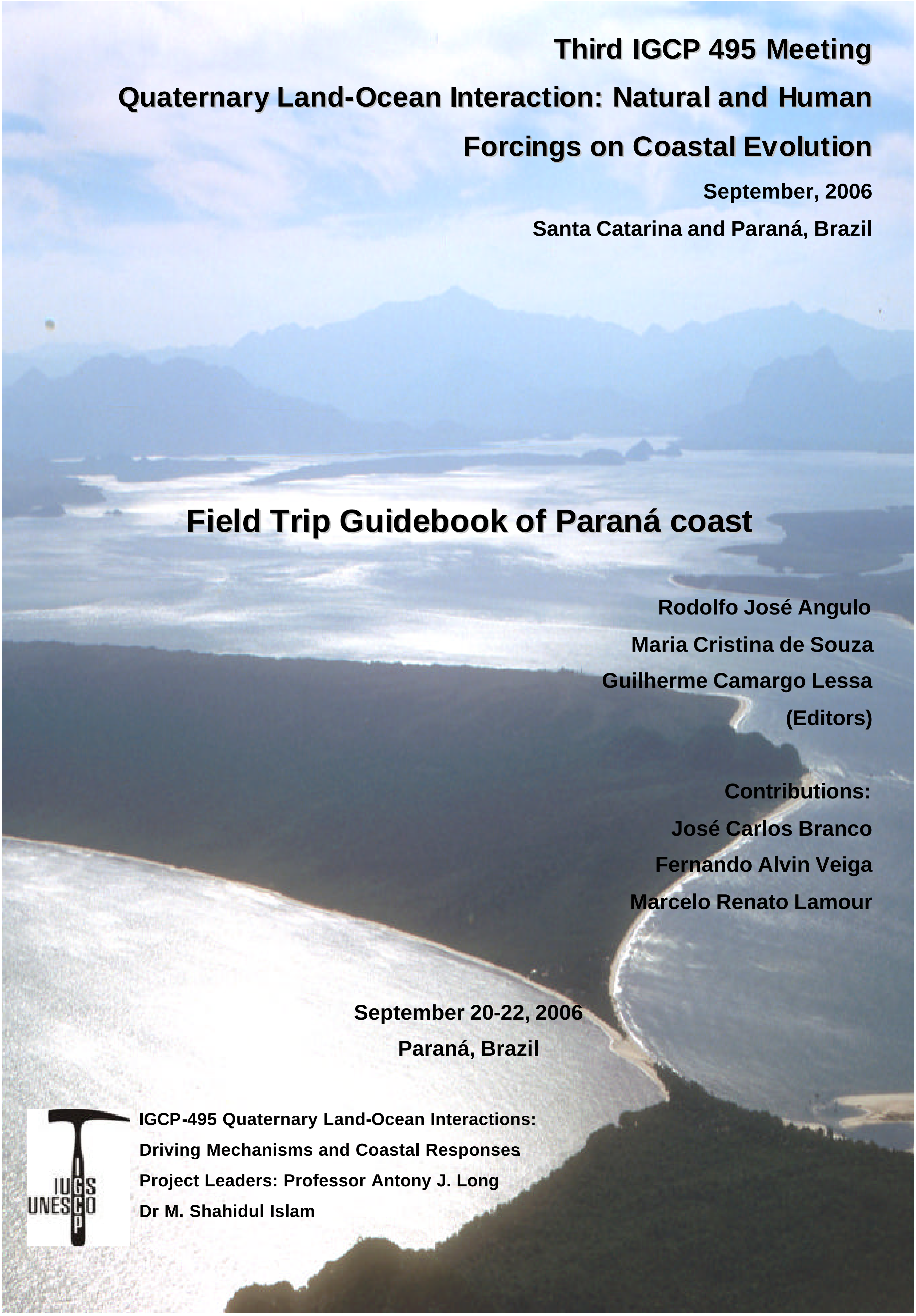

Third IGCP 495 Meeting

Quaternary Land-Ocean Interaction: Natural and Human Forcings on Coastal Evolution

September, 2006

Santa Catarina and Paraná, Brazil

Field Trip Guidebook of Paraná coast

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Paraná, Brazil

IGCP-495 Quaternary Land-Ocean Interactions:

Driving Mechanisms and Coastal Responses

Project Leaders: Professor Antony J. Long

Dr M. Shahidul Islam

PARANÁ FIELD TRIP SCHEDULE

SEPTEMBER 20th

17:50-18:10 h. **Stop 1** Saí-Guaçu shell-midden

18:30 h. Arrived to the Guaratuba Hotel *Pousada da Lua*

Suggestion: Walk to Morro do Cristo lookout.

20:00 h. **Dinner** at Guaratuba city

SEPTEMBER 21st

08:00 h. **Departure** from Hotel *Pousada da Lua*

08:40-09:30 h. **Stop 2** Serra da Prata, Caiobá

09:40-10:00 h. **Stop 3** Caiobá beach

10-10-10:30 h. **Stop 4** Brava beach

11:30-12:10 h. **Stop 5** Paranaguá sand quarries

12:20-16:00 h. **Stop 6** Paranaguá: boat trip to Ilha do Mel (mouth of Paranaguá estuarine complex) and lunch.

16:00-16:30 h. **Stop 7** Saco do Limoeiro, Ilha do Mel.

16:30- 17:00 h. Walk to the Hotel Pousada Grajagan

20:00 h. Dinner at Pousada Grajagan

SEPTEMBER 22nd

08:00 h. Departure from Pousada Grajagan

08:00-09:00 h. **Stop 8** Climbing to Morro do Farol das Conchas

09:20-09:40 h. **Stop 9** Farol beach

10:00-10:20 h. Boat trip to Encantadas beach

10:20-12:00 h. **Stop 10** Encantadas beach

12:00-12:30 h. Boat trip to Pontal do Sul

12:30-14:00 h. Lunch at Pontal do Sul

14:00-17:00 h. Trip to Curitiba through Graciosa road

18:00 h. Arrival at Curitiba: Hotel Interpalace or airport

SHORT REGIONAL DESCRIPTION

1. REGIONAL SETTING

The southeast Brazilian coast rests against crystalline massifs that forms the Serra do Mar coastal range. Its most prominent geomorphologic characteristic is the scarped coastal range that, when intersecting the coastline, creates coastal embayments where strandplains, and less frequently estuarine systems, are observed (Figure 1).

The broad structural setting of the Brazilian coast was determined by the opening of the Atlantic Ocean during the Mesozoic. The coasts of the State of Paraná and the northern coast of the State of Santa Catarina are located in a broad structural arc between Cabo Frio (23ºS) and Ilha de Santa Catarina (28ºS). This arc is defined by the structural highs of Cabo Frio and Florianopolis (Figure 2), between which the Santos sedimentary basin (up to 8 km sediment thick) was established.

The subsidence of the Santos basin caused an isostatic rebound that gave rise, between the lower Cretaceous and the Paleocene, to the neighboring sector of the Serra do Mar mountain range (Almeida 1976, Vignol-Lelarge et al. 1994, Almeida & Carneiro 1998). The uplifted block, with its seaward boundary apparently defined by the Santos Fault (Figure 2), underwent hundreds of kilometers of erosion and in its retreat left behind several topographical highs that became islands during sea level highstands.

Four coastal plains and three estuarine systems exist in the area that extends from Barra Velha in the south to Ilha do Cardoso in the north, a coastal segment of about 200 km that harbors the largest estuarine systems and the widest strandplains of southeastern Brazil (Figures 1 and 2).

1.1. Holocene paleo-sea level trend

According to a review of the Holocene paleo sea-level trend for the eastern Brazilian coast (Angulo & Lessa 1997, Angulo et al. 2006a), a smooth or gently oscillating decline of sea level occurred after a Holocene sea-level maximum of 2 to 3.5 m between 7,000 and 5,000 cal years BP (Figure 3). Sea level maximum occurred between 7,000 years BP and 5,000 years BP (more likely between 5,000 years BP and 5,800 years BP), with an elevation of 3,5 ± 1,0 m (Angulo et al. 2006a). A relatively high elevation was apparently sustained until about 3,500 years BP, when falling rates increased.

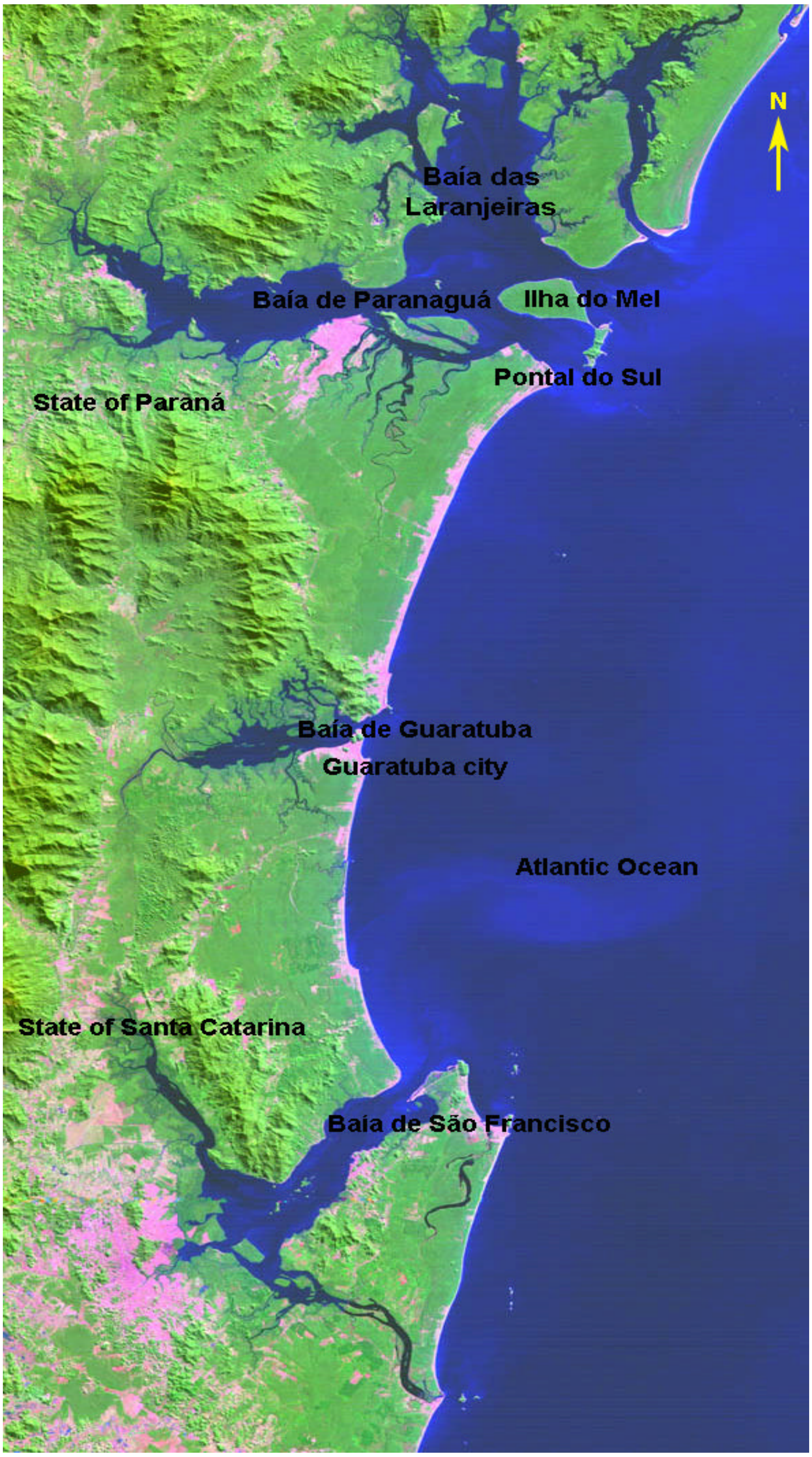

Figure 1: Landsat image of northern Santa Catarina and Paraná coastal zone.

