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Geologic evidence for the incorporation of flood tidal deltas at Tavira Island, southern Portugal

Walter A. Barnhardt[1], Ramon Gonzalez[2], Joseph T. Kelley[3], William J. Neal[4], Orrin H. Pilkey, Jr[5]., Jose H.[6], Joao A Dias[7].

[1] Department of Geological Sciences, University of North Carolina, Chapel Hill, NC 27599-3315 USA
[2] Universidade do Algarve, Faro, Portugal
[3] University of Maine, Orono, ME, USA
[4] Grand Valley State University, Allendale, MI, USA
[5] Duke University, Durham, NC, USA
[6] Monteiro, Instituto Geologico e Mineiro, Alfragide, Portugal
[7] Universidade do Algarve, Faro, Portugal

ABSTRACT

Tavira Island, the largest barrier island on Portugal's Algarve coast, exhibits a broad backbarrier area that probably consists of relict flood tidal deltas that were incorporated when associated tidal inlets closed. The tidal deltas are preserved as lobate landforms extending into the marsh, and are bordered by linear, partially infilled depressions that resemble flood channels on modern tidal deltas in the region. The origin and evolution of the incorporated deltas and the location of former inlets were investigated using a dataset of 6.7 km of ground-penetrating radar (GPR) profiles and more than 30 cores. The data reveal a complex stratigraphic framework including a series of lateral facies changes that are interpreted relative to the incorporated tidal delta model and sedimentary environments as seen in the modern barrier chain.

ADDITIONALINDEXWORDS: *barrier island, flood tidal delta, inlet migration, ground-penetrating radar*

INTRODUCTION

Tavira Island is the largest (10 km long) in a chain of sandy, transgressive barrier islands on Portugal's Algarve coast, and is separated from the mainland by a narrow lagoon, the Ria Formosa (Fig. 1). Although the spring tidal range is almost 4 m, wave energy is high and the islands are classified as wave-dominated (DAVIS and HAYES, 1984). In wave-dominated systems, a small tidal prism and wave-generated longshore currents typically produce elongate islands and relatively small, widely spaced inlets with flood tidal deltas of small to moderate size (HAYES, 1979). Instability in the location of tidal inlets is common because longshore currents drive downdrift spit accretion, and cause inlets to narrow, migrate, and sometimes close.

Inlet migration and closure are important processes in the formation of barrier-island stratigraphy. On a barrier in North Carolina, for example, MOSLOW and HERON (1978) defined numerous channel-fill sequences that correspond to former inlets, and calculated that the deposits comprise over 30% of the Holocene stratigraphy. Evidence of former inlet positions can also include lobate sand deposits and marsh islands. These are often interpreted as abandoned flood tidal deltas attached on the backside of barrier islands and colonized by salt marsh plants (BERELSON and HERON, 1985). Understanding the history of moving inlets, and locating former inlets that have opened and closed, have important consequences for coastal protection issues and land-use decisions on barrier islands everywhere.

Much of Tavira Island is fronted by a single, continuous dune ridge and is backed by a 100-200 m wide overwash terrace. In recent years the frontal dune has deteriorated and been breached due to storm erosion and overwash processes, often in areas of beach access paths. The bulk of the island's width consists of what are believed to be incorporated flood-tidal deltas, the surfaces of which were later modified by aeolian processes. Similarly vegetated, lobate platforms also are seen on Armona Island, the adjacent barrier to the west of Tavira Island (Fig. 1). These relict features correlate to the geometry of modern flood-tidal deltas associated with inlets in the barrier chain. Dune fields occupy the former flood ramp and ebb shield, and networks of abandoned channels now exist in or near the position of channels formed when the delta was active. When the inlet closed, dunes began to form on the higher part of the incorporated delta and eventually closed the mouth of the breach. Inlet fill, overwash, and later dune formation have covered or modified most of the original delta.

