide. L'action éoliennes et le lessivage superficiel sont importants pour la croissance verticale des îles: la plus large d'entre elles s'est trouvée élargie par incorporation d'un delta de marée; après cette incorporation, les actions éoliennes ont modifié la surface du delta en champ de dunes avant sa stabilisation par la végétation. La dissection des arrière-barrières par les marées de vives eaux (4m), s'oppose aux effets de construction dûs à l'incorporation du delta, au lessivage et à la formation de dunes. Un réseau extensif de cheneaux d'érosion s'est développé sur les arrière-barrières, à la suite de l'èrosion par la marée descendante. L'emplacement des chenaux est régi par la morphologie antérieure (chenaux des deltas incorporés, zones interdunaires et interflèches recourbées incorporées). Une fois établis, les chenaux incisent, érodent latéralement et s'étendent sur l'île. Ils se raccordent parfois aux seuils de lessivage et canalisent le transport sédimentaire entre le marais et la lagune. Le transport de sédiments en direction de la lagune est partiellement compensé par l'apport de coquilles et de sables flottants vers l'intérieur de l'île au moment de larrivée du flot. Les inondations des grands marées provoquent aussi la mort de la vegetation et la contamination des eaux souterrains.—*Catherine Bressolier (UA 910 CNRS, EPHE, Montrouge, France).*

□ ZUSAMMENFASSUNG □

Das kleine Barriereinselsystem der Algarve (Süde-Portugal) zeigt einige einzigartige Charakteristika, die sich von anderen untersuchten Systemen unterscheiden. Die Inseln liegen auf einer Ebene, die als Plattform des inneren Schelfs interpretiert werden kann, der whrend des Meeresspiegelanstiegs die Funktion eines Kaps innehatte. Initiale Sandbänke wurden zu Inseln im Verlauf der Transgression. Insgesamt erscheinen die Inseln auch als "Transgressionsformen", obwohl latereale Ost-West-Prozesse dominieren (Wanderung der Meeresarme, Sandbankwachstum). Die Inseln existieren unter der Beeinflussung durch mittlere bis höh-

ere Wellenenergie und mittleren Tidenschwankungen. Tidenflutdeltas herrschen vor, und die Verlagerung der Meeresarme verläuft sehr rasch. Eine Überprägung durch ölische und "overwash"-Prozesse ist wichtig für das vertikale Wachstum der Inseln. Eine Erweiterung der größ Inseln ist i.w. ein Produkt der Inkorporation von Tidendeltas. Eine rückwärtige Zerschneidung bei Springtiden (4m) wirkt den konstruktiven Prozessen von z. B. Deltainkorpo ration oder Dünenbildung entgegen. Ein ausgedehntes Kanalsystem im Bereich zwischen Inseln und Käte hat sich in der Folge der starken Erosion des Ebbstromes entwickelt. Die Anlage der Kanäle wird durch die ältere Morphologie (Tidendeltas, Dünen, Sandbänke) gesteuert. Sind die Kanäle erst einmal entstanden, scheiden sie sich weiter ein und dehnen sich lateral bis in das Inselgebiet aus. Der lagunenwärtige Sedimenttransport wird teilweise ausgeglichen durch die Sand- und Muschelfracht des Flutstromes. Springtiden haben neben einer Vegetationszerstörung auch eine Grundwasserkontamination zur Folge.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G. (West-Germany)*