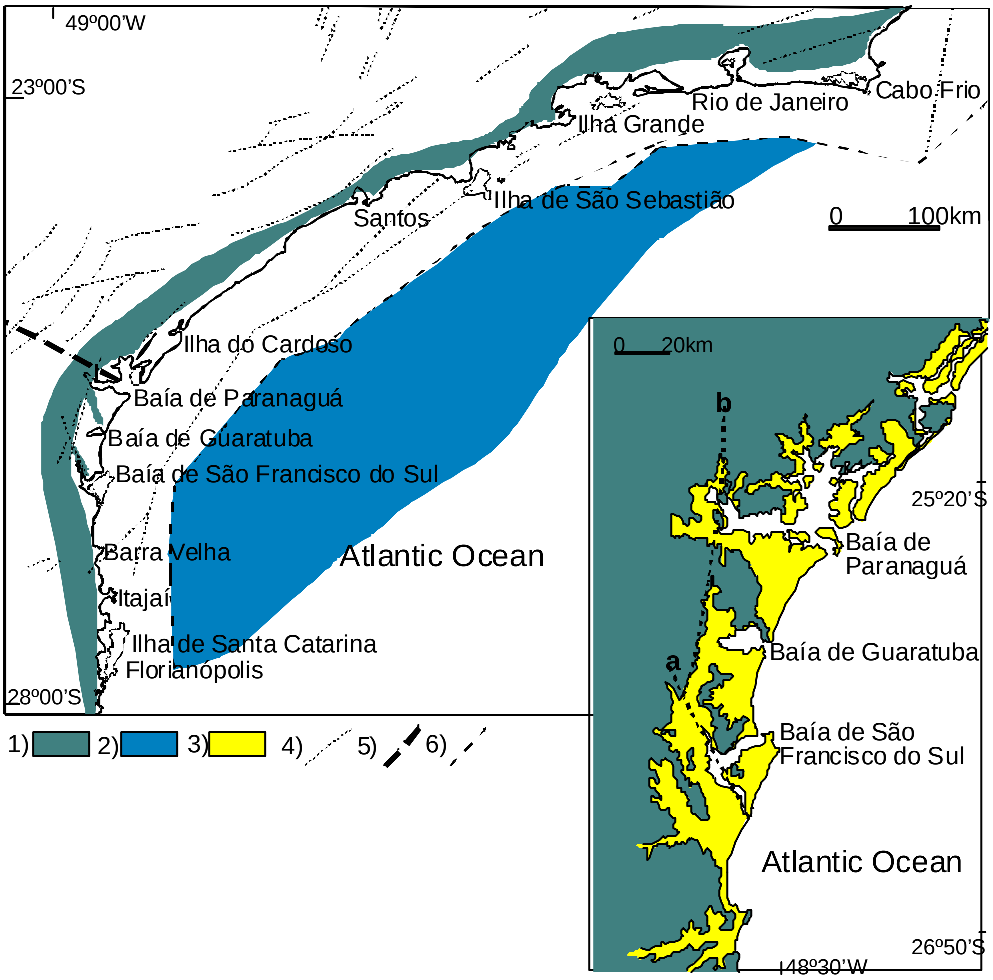

Figure 2: Structural map of the southeastern Brazilian coast showing location of the Serra do Mar range, Santos sedimentary basin (after Almeida 1976). (1) Serra do Mar mountain range, (2) Santos basin, (3) coastal plains, (4) main faults, (5) Ponta Grossa arc axis, (6) Santos fault, (a) Cubatão river fault, (b) Serrinha fault (modified from Angulo et al. 2007).

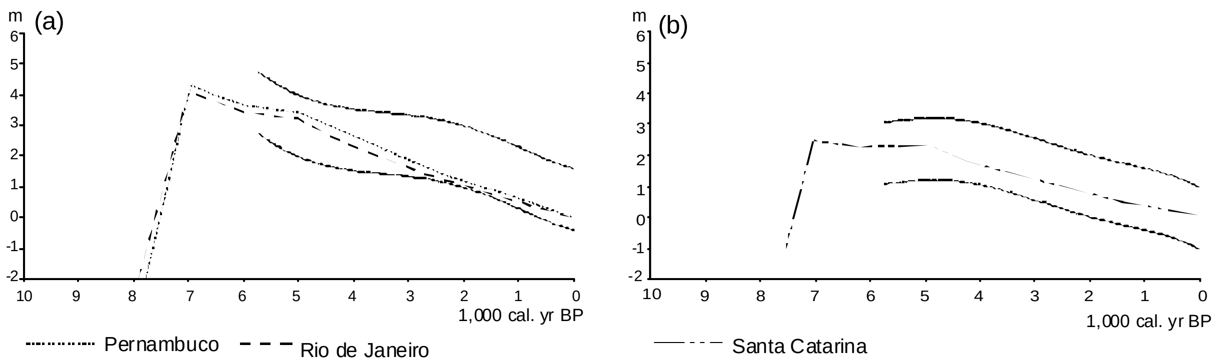

Figure 3: Sea-level envelopes for the region between Pernambuco and Paraná (a), and the southern of Santa Catarina (b), plotted with the paleo-sea level behavior predicted by the geophysical simulations made by Milne et al. (2005) (After Angulo et al. 2006a).

1.2. Oceanography

The tide in the region is microtidal and semi diurnal, with diurnal inequalities. Equinoctial spring tides in front of Baía de Paranaguá reach 1.7 m in range, the largest tide range south of Rio de Janeiro. Storm surges are frequent, and can elevate mean sea level as much as 80 cm (Portobrás 1983, Marone & Camargo 1995).

Two main wave directions are characteristic of the region, ENE and SSE/SE (Portobrás 1983). The wave period varies between 6 s and 10 s and the significant wave height between 0.5 m and 1.5 m (Portobrás 1983). Southeast waves drive a net northward littoral drift, as indicated by several lines of geological and geomorphological evidence, including the migration of estuarine inlets (Angulo 1999, Souza 2005).

1.3. Fluvial discharge and sediment yield

Only two small, neighboring rivers meet the ocean within the Paraná and northern Santa Catarina coast. These rivers are Saí-Guaçu and Saí-Mirim (Figure 4) that together drain an area of approximately 508 km^2. The remaining fluvial network discharges into the estuaries of Paranaguá and Laranjeiras estuarine complex (~601 km^2), Baía de Guaratuba (~50 km^2) and Baía da Babitonga (240 km^2). Therefore, the large majority of the river sediment yield is captured before reaching the coast. Sea level fall and net positive sedimentation resulted in the partial infilling of the large and in the complete infill of the smaller estuaries of Saí-Mirim and Saí-Guaçu rivers (Figure 4)

Although suspended sediment has been shown to reach the coast after heavy rains (Noernberg 2001), the bedload is retained in bay-head deltas inside Baía de Paranaguá and Guaratuba (Lessa et al. 1998, Barbosa & Suguio 1999, Odreski et al. 2003). Geological mapping of Baía de São Francisco do Sul remains to be made, but similar deltaic features are very likely to be found in its headwaters. Despite the retention of the fluvial bedload, large ebb-tide deltas (up to 8 km long, Figure 4) are observed in front of the estuaries. These deltas are associated with ebb-dominated estuarine circulation (Lessa et al. 1998, Mantovanelli et al. 2004), and are fed by a northbound littoral drift system (Bigarella et al. 1966, Angulo 1999, Lessa et al. 2000). Estimates of the alongshore sediment transport vary from 10^4 m^3/year to 10^5 m^3/year (Sayão 1989, Lessa et al. 2000, Lamour 2000, Lamour et al. 2006).

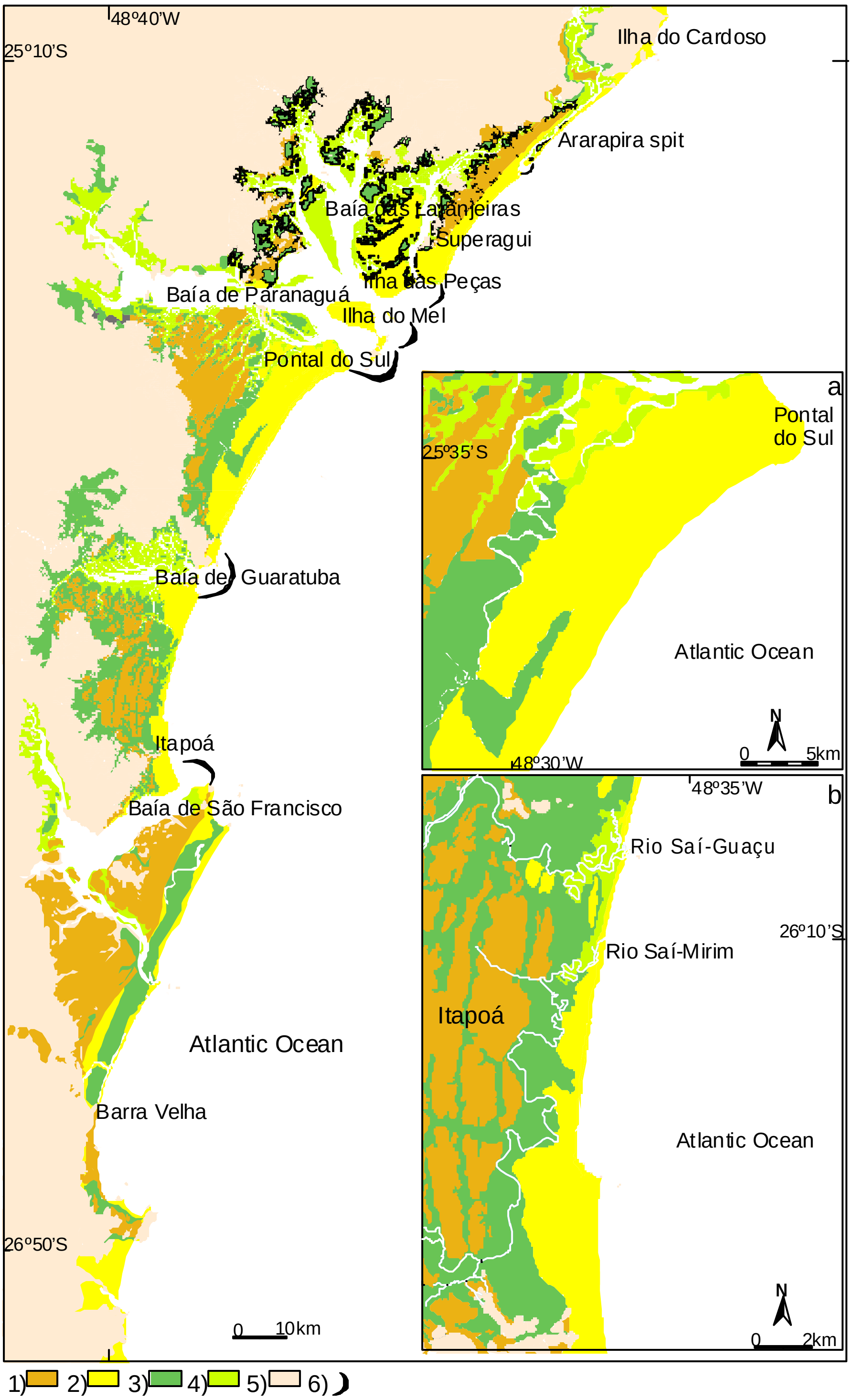

Figure 4: Quaternary geology of Paraná and northern Santa Catarina (inset a: Paranaguá coastal plain; inset b: Itapoá coastal plain). (1)Pleistocene barrier, (2) Holocene barrier, (3) paleoestuarine plains, (4) tidal flat, (5) other unit, (6) ebb tidal deltas. (Modified from Angulo et al. 2007).

SHORT DESCRIPTION OF THE PARANÁ FIELD SITES

The IGCP fieldtrip to Paraná (25º-26º S. Lat.) will visit the Pleistocene and Holocene barriers of Guaratuba, Paranaguá and Ilha do Mel, where it will be discussed the barriers' sedimentary facies and evolution. Also to be discussed are the ebb-tidal delta dynamics, coastal erosion problems, paleo-sea level indicators and the significance of shell-middens for the investigation of the Holocene geology (Figure 5).

Stop 1: Saí-Guaçu shell-midden

The Saí-Guaçu shell-midden was built mainly with *Anomalocardia brasiliana* and *Ostrea sp*. shells and contains many burials and other archaeological remains. The shell-midden was sits on a Pleistocene terrace at the margin of a Holocene paleolagoon (Figure 6). Shells from the surface were dated at 5,040 cal. yr. B.P. (Martin et al. 1988a), which agrees with the time of the mid-Holocene sea level maximum, when the lagoon was at its maximum extension. Shell-middens are widely distributed on the southern Brazil coastal zone. Although almost one thousand middens have been identified, its believed that the total number is much larger. Their height can reach 70-80 m and their area hundred of m^2 (Gaspar et al. 2006). In former papers, shell-middens were considered as food-remains of successive occupations. More recently they started to be considered as complex burial monuments and landmarks. For instance, 43,000 burials have been estimated to exist in a single midden in Santa Catarina (Gaspar et al. 2006).