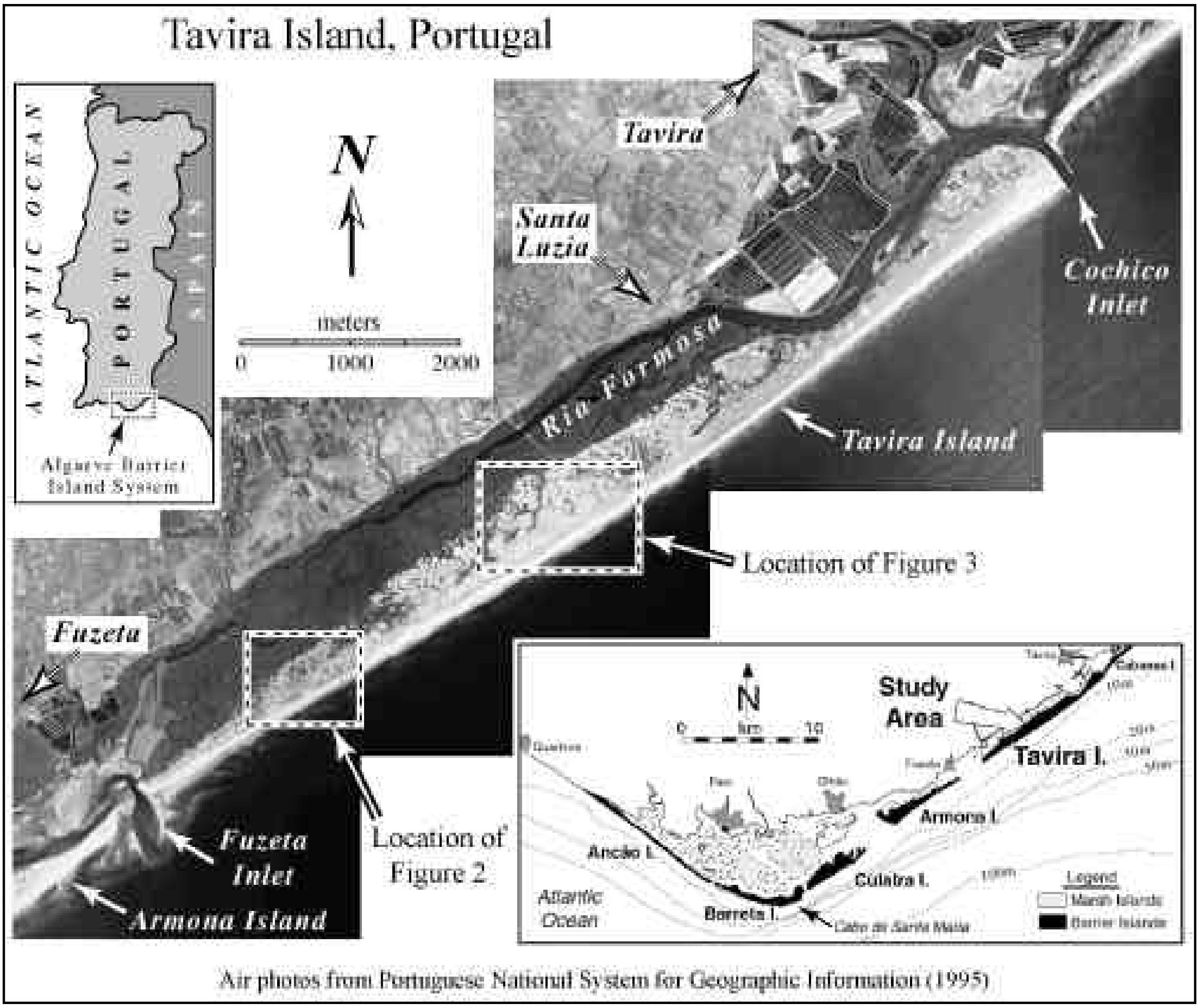

Figure 1. Location map of the Algarve barrier island system in southern Portugal, and an air photo of Tavira Island. The wide parts of the island probably represent the incorporation of flood-tidal deltas after inlet closure or migration. Figures 2 and 3 (boxes) show two of these features in detail.

This study examined the sedimentology and near-surface geology of the Algarve barrier islands. The main objective was to determine the origin of delta-like landforms comprising the wider parts of several islands. Specifically, the goals were to: 1) determine the location of paleo-inlets on Tavira Island, 2) identify the general facies associated with subenvironments; and 3) couple the stratigraphy of lagoonal deposits (i.e., flood tidal deltas) with the history of inlet dynamics on the adjacent barrier island.

SETTING

The barrier system on the Algarve coast consists of five islands and two spits that stretch about 50 km from Ancao to Cacela, and form the cuspate foreland of Cabo de Santa Maria, which encloses the harbors of Faro and Olhao (Fig. 1). The south-facing, transgressive barriers exist along a mainland coast of moderate relief ranging from fluvial plains to hills, not in the more common coastal-plain setting. This unusual setting probably resulted from flooding of a shallow inner-shelf platform by Holocene sea-level rise (PILKEY *et al*., 1989).

Mean wind velocities in the Algarve region are 6-9 km/hr and the spring tidal range is 3.9 m (INSTITUTO HIDROGRÁFICO, 1978). Lateral accretion of recurved spits indicate that the predominant longshore drift is from west to east. Longshore transport is estimated at 40,000 m3 of sand per year at the western end of the Algarve barrier chain (CASTANHO *et al.*, 1981), and as high as 180,000 m3 per year at the eastern end (GONZALEZ *et al*., 2001). Tidal inlets migrate rapidly from west to east and exhibit well developed flood tidal deltas. As inlets close or migrate to the east, inlet-related sand bodies apparently attach to the back sides of the islands (PILKEY *et al*., 1989).

METHODS

Cores were taken from the central to the eastern end of the Algarve barrier island chain, including: 1) the eastern end of Culatra Island at the edge of a tidal inlet, 2) Armona, Tavira and Cabanas Islands, and 3) the area of attachment of the Cacela Peninsula (Fig. 1). The core sites focused on selected areas where the surficial sediments were representative of extant facies (e.g., the Culatra spit for inlet fill; the old Fuzeta flood-tidal delta for delta platform and associated facies; and surficial environments such as marshes, dunes, and overwash terraces). The sedimentary characteristics observed in modern environments were compared with cores from relict landforms, and were useful in the interpretation of their original depositional setting.

About 30 vibracores and push cores were taken on Tavira Island in 1987 and 1988. Lines of cores cross several of the delta-like features making up the width of the island, and extend into the adjacent marsh areas behind the island (Figs. 2 and 3). Core penetration was poor in the sandy, central parts of the island, but cores of nearly 5 m length were obtained in the marshes. Cores were opened, described, subsampled and epoxy peels prepared in the field. The peels and subsamples were later analysed for grain size parameters, percent carbonate, and megafauna identification. Three radiocarbon dates were obtained on samples of salt marsh peat.

The interior of Tavira Island was surveyed using ground-penetrating radar (GPR) to image large scale bedding surfaces and complex facies relationships that are common to most barriers. A total of 6.7 km of GPR profiles were collected on the beach and dunes in the central part of the island (Fig. 3). Profiles were run in a grid of shore-parallel and shore-normal lines with a pulseEKKO 100* system, using a 400 V transmitter and 100 MHz antennas. The digital system was operated with a shooting rate of 4 shots/s, or approximately one data point every 25 cm along the tracklines. The GPR signals typically penetrated the sandy barrier to subbottom depths of 5-6 m, except in areas of near-surface clay deposits or saline groundwater, which attenuated the GPR signals. Conversions from travel time to depth were based on an average velocity of 0.1 m/ns in the sandy sediment. The depths are approximate and do not account for the variable velocities of saturated and unsaturated sediment. Image quality was optimized in the field by stacking 32 shots at each point along a profile and by subsequent processing of the data. Each GPR line was surveyed with a Dassault Sercel NP differential GPS to correct the profiles for changes in topography. The error in height given by the GPS system is about ±5 cm.

SEDIMENTARY FACIES OFALGARVE BARRIERS

Table 1 summarizes the characteristics of seven facies recognized in cores collected from all of the islands in the Algarve system. The two major lithosomes are the mud-dominated sediments of the back-island lagoon and marsh fill, and the sandy sediments that make up the bulk of the barrier island, including facies representing the upper flood-tidal delta, backbarrier channels, the surficial sands of the supratidal island (overwash and dunes), and the spring-tidal channels and tidal creeks that dissect the backside of the island. Shells of the macrofauna (Table 2) are common in the sediments and are useful to distinguish between facies that are lagoonal vs. those that have mixed marine and back-island assemblages (e.g., inlet fill and active delta sediments).

Although the cores in the interior of Tavira Island are short, the general facies geometry is implied in cross sections of the delta forms. Figure 2 is a cross section of the western most delta-like landform on Tavira based on cores #12-17. Surficial deposits of supratidal island sand form a wedge that thins progressively toward the modern marsh. A sample of marsh peat at 25-34 cm depth in core #12 returned a radiocarbon date of 330±170 yr B.P. In mid-island the sand overlies muddy lagoonal and marsh deposits about 1 m thick. The marsh facies, in turn, overlies an older deposit of horizontally laminated to cross bedded, medium-coarse sand that is interpreted as backbarrier channel facies. This sandy facies is associated with tidal inlets and flood tidal deltas based on analogy with modern environments (Table 1). These sands interfinger with and overlie additional units of lagoonal muds beneath the modern