The shell-middens have been used as paleogeographic and paleo sea-level indicators (Martin et al. 1986a, b), although controversies exist in regard to the latter. The potential of shell-middens for sea-level studies was anticipated by Laming-Emperaire (1968), and thoroughly discussed by Martin et al (1986a, b). Laming-Emperaire (1968) mentioned the existence of several shell-middens, whose base are below present sea level, as evidence of paleo-sea levels at or below the present level. The main assumption made by Laming-Emperaire (1968), Martin & Suguio (1976) and Martin et al. (1986a, b, 1987, 2003) in the use the middens as paleo-sea level indicators is that the base would have to be originally above the spring high tide level at the time of construction. Lessa & Angulo (1998) and Angulo et al. (2006a) questioned the validity of the historic sea-level data obtained from shell-middens, given the various possibilities that could have led an unknown culture to initiate a mound underwater. Furthermore, the nature of the midden's substrate and the midden's complex internal structure bring in additional complexity to the assessment of the original substrate elevation and paleo-sea levels. Detailed stratigraphic studies of shell-middens reveal a highly complex internal structure, making it difficult to assess where the earliest layers are. For more information see Angulo et al. (2006a).

Suggestion: Walk to Morro do Cristo lookout

Coastal plain, beaches and ebb tidal delta overview. Visible from the look out are the Holocene barrier, the Guaratuba and Brejatuba beaches and the southern part of the Guaratuba estuary ebb-tidal delta (For explanation see stop 2)

Stop 2: Serra da Prata, Caiobá.

Overview of the coastal plains, beaches and ebb-tidal deltas. At this point it is possible to see the Holocene barrier, the Guaratuba ebb tidal delta and Guaratuba and Prainha beaches.

About 6,000 years B.P., when sea level was about 3.5 m higher than present, Guaratuba bay was almost twice as large than today (Figure 6 and 7). The estuary inlet was located to the south of the Guaratuba hill and at that time a large flood-tidal delta was active (Figure 8). At present a large ebb-tidal delta is active. At this stop some of the ebb-tidal delta morphology can be seen. At low tide and/or big swell the waves break over sandy ebb-delta lobe and the channel margin linear bars. For more information about Paraná ebb-tidal deltas see Angulo (1999)

Figure 5: Location of field trip sites.

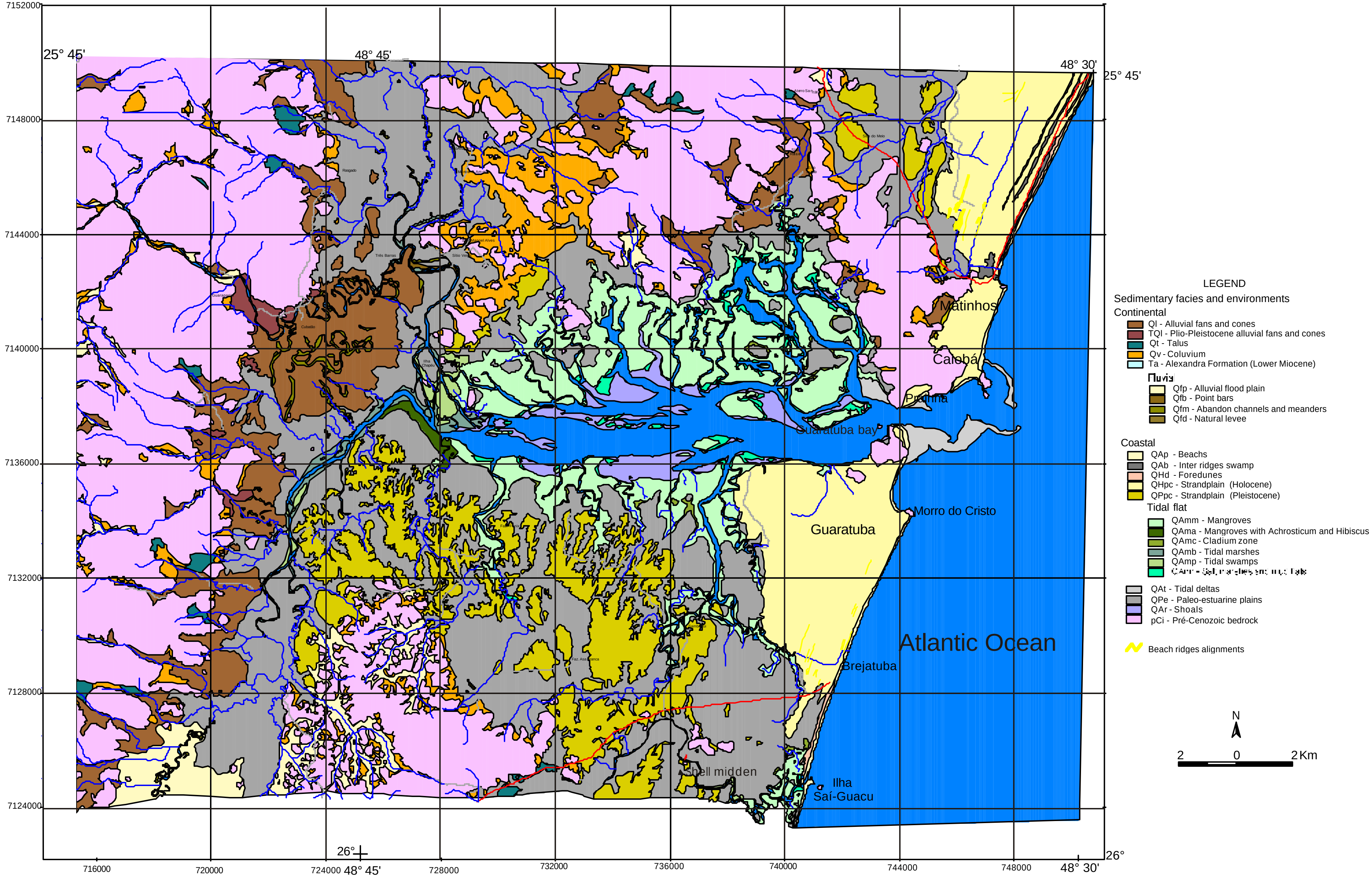

Figure 6: Geological map for the Cenozoic around Baía de Guaratuba (After Angulo 2004).

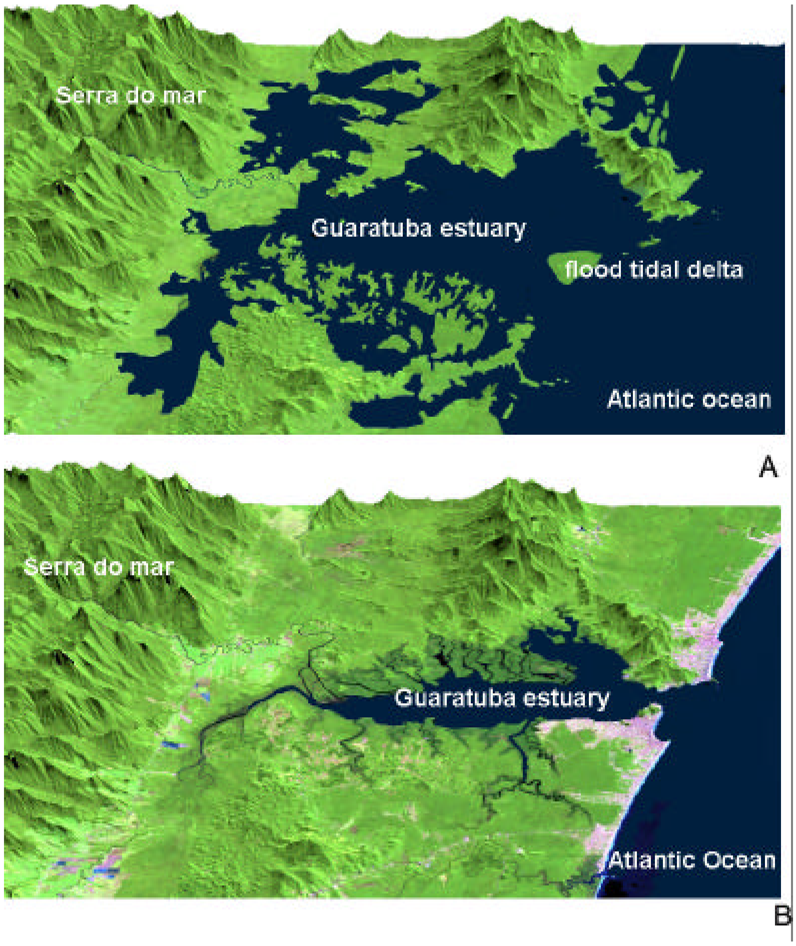

Figure 7: Paleogeographic reconstruction of Guaratuba estuary at the Holocene sea-level maximum (A) and Guaratuba estuary at present sea-level (B) (Source Mineropar-Minerais do Paraná S/A)

Figure 8: Entrance of Baía de Guaratuba with the position of the ebb-tidal delta highlighted by breaking waves.

The Prainha beach morphodynamics is strongly influenced by the shift of channel-margin linear bars. Newly emerged areas after 1950 were quickly occupied (Figure 9). These areas are prone to fast erosion if a change of the main ebb channel occurs.

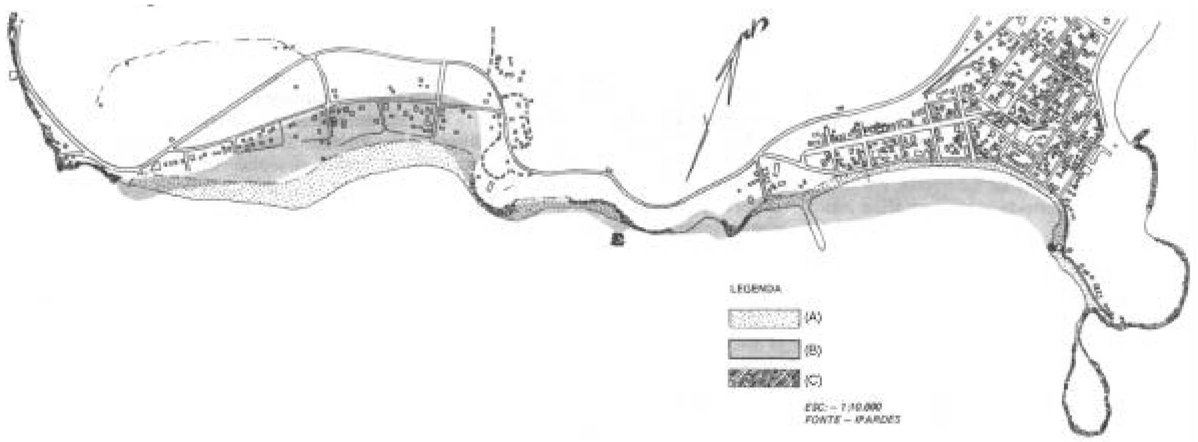

Figure 9: Contour of Prainha beach in 1980 (A) and 1954 (B). Note the occupation over recently emerged areas. Rocky coast (C). (after Angulo & Andrade 1984)

Stop 3: Caiobá beach.

Caiobá is one of the most famous beaches of the Paraná coast. Several problems have occurred since the 70's with widespread urbanization. The morphodynamics of this beach is particular because its southern part is influenced by de Guaratuba estuary ebb-tidal delta (Figure 8). The tidal delta terminal lobe have changed is location since the 50's, migrating more than 300 m northward, changing wave refraction patterns and the direction of the littoral drift. At this point the longshore current convergence, induced by the delta lobe, causes a huge sand accumulation (Figure 10). For more information see Angulo (1996)

Stop 4: Brava beach.

Brava beach has undergone erosion problems since the 80's with the construction over the backshore (Figure 11). Several different coastal erosion works have unsuccessfully attempted to curtail the erosive process. For more information see Angulo & Soares (1994).

Figure 10: Caiobá hill and Caiobá beach. Note the beach enlargement and the wave refraction pattern induced by the ebb tidal delta lobal front.

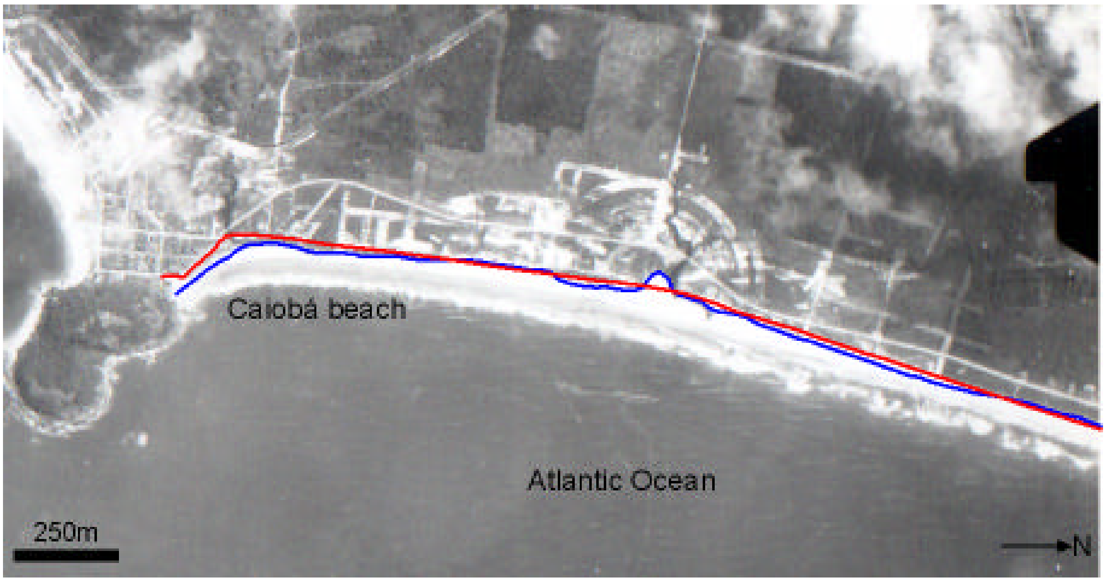

Figure 11: Caiobá beach in 1980 with the 1954 coastline (blue line) and Littoral Avenue partially built up over the beach (red line).