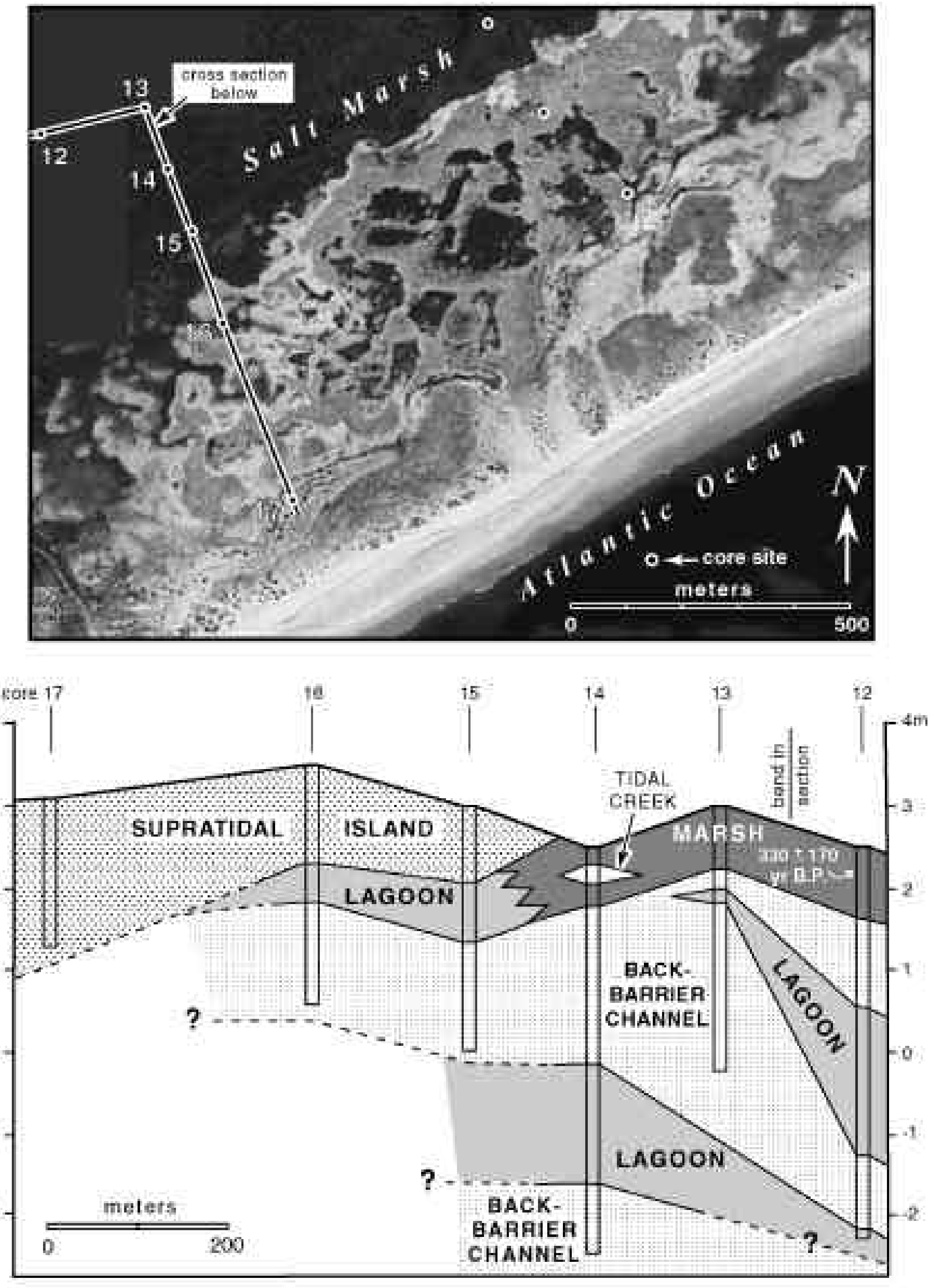

Figure 2. Air photo of western Tavira Island showing lobate plan view of an incorporated tidal delta and the location of cores. The shore-normal cross section (below) exhibits transgressive sequence of supratidal deposits (dune and washover) overlying more landward deposits (lagoon, marsh and backbarrier channel).