Stop 5: Paranaguá sand quarries.

Pleistocene barrier facies are fully exposed at these quarries. The Holocene barrier facies are no longer visible because the pits were abandoned and drowned by the rising water table. Figure 12 shows the Pleistocene and Holocene barrier distribution in Paranaguá coastal plain.

THE PARANÁ BARRIERS

Barrier elevation appears to be lower than 10 m, which is the elevation of the landward most part of the Pleistocene barrier at Paranaguá coastal plain. The elevation falls gradually to about 3 m at the present backshore (Figure 13). Elevation of the backshore varies along the study area as a function of the local wave height and sediment size. Beach-ridges and foredune ridges are common features

The barriers are underlain by continental deposits that tens of meters thick close to the shoreline. The crystalline basement outcrops at the landward side of the barriers, but deepens to about 100 m at the shoreline in Paranaguá coastal plain (Bigarella et al. 1978).

Sedimentary composition

The barriers are composed of well-sorted, medium and fine quartzose sand, with subordinate proportions of carbonate bioclasts, heavy minerals, silt and clay (Angulo 1992, 2004).

In the upper part of the barriers (both Holocene and Pleistocene), diagenetic processes, associated with concentration of iron hydroxides and organic matter (spodozol horizon), lend a brown color to the sediments at a level apparently associated with the water table (Figure 14). This diagenetic process is observed in sediments younger than 3,000 yr cal ^{14}C BP. Trends in heavy mineral concentration (Souza 1999) suggest a net-northward littoral drift transport. The northward trend can be locally reversed due to small-scale circulation cells or the presence of inlets.

Pleistocene and Holocene barriers differ in relation to their heavy mineral content. Unstable minerals account for an average of 43% of the heavy mineral content in the Holocene whereas they make up for an average of 13% in the Pleistocene barriers, indicating a larger degree of mineral dissolution (Giannini 1993, Lessa et al. 2000).

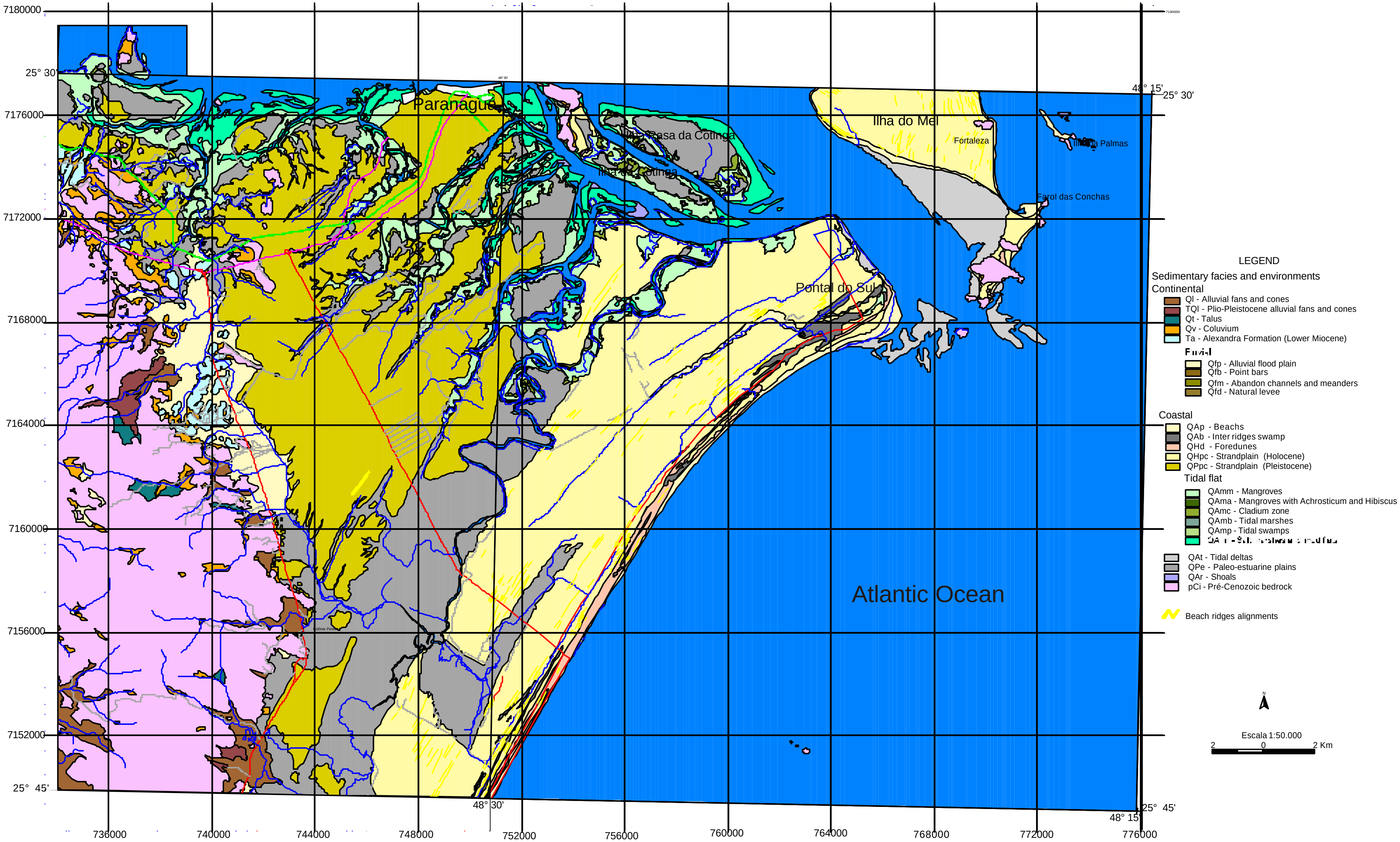

Figure 12: Paranaguá geological map for the Cenozoic (After Angulo 2004)

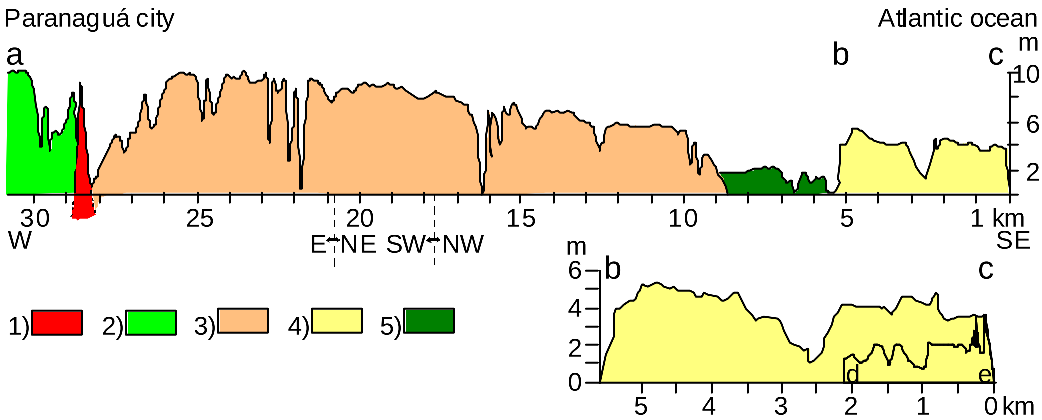

Figure 13: Topographic profiles of the Paranaguá coastal plain (after Bigarella et al. 1978 and Lessa et al. 2000). (1) bedrock, (2) continental sediments, (3) Pleistocene barrier, (4) Holocene barrier, (5) paleoestuarine sediments.

Figure 14: Sand cliff sculpted in the Holocene barrier at Ilha do Mel. Concentration of iron hydroxides and organic matter is observed at the cliff's base and laminas with heavy mineral concentrations in the upper part.

THE HOLOCENE BARRIERS

The Holocene barriers make up the present shoreline in the entire area except in the southern extremity close to Barra Velha, where erosion caused significant recession of the shoreline and sculpted cliffs on the Pleistocene barrier (Figure 4). Lessa et al. (2000) have suggested that widening of the Holocene barriers towards the north is a result of a net northward sediment drift associated with a cell of sediment circulation that starts south of Barra Velha. The northward sediment transport would bypass the ebb-tidal deltas and the few existing headlands fronted by sea floors less than 10 m deep.

Sedimentary Facies

Two-dozen sedimentary facies were identified above an erosive surface imprinted upon Pleistocene sediments. These facies are associated with the following environments of deposition: innershelf, shoreface, foreshore, flood-tidal delta and tidal channel (Angulo 1992, Lessa et al. 2000, Araújo 2001, Souza 1999, 2005).

The innershelf facies within the barrier occur at an elevation interval between -7 m and -10 m. Characteristic sedimentary structures are linsen, wavy and mud drapes (Figure 15). Similar sedimentary sequences are observed on the present innershelf (depths between 12 m and 15 m), where a series of erosive surfaces and shelly, lag deposits occur between 20 to 40 cm below the sea floor (Veiga 2005).

Figure 15: Innershelf muddy sand highly bioturbated with bivalve (Tivela foresti) in living position (after Souza 2005)

Shoreface facies occur at an elevation interval between +1 m and -7 m. The lower shoreface is dominated by fine to very fine sand and bioturbated mud intercalated with swaley cross stratification 15-25 cm high and 1-4 m long (Figure 16). Muddy sediments are presently observed in the lower shoreface between 6 and 9 m of depth, in agreement with the elevation of the bioturbated muds in the pits.

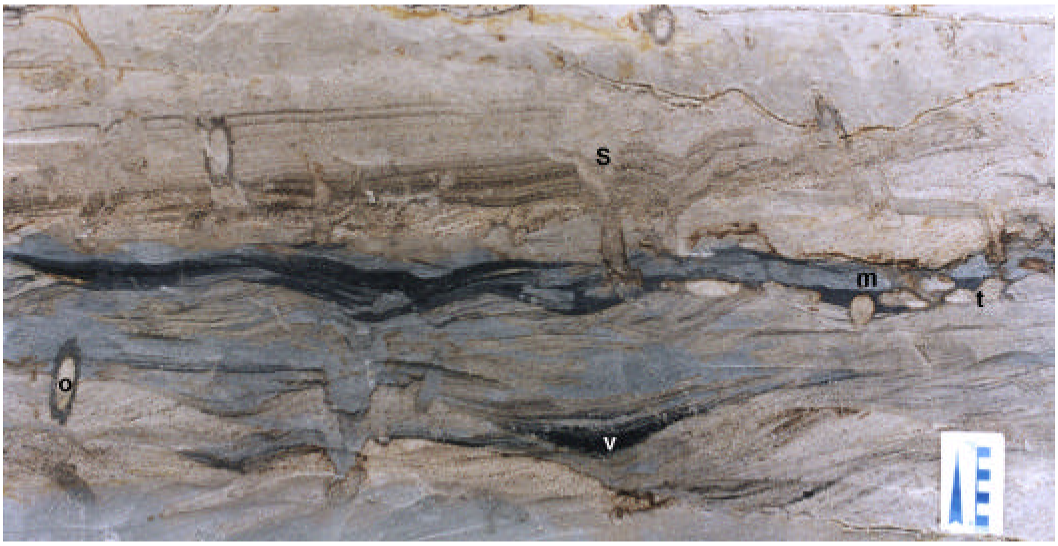

Figure 16: Section of the pit showing the paleo lower shoreface facies with very fine and coarse sand, mud (m) and vegetal debris (v). The picture shows swaley cross stratification, Ophiomorpha (o) and other tubes (t) as well as escape structure (s) (after Souza 2005).

The upper shoreface is dominated by several types of cross stratification: planar, tangential, trough and sigmoidal, 4 cm to 50 cm thick (Figure 17). The foreshore occurs at an elevation interval between +1 and - 4 m, and is dominated by low-angle cross stratification (Figure 18).