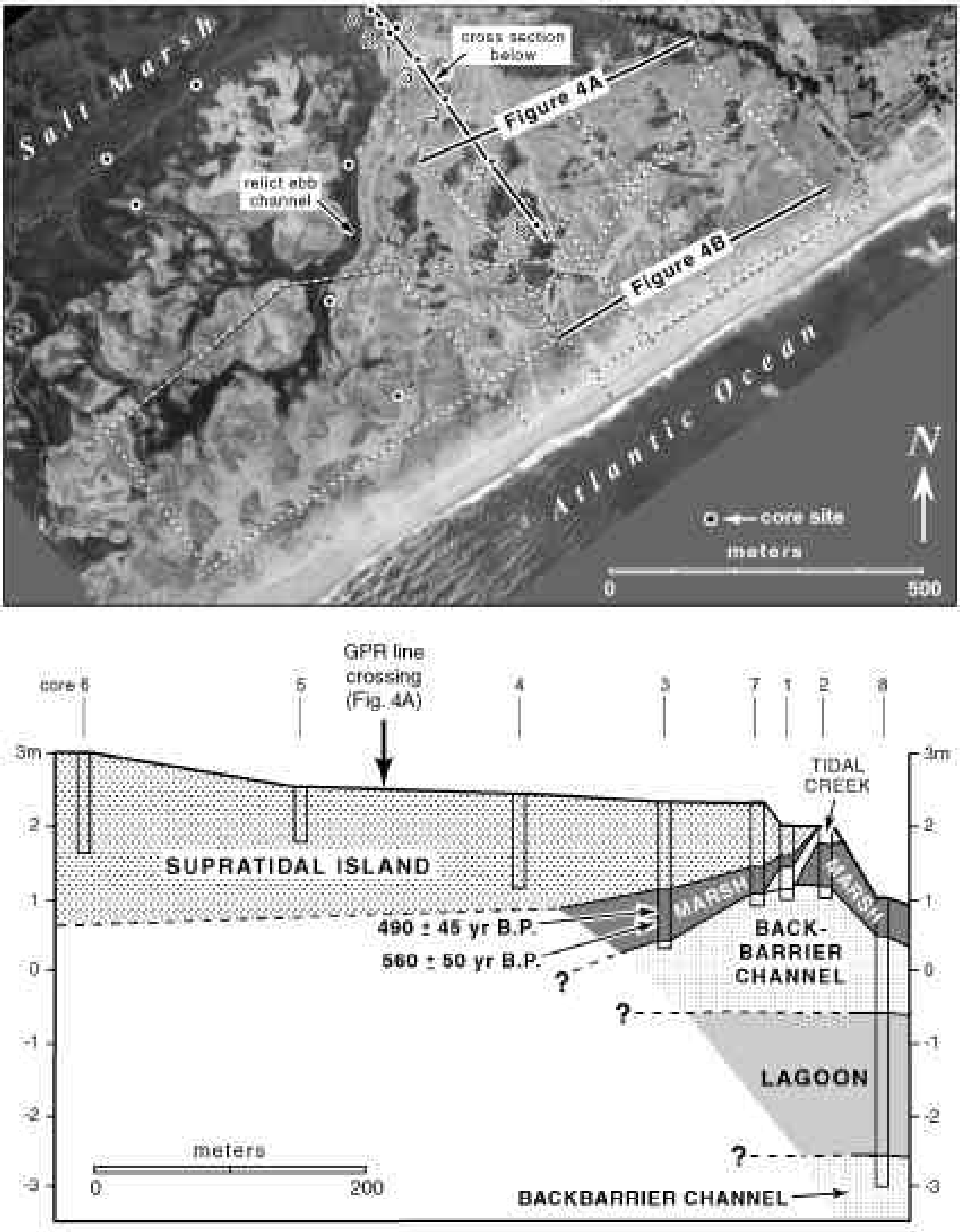

Figure 3. Air photo of central Tavira Island showing a large, delta-like landform with a complex pattern of relict channels. White circles indicate locations of cores. Thin dashed lines indicate locations of GPR profiles. The shore-normal cross section (below) is based on interpretations of sedimentary environments in 8 cores, and shows a transgressive stratigraphy similar to the relict delta in Figure 2.

Table 1. Summary of sedimentary facies observed in cores.