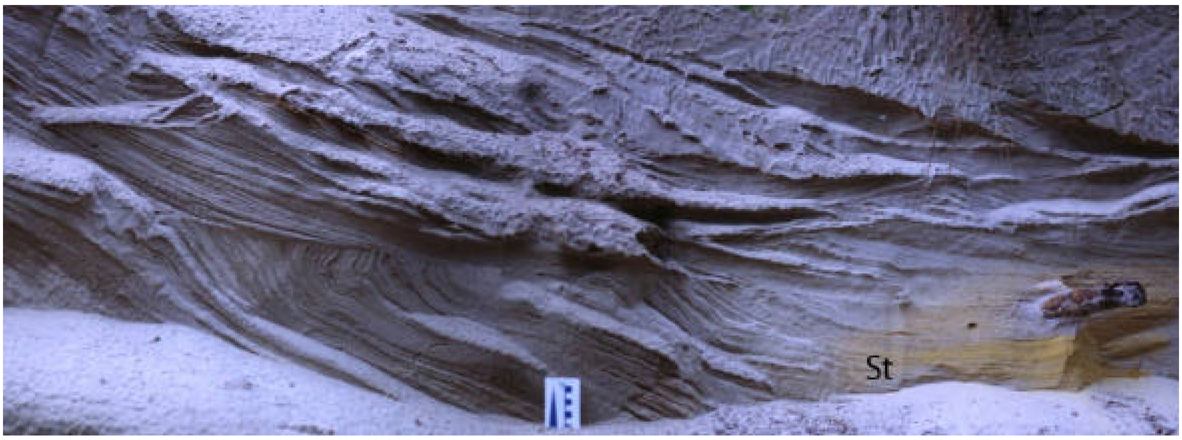

Figure 17: Section of the pit showing the paleo upper shoreface sandy facies with trough cross stratification (st). Foresets are deformed by fluidification (after Souza 2005).

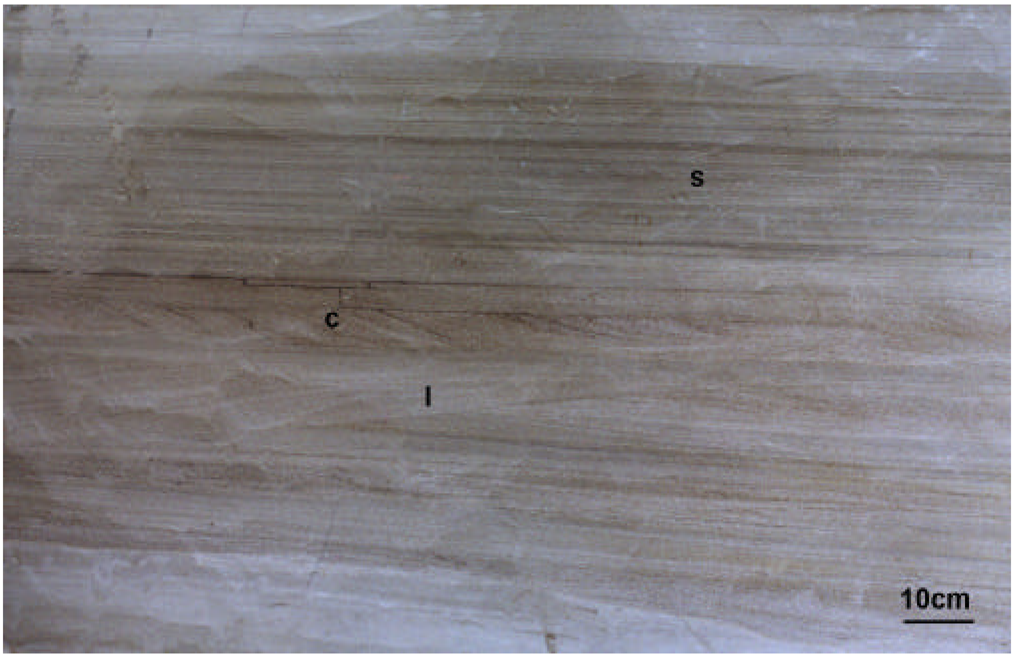

Figure 18: Section of the sand pit showing the paleo foreshore sandy facies with small planar cross stratification (c) and low-angle cross stratification dipping both seaward (s) and landward (l) (after Souza 2005).

Flood-tidal delta facies occur between 0 and 2 m of elevation. Its upper part is characterized by large scale tangential cross stratification 0.4 to 1.1 m thick (Figure 19) (Lessa et al. 2000, Araújo 2001). The foresets dip to the NW and indicate landward sediment flux. The flood-tidal delta facies is overlain by foreshore facies 1 to 2.5 m thick (Figure 20) that indicates reworking of the delta surface by waves during sea level fall.

Figure 19: Large planar cross stratification corresponding to the flood tidal delta facies at Ilha do Mel (after Araújo 2001).

Figure 20: Horizontal laminations of the foreshore facies overlying large tangential cross stratification corresponding to flood tidal delta facies at Rio Maciel (after Lessa et al. 2000).

Barrier thickness and limiting surfaces

The contact between the Holocene and the Pleistocene was determined on the basis of radiocarbon dates and GPR profiles (Souza 2005). At the sand pits, textural changes and radiocarbon dating of organic mud and shells indicate an erosive contact at - 8 m (Figure 21), resulting in a thickness of 12 m at the center of the Paranaguá barrier. The contact is erosive, and is well marked by strong reflectors in the GPR profiles obtained further inland. As indicated in Figure 22 these reflectors rise landwards to an elevation of -1 m at the contact between the Holocene and Pleistocene barriers. It implies that Holocene barrier thickness varies from about 13 m to 14 m close to the shoreline to 5 to 6 m on the landward side. The erosive contact underlying the Holocene barrier may define three sorts of stratigraphic surfaces: a wave ravinement surface, a tide ravinement surface, and a regressive surface of erosion.

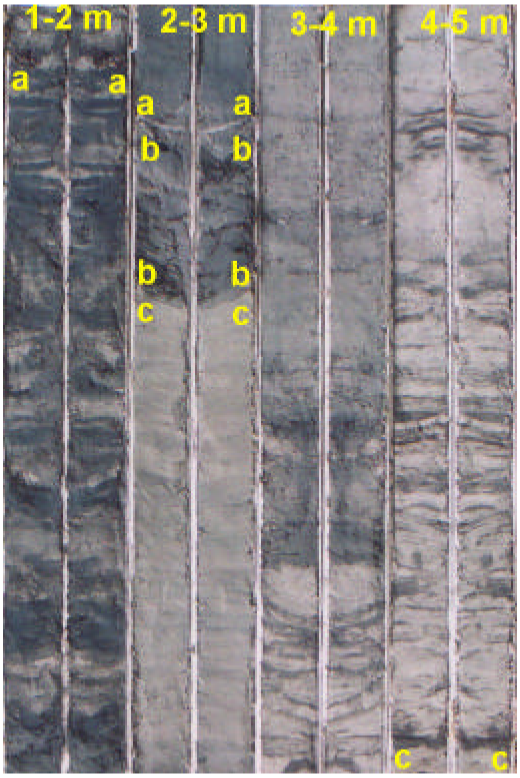

Figure 21: Section of a core showing the association of Holocene and Pleistocene facies at Paranaguá (after Souza 2005): (a) innershelf Holocene facies, (b) Pleistocene mud and (c) Pleistocene sandy-mud Tubes are 1 m long and 7 cm wide. The core begins at the upper left corner.

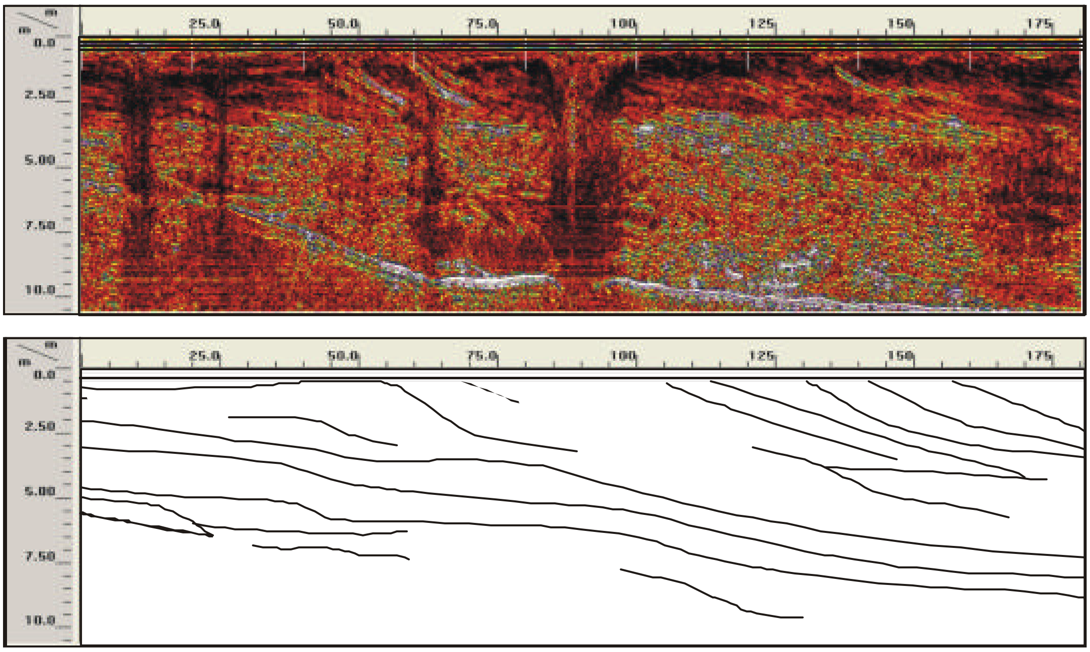

Figure 22: Interpretation of a GPR profile from the Holocene regressive barrier at Paranaguá (after Angulo et al. 2005) showing clinoforms dipping seaward (thin lines) and an erosional surface (thick line) that defines the limit between the Pleistocene substrate and the Holocene barrier.

Barrier evolutionary model

Curved ridges visible in aerial photographs, as well as channel scouring and inlet fill sequences in the GPR profiles (Figure 23) in the most internal part of the barriers of Itapoá-Guaratuba and Paranaguá, suggest that spits might have been common features at the initial stages of the Holocene barrier formation. Radiocarbon dating of estuarine deposits provided an age of 6,489-5,629 ^{14}C cal BP, which coincides with the time of sea level maximum suggested by Angulo et al. (2006a).

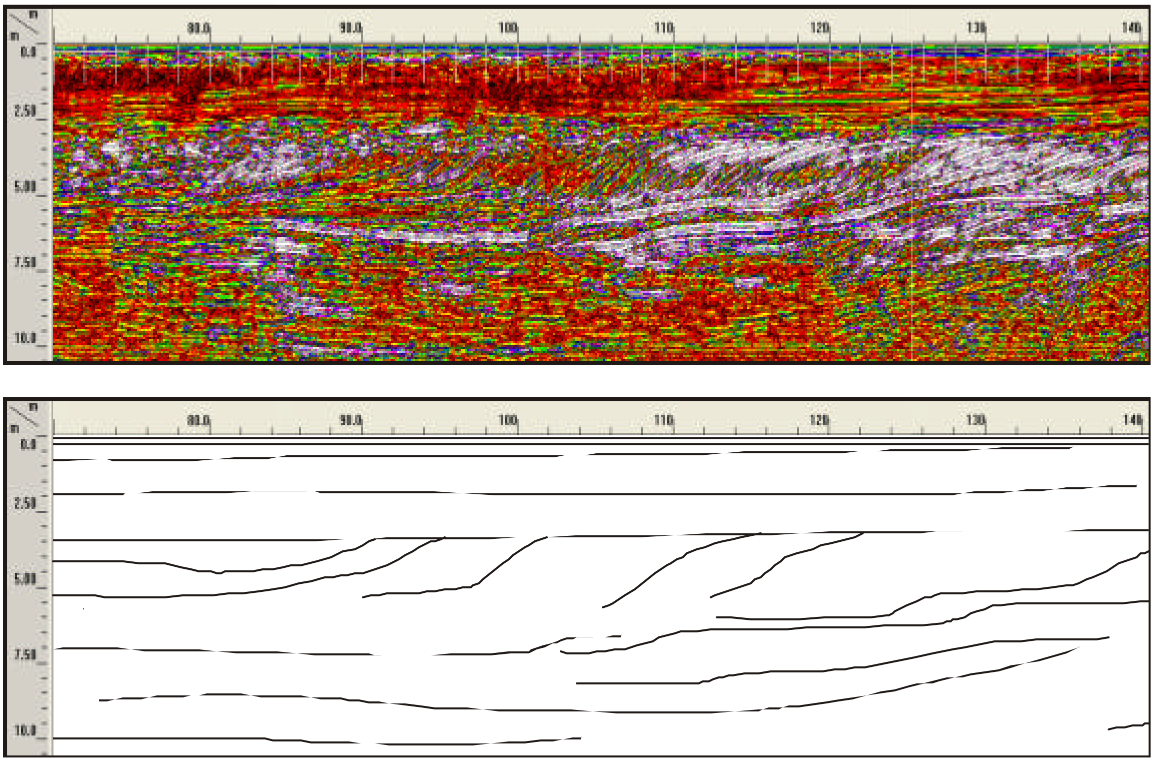

Figure 23: GPR profile longitudinal to the barrier of Itapoá (after Angulo et al. 2005) showing clinoforms dipping parallel to the coast.