FACIES	GENERAL LITHOLOGY	TEXTURE	SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	MACROFAUNA AND FLORA	COMMENTS
MARSH high and low marsh	sandy mud, peaty mud, peat black to dark gray to brown	silty clay to fine and medium	generally absent; rare sand laminae	abundant plant roots and fibers; sparse sand-filled burrows	sparse to absent; lagoonal molluscs	low carbonate (2.0-2.1%); often fines upward
LAGOON tidal flat, low-energy channel, channel bank, marsh pond	mud to sandy mud dark green to black	sand silty clay to sandy, silty clay	generally absent	sand-filled burrows	common; lagoonal molluscs dominant (Bittium, Gibbula)	low carbonate except for layers of shell debris; contacts erosional and gradational
FLOOD TIDALDELTA deltoid area in back of inlet (platform, ramp, spit); subaerial at spring low tide	muddy sand to sand and shelly sand usually gray	fine-skewed medium sand to coarse- skewed medium and coarse sand	structureless to bedded; horizontal and cross laminae, cross beds	variable; burrows and mottling common to scarce	common; lagoonal molluscs dominant; some mixing with marine forms; whole and broken	carbonate varies (2-18%); basal contact erosional, may coarsen, then fine upward
BACKBARRIER CHANNEL main channels associated with flood tidal deltas	sand, granular and shelly sand brown to gray	coarse-skewed medium sand to coarse granular sand	common cross laminae, thin horizontal beds, cross beds	absent	common to sparse; mixed assemblage of lagoonal and marine forms	carbonate varies (1.9-12.2%), typically low to moderate (1.9-6.0%), usually fining upward
INLETCHANNEL inlet throat and main channel in front of flood tidal delta	muddy sand to granular sand usually brown	medium to coarse sand, often coarse skewed	structureless to well-developed graded beds, horizontal laminae, cross beds	absent	abundant to sparse; marine and lagoonal	carbonate varies (5.0-14.3%); may coarsen or fine upwards
SUPRATIDALISLAND subaerial environments; overwash, aeolian	shelly sand to sand brown	medium to fine sand; fine skewed	structureless to bedded; horizontal laminae and cross beds	structureless to root disturbance; mottling	absent to common; shelly horizons in overwash; broken marine forms	reworked sediment of relict delta and recurved spit
TIDALCREEK shallow drainage channels on back island and/or marsh	sand to muddy sand gray to brown	medium to fine sand; fine skewed	structureless to laminated; ripple laminae and horizontal laminae	generally absent	sparse to common; lagoonal molluscs dominant	low carbonate (2.0-2.1%); basal erosional contact; may fine upward

marshes that lie behind the island. Beneath the buried lagoonal muds, one deep core sampled a second unit of backbarrier channel sand at an elevation of -2 m below modern sea level that may represent an earlier tidal delta.

The stratigraphy of the incorporated delta in the central part of Tavira Island is similar to the western end of the island. Figure 3 is a cross-section based on cores #1-8. The surficial unit covering most of the island consists of sandy dune and overwash deposits, or the sandy "supratidal island" facies. This facies thins toward the lagoonal side of the island, and overlies marsh and tidal creek facies. Two samples of peat from the buried marsh returned radiocarbon dates of 490±45 yr B.P. and 560±50 yr B.P. from depths of 140-150 cm and 165-180 cm, respectively. This indicates that burial of the marsh by the upper sand facies occurred on the order of at least 400 to 500 yr B.P. at the location of core #3. The marsh facies overlies a 1-2 m thick layer of sand that is interpreted as backbarrier channel facies, or sediment deposited in main channels associated with inlets and tidal deltas. These sands overlie lagoonal muds and a second unit of backbarrier channel sand that suggest an earlier cycle of inlet opening and closing.

Table 2. Shelly macrofauna found in the cores (nonsystematic identification). Several of the species listed as lagoonal also occur on the ocean side, but are associated here with other lagoonal species.

MARINE SPECIES	LAGOONAL SPECIES
Cardium sp.	*Bittium reticulatum* (Da Costa)
Cerastoderma sp.	*Cerastoderma edule* (Linne)
Chamelea gallina (Linne)	*Cerithium vulgatum* (Bruguire)
Donax trunculus (Linne)	*Conus mediterraneus* (Bruguire)
?*Dosinia* sp.	*Dosinia lupinus* (Linne)
Ensis sp.	*Gastrana fragilis* (Linne)
Gibbula sp.	*Gibbula magnum*
Hidrobia sp.	*Gibbula* sp.
Hinia sp.	*Hidrobia* sp.
Laevicardium sp.	?*Hinia reticulata* (Linne)
Loripes lacteus (Linne)	*Jujubinus* sp.
Spisula solida (Linne)	*Mesalia brevialis* (Lamark)
	Murex trunculus (Linne)
	Ostrea edulis (Linne)
	Panopaea glycymeris (Born)
	Psamophila magna (Da Costa)
	Scrobicularia plana (Da Costa)
	Solen sp.
	Tapes aureus (Gmelin)
	Tellina tenuis (Da Costa)
	Venerupis decussata (Linne)