Few paleo-shoreline positions with chronological control are identified in the Paranaguá barrier: the shoreline associated with the transgression maximum and the shorelines associated with the paleoshorefaces dated at the sand pit in the middle of the Holocene barrier. If the transgressive barrier ever existed, the meandering estuarine channels must have eroded most of them in Paranaguá and Itapoá-Guaratuba coastal plains. In Superagüi coastal plain, where the Holocene barrier is apparently fully encroached against the Pleistocene one, the contact between the barriers illustrates (Figure 24) what would have happened in Paranaguá and Itapoá in the case the estuarine channels did not exist.

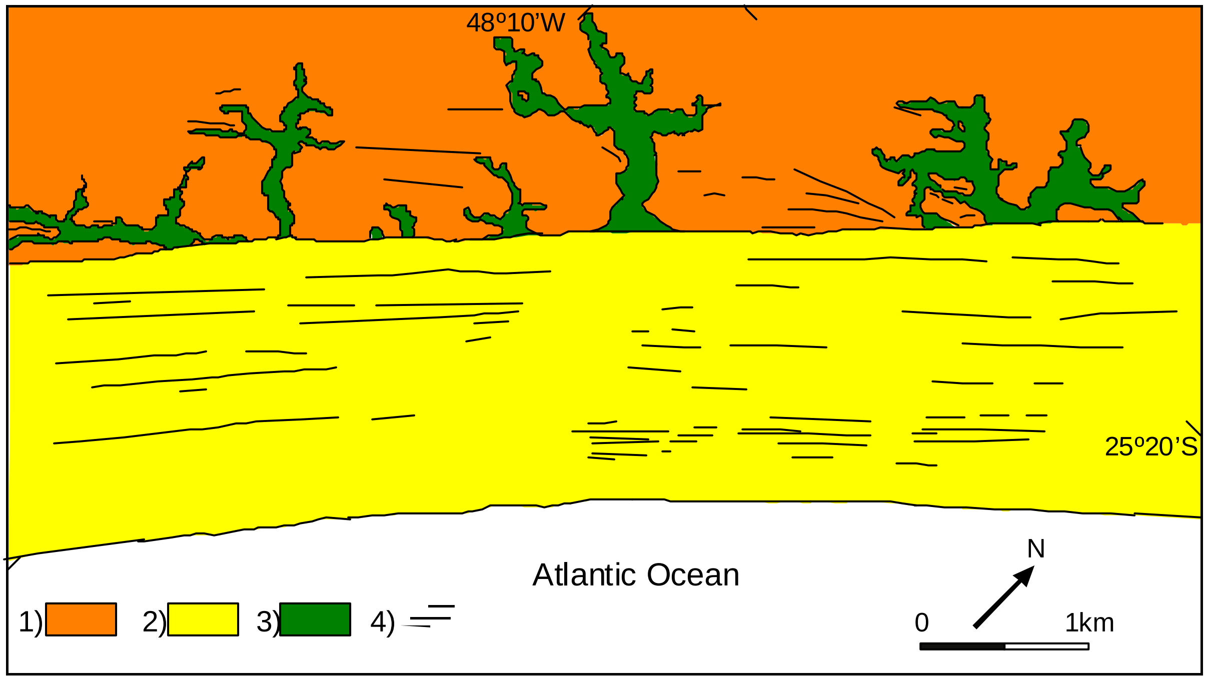

Figure 24: Pleistocene and Holocene barrier limit at Superagüi (after Angulo 1992). 1) Pleistocene barrier, 2) Holocene barrier, 3) infilled drainage channels, 4) ridge trends

At the sand pit in Paranaguá barrier, the isochrones plotted in figure 25 point to very little coastal progradation in the first 1,000 years after sea level maximum, when sea level might have fallen between 0.5 to 1 m. Limited or no coastal progradation of Paranaguá, and possibly Itapoá-Guaratuba barrier within this time period could be related to the morphodynamic character of the estuaries at the Holocene sea-level maximum. Extensive marine sand deposition inside Paranaguá estuary is indicated by a transgressive sand sheet (Lessa et al. 1998) and extensive flood-tidal delta deposits that encompass the core of the islands of Guaraguaçu, Cotinga, Rasa da Cotinga and do Mel (Lessa et al. 2000, Araújo 2001). Barbosa & Suguio (1999) also indicate a paleo flood-tidal delta inside Baía de Guaratuba. The initial estuary sand trapping is ascribed to a flood-dominant tidal-current regime at a time the estuary had not yet developed intertidal areas extensive enough to promote the present ebb-dominant condition.

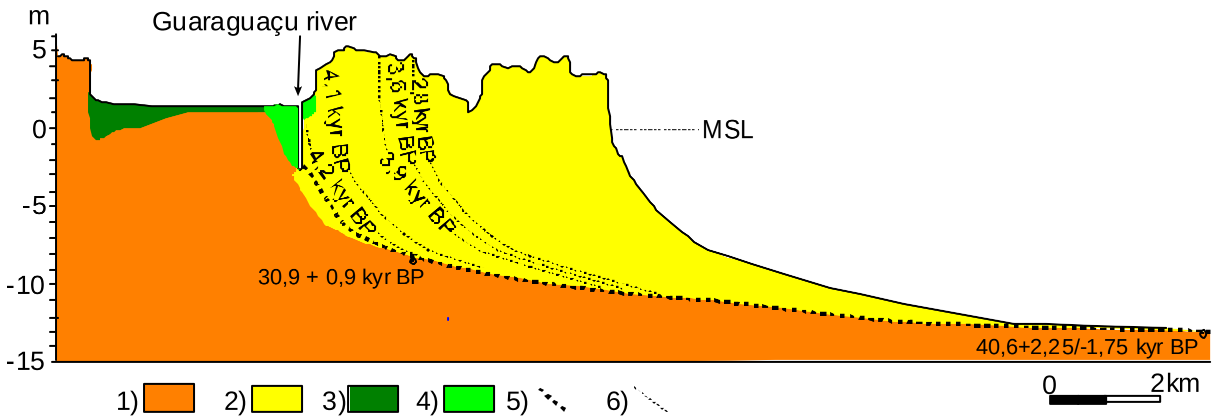

Figure 25: Schematic profile of Holocene regressive barrier at Paranaguá. Topography is based on a surveyed cross section along the highway. 1) Pleistocene substrate, 2) Holocene barrier, 3) Holocene paleolagoon, 4) alluvial sediments, 5) ravinement surface, 6) isochrones.

Coastal progradation in Paranaguá apparently started at about 4,000 yr ^{14}C cal BP and shifted the shoreline 2,000 m seawards during the next 1,500 years (Figure 25). Figure 25 also suggests that 3.5 km of barrier progradation in Paranaguá occurred in the last 2,800 years, with a sea level fall of about 2.0 m as indicated by the paleo-sea level envelope. Within this time the northern extremity of the barrier continued to extend northwards, generating the offset that presently exists between the orientation of the estuary mouth and the flood-tidal deltas at the islands of Guaraguaçu, Cotinga and Rasa da Cotinga. Reverse-circulation drill holes performed along the present shoreline do not identify the muddy shoreface deposits in the northern section of the barrier. It suggests that the core of the barrier sediments are related to channel fill, as the barrier migrated over an estuary entrance that might have become increasingly narrower and deeper, with the onset of ebb-dominant conditions. A tidal diastem is likely to occur at the base of the Holocene barrier deposits at this location.

A fully ebb-dominant condition in Baía de Paranaguá might have been established in the last few thousand years, with the onset of a hydraulic groin that helped to steer the shoreline further to the northeast. The growth of an ebb-tidal delta dampened wave height close to the entrance of the Baía de Paranaguá, lowering the elevation of the barrier in the last 3 km at the northern end of the barrier by at least 1 m in relation to sections further south (Figure 13, profiles b-c and d-e).

THE PLEISTOCENE BARRIER

Information on the Pleistocene barrier are few and fragmented (Bigarella et al. 1978, Tessler & Suguio 1987, Angulo 1992). Investigation of the Pleistocene barrier facies and evolution are presently under way.

At the quarries the barrier thickness is about 10 m, but the upper barrier facies (upper shoreface and beach) are missing. The barrier has apparently been eroded by fluvial drainage during sea-level lowstands. Morphological evidences of fluvial erosion over the Pleistocene barrier are conspicuous at Paraná and Santa Catarina coastal plains (Angulo & Suguio 1994, Angulo & Souza 2004).

The main sedimentary structures identified so far are swaley cross stratification (Ssc), tabular cross stratification (Sp), trough cross stratification (St), sigmoidal cross stratification (Ssg) within sandy sediments. Linsen (Fl), as well as massive mud beds (Fm), are observed within finer sediments. Tubes, borrows, shell moulds, trunks and roots fragments and vegetal debris have also been identified (Figures 26 to 29).

Radiocarbon dating of wood sample provided an age of 41,200 + 3,400/-2,350 years B.P. This age is close to the ^{14}C range. Similar ages obtained from Pleistocene barriers samples at different Brazilian coast sector were attributed to contamination (Martin *et al*. 1988b; Angulo 2002; Souza 2005). Age determination of corals using U^{234}/U^{238} provided dates around 120,000 years B.P. below a correlate Pleistocene barrier (Martin et al. 1988b). Therefore the Paranaguá barrier could be attributed to isotopic stage 5e.

The facies association and paleocurrent directions suggest that the barrier, at the study sector, developed as a spit growing to the northwest over an estuarine inlet.

Figure 26: Swaley cross stratification (Ssc)

Figure 27: Tabular cross stratification (Sp)

Figure 28: Sigmoidal cross stratification (Ssg)