A RELICT TIDAL INLET ON TAVIRA ISLAND

The position of a former inlet in the central part of Tavira Island was recognized in several GPR sections that were run parallel to the coast. Cores in this area were short (1-2 m long) and only sampled the upper dune and overwash facies (Fig. 3). As a consequence, the deeper stratigraphy of the former inlet in this study is primarily based on interpretations of GPR data. The GPR profiles show broad cut-and-fill structures that are up to 375 m wide with a base that lies at least 4 m below present sea level. Two representative GPR lines are described below.

Line 5 was run in a NE-SW direction across a series of dunes 2-3 m high covering the broad, central part of the island (Fig. 4A). At the base of this section is a high amplitude, continuous reflection that exhibits several meters of relief. The highly reflective surface probably represents an erosional lag at the base of a tidal inlet and is notable for a pair of broad, U-shaped lows, which are interpreted as former flood channels. The channels flank a stratigraphic high in the center of the profile that may represent a former flood ramp or ebb shield. Overlying the buried surface is a unit that exhibits little internal stratification and is interpreted as muddy deposits of the lagoon and/or marsh facies (Table 1). Cores in this area were short and no samples are available to confirm this hypothesis, but several cores taken about 100 m north of the profile did contain muddy marsh sediment (Fig. 3). Preservation of the material in these antecedent topographic lows is relatively high in a transgressive barrier setting (i.e., BELKNAP and KRAFT, 1981). The top of the lagoon and marsh facies is truncated by a relatively flat, continuous reflection that is, in turn, overlain by sandy dune and overwash deposits of the "supratidal island" facies.

Line 4 was also run in a NE-SW direction about 400 m seaward of line 5, and is locate behind and parallel to the frontal dune ridge along a broad, flat terrace (Fig. 4B). Subbottom penetration by GPR signals was less in this location and no strongly reflective, deeply buried surface was observed as in the more landward section (Fig. 4A). Chaotic reflections at the NE end of the profile were generated by buried tires, cans, and other refuse in an old garbage dump. The GPR profile consists mostly of sigmoidal, concave-up reflectors that gently dip northeastward. Several prominent beds extend across the image and define several packets of more steeply dipping clinoforms. The angle of dip suggests that an inlet filled by material transported alongshore from the southwest, and