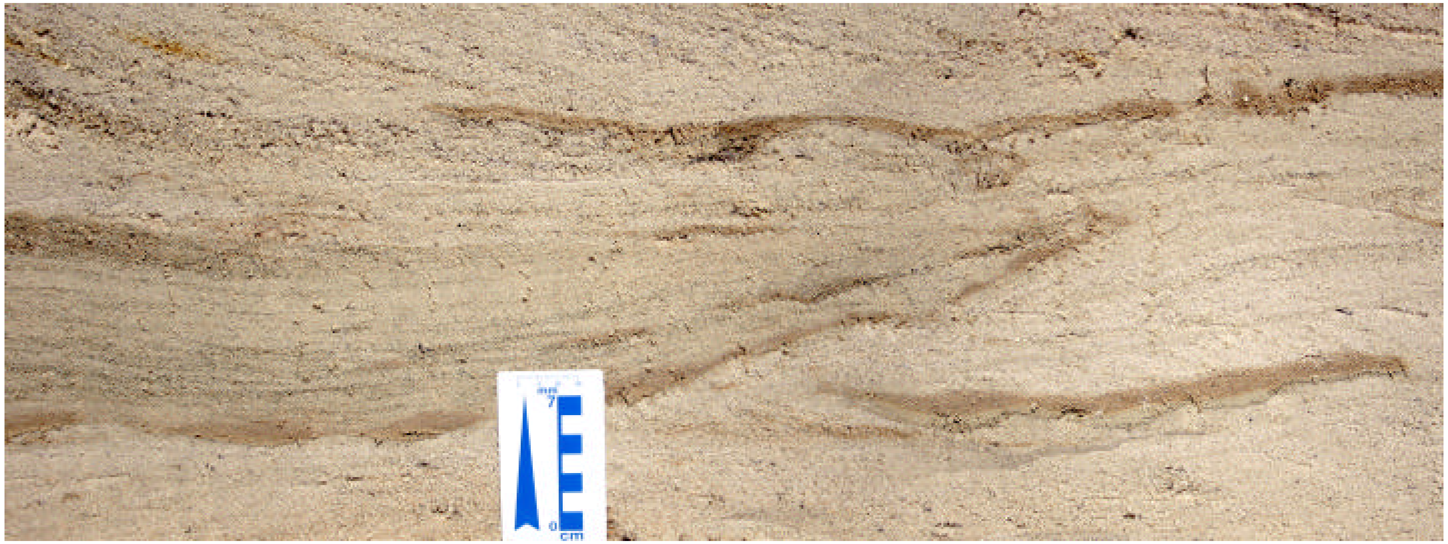

Figure 29: Mud drapes

Stop 6: Paranaguá estuarine complex

The Baía de Paranaguá estuary is part of an estuarine that incorporates two main water bodies: the Baía de Paranaguá itself, which stretches for 50 km on an east-west axis and is about 7 km wide, and the Baía das Laranjeiras, which runs along a north-south axis and is approximately 30 km long and up to 13 km wide (Figure 1). Mean neap and spring tidal heights are, respectively, 1.3 and 1.7 m at the bay mouth, and 2.0 and 2.7 m at Antonina (Marone & Jamiyanaa 1997). Mean freshwater inputs of about 40 m^3/s in the winter and close to 180 m^3/s in the summer have been quantified for the drainage area upstream the Paranaguá Harbour (Mantovanelli 1999). The estuary can change between highly-stratified (summer neap), partly mixed (summer spring) and well-mixed (winter springs) in a fortnight and seasonal bases (Mantovanelli et al. 2004). The estuary displays the longitudinal tripartite zonation of surface sedimentary facies (marine sand - estuarine mud – fluvial sand) that is characteristic of many coastal-plain estuaries (Figure 30). Five sedimentary facies were identified overlying the bedrock. Pre-Holocene fluvial and continental deposits within the paleo-valley form the substrate for the more recent sedimentation. A transgressive mud facies marks the initial stages of estuary inundation. This deposit is observed only in the lower half of the estuary, where greater accommodation space existed and less intensive tidal scouring associated with the subsequent deposition of the transgressive sand facies occurred. The onset of the regressive stage is marked by the deposition of the regressive mud facies, which is presently the most extensive sedimentary deposit within the estuary. The regressive sand facies, which is composed of fluvial derived sediments and is restricted to the head of the estuary, is the least developed sedimentary facies. The vertical succession of the sedimentary facies shows an almost complete stratigraphic sequence and the presence of several bounding surfaces: a transgressive surface, a maximum flooding surface, a tidal ravinement surface, and a tidal diastem. Present ebb tide dominance of the current regime is detrimental to the intrusion of marine sands far into the estuary (marine sands are observed much farther upstream than the shoreline at the transgression maximum). It appears that a morphodynamic change, implying the switch from a flood to an ebb-dominant tidal condition, may have occurred with the partial infilling of the Paranaguá Bay estuary

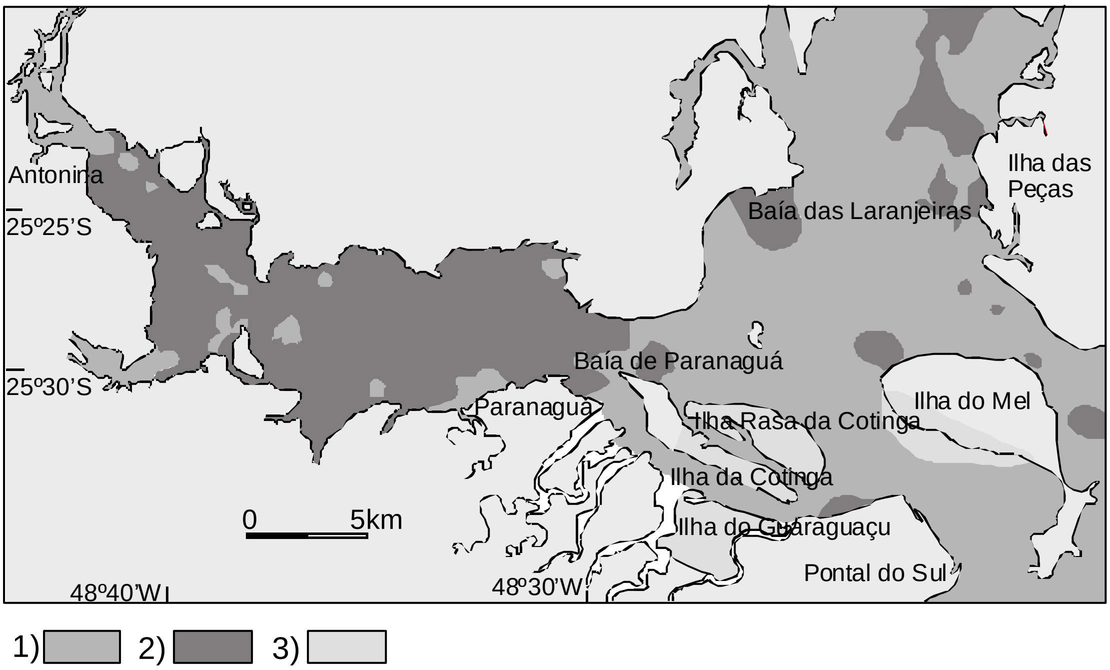

Figure 30: Surface sedimentary facies of Baía de Paranaguá. 1) sandy sediments, 2) sandy-mud and muddy-sand sediments, 3) paleo food-tidal deltas (after Angulo et al. 2007)

Stop 7: Saco do Limoeiro, Ilha do Mel*

At this point, a field of flood-oriented dunes associated to a hemi-flood tidal delta ramp can be seen at low tide (Figures 31 and 32). Tidal current measurements during spring cycles indicate, however, that ebb-tidal currents are faster than flood tidal currents (Figure 33). It is likely that sand transport and dune migration occurs mainly during storm events, with waves reaching the area. The westward sand dune migration was well known by natives, who navigated through the swales to reach the island.

* About the name Ilha do Mel. Mel means honey in Portuguese, but there are different versions of the name. (a) The Carijó Indians appreciate honey, and the name might have been given a while ago. (2) Before the II world war the island was known as Almirante Mehl Island, that was an apiculture man. (3) Until de 60's retired sailors living in the Island produced large quantities of honey. (4) The island fresh water, in contact with salt water, takes a honey color.

Figure 31: Ilha do Mel hemi-flood tidal delta

Figure 32: Sand waves, associated with the flood-tidal delta, emerging at low tide.

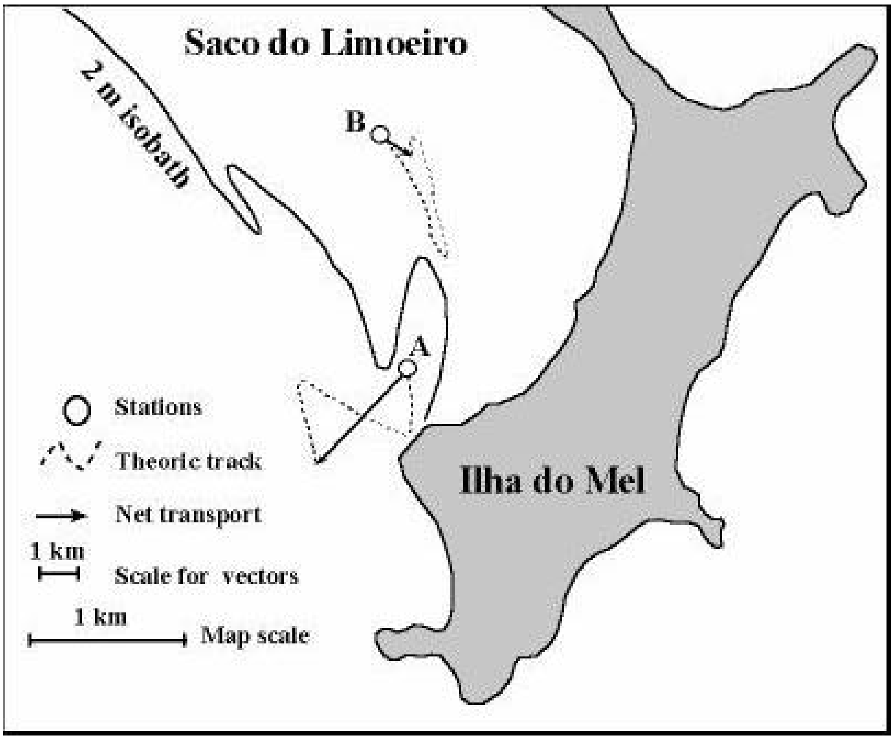

Figure 33: Tidal current velocities at Saco do Limoeiro, Ilha do Mel (After Araújo 2001).

Stop 8: Climbing to Morro do Farol das Conchas

At this point it's possible to see (a) the outer part of the Paranaguá estuarine complex; (b) the northern inlet complex, (c) the Palmas islands, (d) the ebb-tidal deltas and (e) segmentation of Ilha do Mel.

At low tide and/or high swell, waves break over the sand banks of the Paranaguá ebb-idal delta complex (Figure 34). For tidal-delta description see Angulo (1999).

The ebb tidal delta sand shoals have been dredged since the 50's to open, maintain and augment the depth of the channels leading to the harbor (Figure 35). Before the dredging, sand would probably bypass the ebb-tidal delta terminal lobe in a much larger volume. (See Angulo et al.2006b).

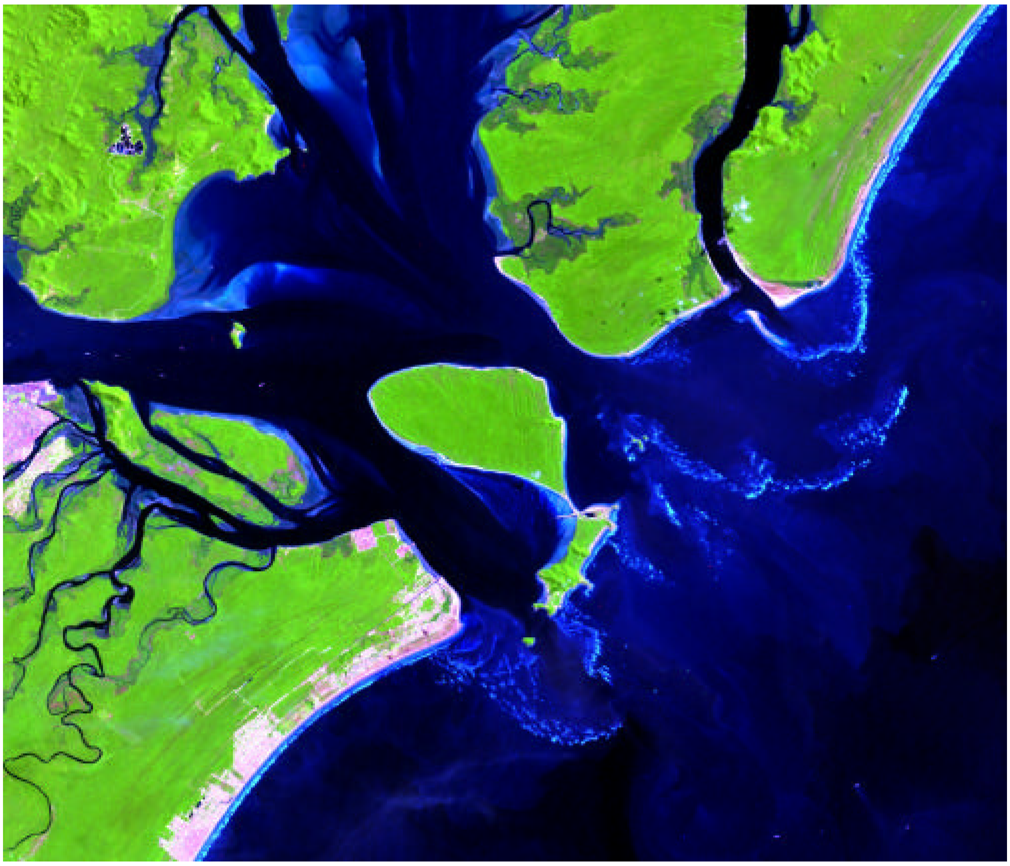

Figure 34: Ebb-tidal deltas fronting Paranaguá estuarine complex inlets.

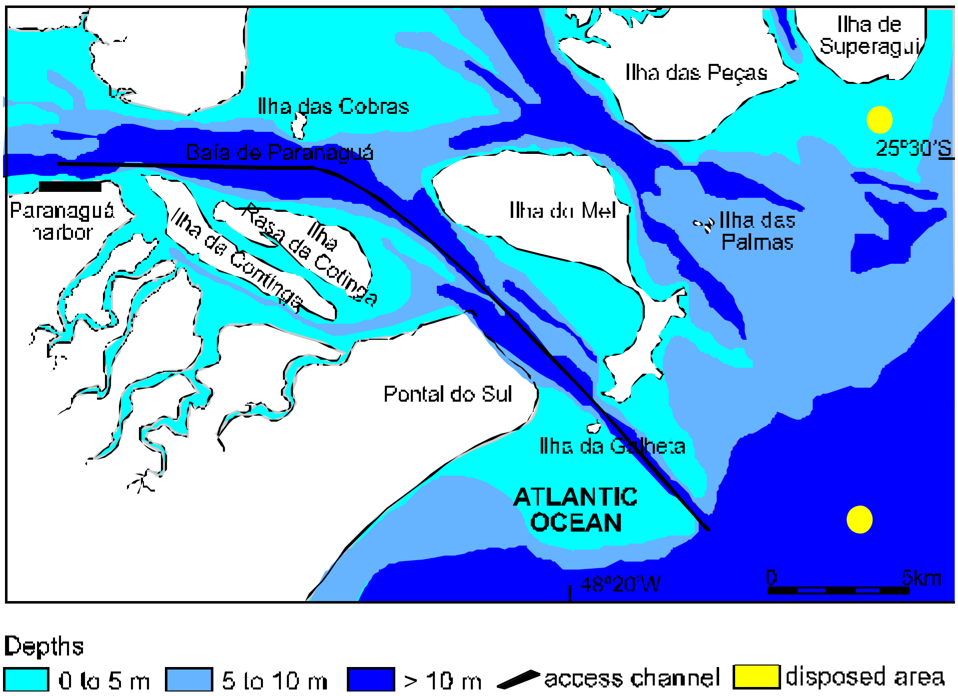

Figure 35: Bathymetry of the Paranaguá estuarine complex and the route to Paranaguá harbor (dark line) through the dredged section of the ebb-tidal delta.

At Farol das Conchas (Shell Firelight) beach a large sand spit with foredunes emerged and enlarged in the last 25 years at (Figure 36). The shoreline near estuary inlets is naturally highly dynamic, and spit growth rates over 200 meters per year have been recorded (Figure 36). However spit growth in Farol beach was related to human activities. The dredged sand was dumped in shallow areas and transported by waves toward the coast (Giannini et al. 2004 and Angulo et al. 2006b). Sand deposition changed the wave refraction pattern and longshore current direction. As a consequence some sectors of the Ilha do Mel are under strong erosion (Figure 37.

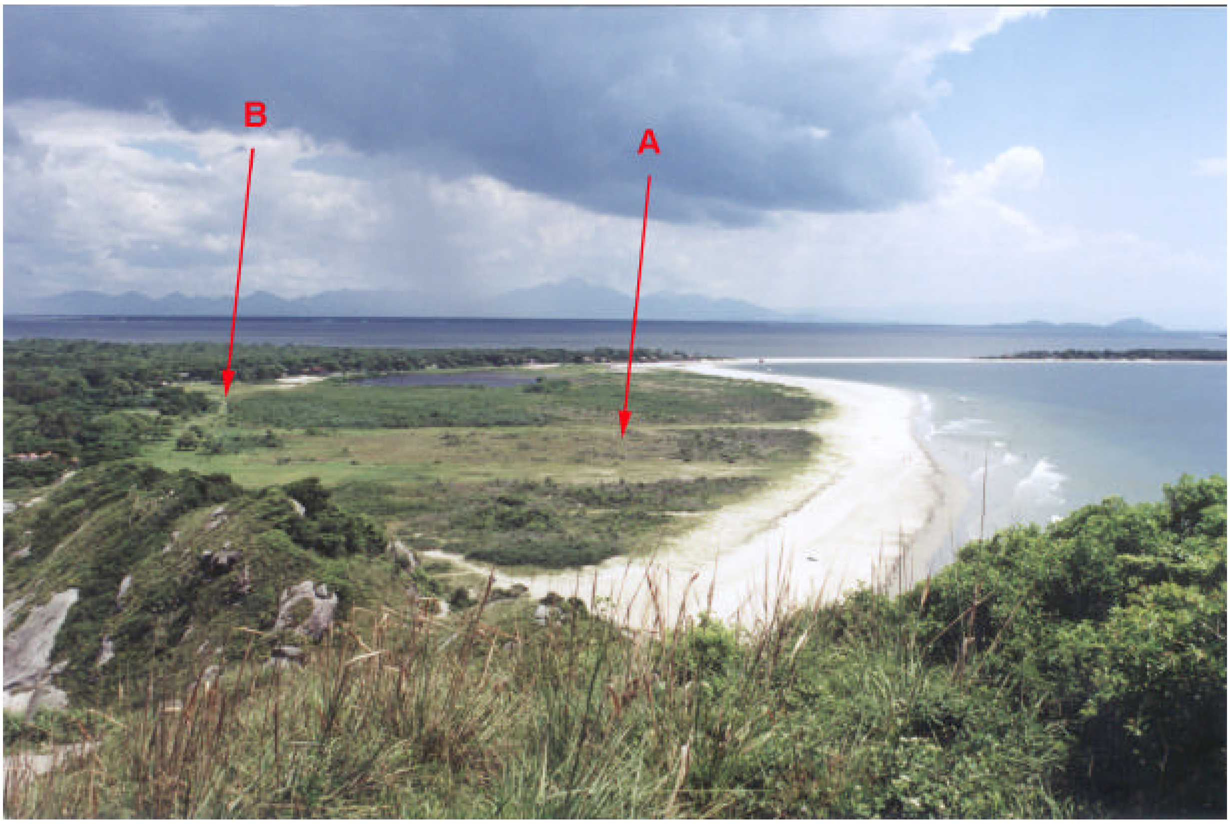

Figure 36: Position of the coastline in the 80's (A) and the progradation that followed (B) at Farol beach, Ilha do Mel.

Figure 37: Coastal erosion at Fortaleza beach induced by changes in the wave refraction pattern.

Stop 9: Praia do Farol (firelight beach)

Vermetid remains between 0.3 m and 3.5 m above its present living position have beem found in this rocky section. Vermetid reef remains are one of the more reliable and precise space-temporal sea-level indicators (Laborel 1986, Angulo & Lessa 1997, Angulo et al. 1999, 2006a). The vermetid *Petaloconchus (Macrophragma) varians* is a sessile gastropod that builds up reefs in the intertidal zone (Laborel 1979, figures 38 and 39). According to Laborel (1986) and Angulo et al. (1999) it is possible determine paleo-sea level with precision $\pm$ 1.0 m, depending on the exposure to waves (Figure 40) and paleo-oceanographic conditions (see Angulo et al. 1999). Mid-Holocene sea-level curves in Brazil have recently been defined with the aid of Vermetid remains (Angulo et al. 2006a).

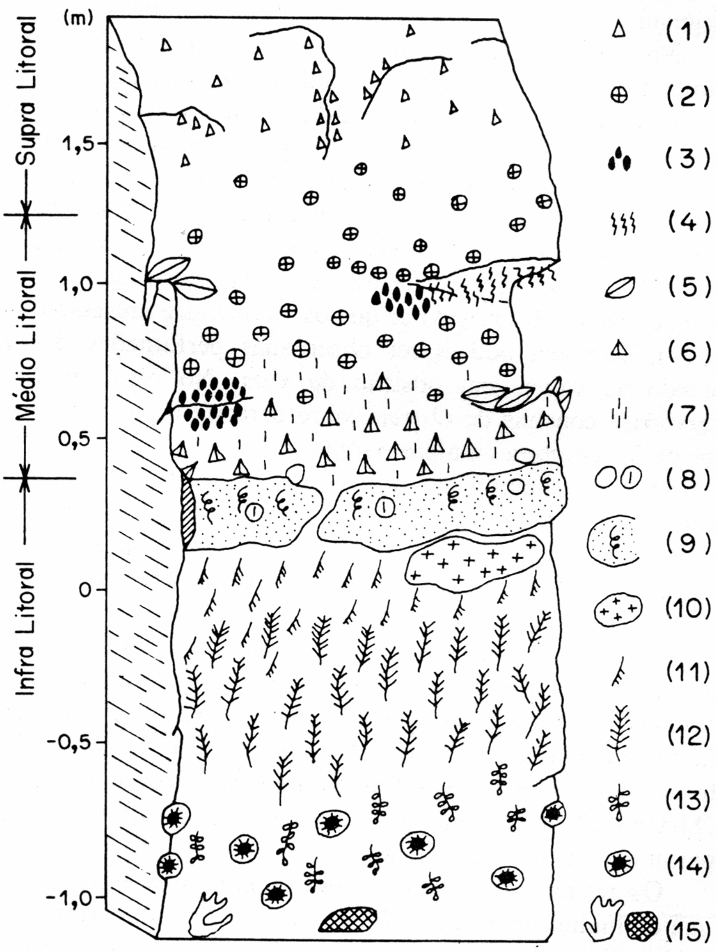

Figure 38: Biological zonation on the rocky coast of northeastern Brazil. 1) Littorina, 2) Chthamalus, 3) Brachydontes, 4) Bostrychia, 5) Grassostrea, 6) Tetraclita, 7) Cyanophytes, 8) Limpets, 9) Vermetids and calcareous algae, 10) Zoanthids, 11) Algal turf, 12) Sargassum, 13) Caulerpa, 14) Echinometra, 15) Coarls (After Laborel 1979).

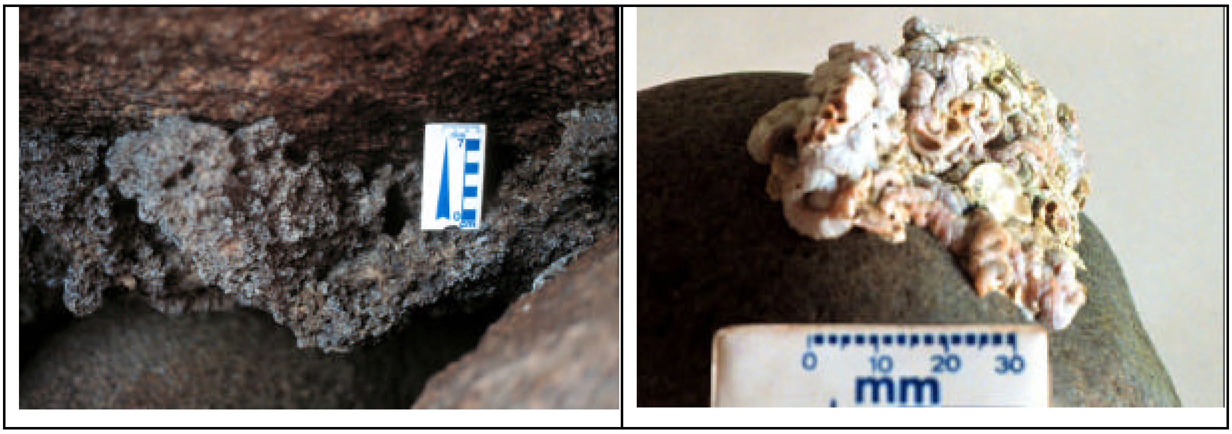

Figure 39: Holocene vermetid reef remains.

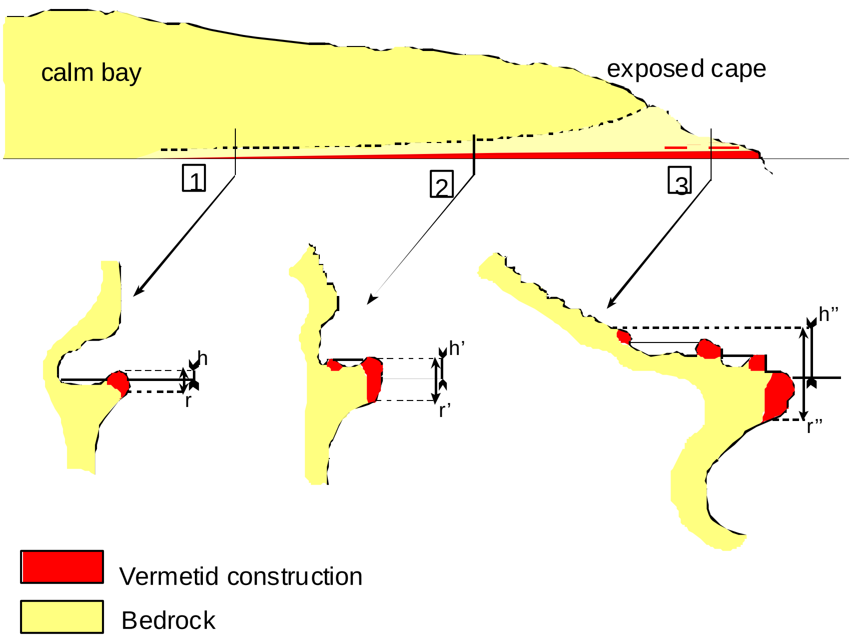

Figure 40: Changes in height and morphology of vermetid constructions and erosion notches going from a calm, sheltered bay to the tip of an exposed cape (After Laborel 1986).

Stop 10: Encantadas beach.

At this point it's possible to see a cave formed by differential erosion between pre-Cambrian migmatites and Juro-Cretacic diabase dikes (Figure 41).

Figure 41: Encantadas cave at Ilha do Mel.

Trip to Curitiba through Graciosa road

Graciosa is a tourist road built in the XIX century to link the coast with the Curitiba plateau. From the road there are beautiful views of the Serra do Mar (up to 1800 m high) with its exuberant rain forest. In some places rainfall can reach 3,500 mm per year.

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