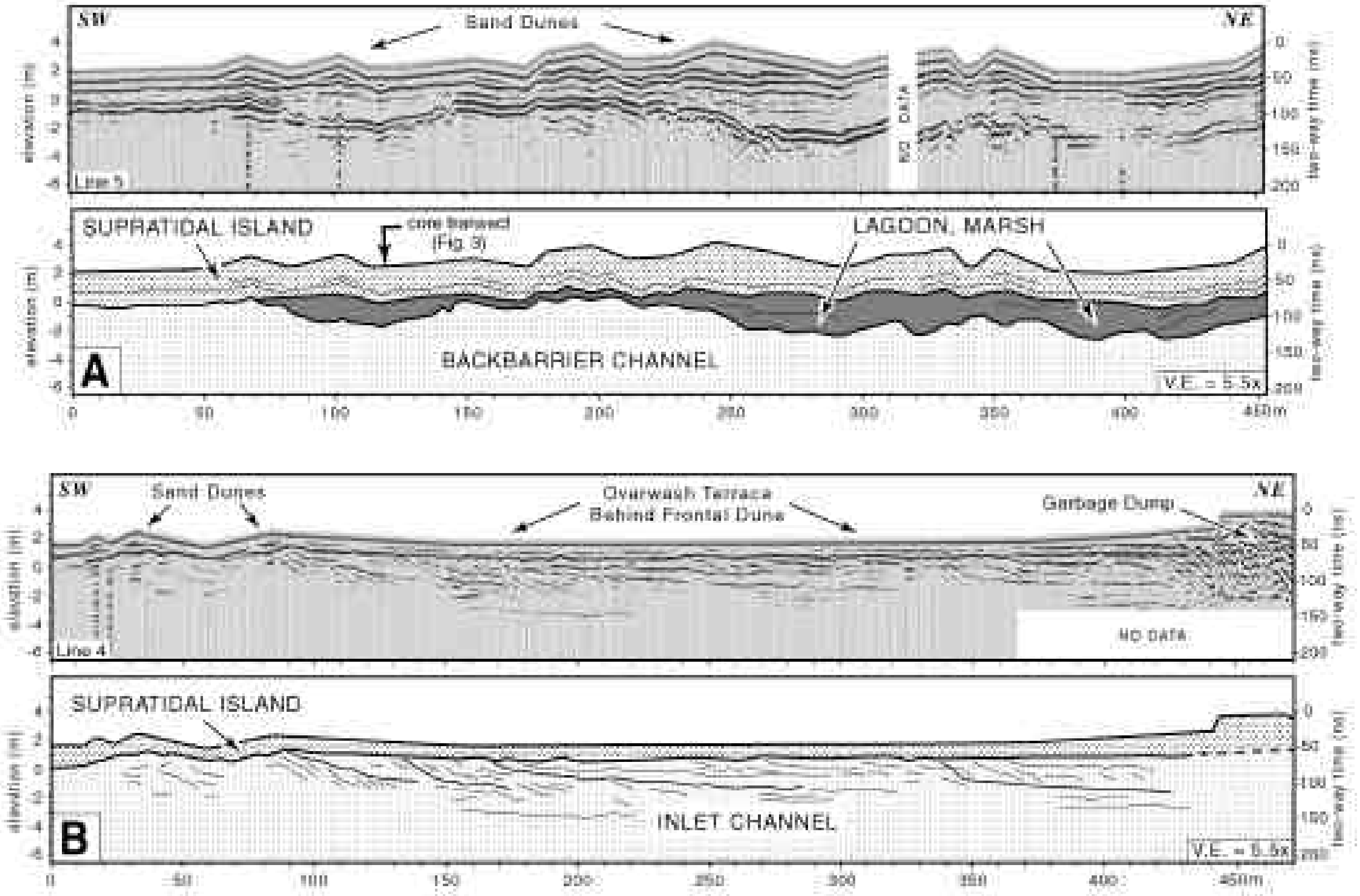

Figure 4. Ground-penetrating radar (GPR) profiles from central Tavira Island. A) Shore-parallel profile across dunes near the center of relict delta complex. B) Shore-parallel profile across flat overwash terrace located just behind frontal dune. See Figure 3 for location of profiles. Frequency is 100 MHz; velocity is 0.1 m/ns.

may record accretion and infilling of the channel by a prograding spit. This "inlet channel" facies (Table 1) was probably deposited in the main channel of the inlet at a position well seaward of the flood tidal delta. No evidence of lagoon or marsh deposits was observed above the channel-fill deposits. A strong, flat reflection truncates the dipping strata of the channel-fill deposits at or near mean sea level. A thin cap of dune and overwash sand ("supratidal island" facies) forms the surficial unit on this section and is generally less than 1 m thick.

SUMMARY AND CONCLUSIONS

The Algarve barrier system is characterized by west-to-east lateral process and high rates of inlet migration. Tavira Island exhibits lobate landforms, covered with sand dunes and marsh, that extend into backbarrier lagoons at several locations along the length of the island. Based on observations of modern environments in the region, sediment underlying the dunes and marshes is interpreted to represent former flood tidal deltas. The preservation of distinct delta forms suggests that inlets formed and closed at different locations along the length of the island, rather than opening and then migrating laterally. There is evidence for this type of scenario in the area of the Guadiana delta, about 10 km west of the study area, where aerial photographs record the opening of a stationary inlet in the early 1960s, and its closure around 1980 (GONZALEZ *et al*., 2000).

Coring in the muddy marshes and lagoons along the back edge of the islands revealed a transgressive stratigraphy of dune and overwash sand overlying backbarrier marsh and lagoonal sediment. Channel-fill sands underlie at least two of the deltaic landforms on Tavira Island and form lobate platforms for modern marshes. Core penetration was limited in the interior of the island but GPR was an effective technique in the dry, sandy dunes. GPR profiles penetrated up to 6 m below the ground, and revealed a series of subsurface reflectors that are interpreted as an inlet complex in the central part of the island. Shore-parallel profile across the delta-like landform indicate that the inlet was at least 400 m wide and probably consisted of two or more shallow flood channels. After inlet closure, backbarrier sediment (lagoon or marsh) accumulated in the incised channels and was subsequently buried by dune and overwash sand as Tavira Island retrograded landward. In more seaward parts of the barrier (i.e., behind the frontal dune), the sandy fill consisted of several packages of northeast-dipping clinoform reflectors, indicating that the inlet either migrated to the northeast (in the direction of dominant sediment transport), or narrowed and filled in place.

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