Coastal Erosion and Beach Morphodynamics along the State of São Paulo (SE Brazil)

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ABSTRACT

Coastal erosion seems to be a worldwide phenomenon. In the Atlantic coast of South America, there are several localities that have been referred to in the literature as having already been adversely affected by erosional processes, such as the muddy coasts of Guyana and Venezuela, and the sandy beaches of Brazil (states of Ceará, Rio Grande do Norte, Pernambuco, Bahia, Rio de Janeiro and Rio Grande do Sul), Uruguay (Punta del Este) and Argentina (Mar del Plata).

In the state of São Paulo, coastal erosion occurs along both open and sheltered beaches, around whole Comprida barrier island, and even within lagoonal and estuarine environments. The phenomenon is analogous to occurring in other parts of the Brazilian coast, albeit in other orders of magnitude.

Coastal erosion in the SE sector of the Brazilian coast is being investigated for the first time and only preliminary data and evaluation are still available. Sedimentological-geomorphological studies are in progress along the main beaches of this state. It is intended with this paper to provide a general synthesis of recent preliminary results of our study, including its morphodynamic compartimentation and the reconnaissance of sectors where erosional processes are presently active. This study is very important to better understand the mechanisms that are causing coastal erosion, and to supply subsidies for appropriate erosion prevention and its future mitigation procedures, and consequently beach preservation.

Key words: coastal erosion, beach morphodynamics.

INTRODUCTION

The littoral worldwide has been overwhelmed by the rapid populational growth which is one of the consequences of economic development. Presently, about 2/3 of the world's population live along the coast and, in Brazil, five out of nine of the most populous metropolitan areas are situated on the coast.

About 3.9% of the state of São Paulo population, corresponding to 1,300,000 inhabitants, live on the coast. This number is duplicated during vacations and some consecutive holidays, mostly in the Santos lowland area, named "*Baixada Santista*". Embracing about 50% of the state of São Paulo coastal municipalities (Bertioga, Guarujá, Santos, São Vicente, Praia Grande, Itanhaém and Peruíbe) the *Baixada Santista* is the most industrialized and densely populated coastal region of the country which places it in an over-developed, overcrowded and over-exploited situation.

Many conflicts, generated as a consequence of disordered land occupation of coastal areas, could be minimized or even completely eliminated, if the geological-geomorphological factors which control or affect that area were better understood. These factors, according to Peck & Williams

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(1992) are: eustatic changes of sea-level, sand supply at the coast, land subsidence (sediment compaction), isostatic uplifting, regional tectonic movements, storm impacts, coastal processes (activities related to waves, tides and winds), and human activities (dredging, mining, dams, engineering structures, withdrawal of fluids like oil and groundwater).

Beach erosion is one of the most striking phenomenon among the coastal processes and it has became an emergencial problem for the majority of the world's coastlines. According to Bird (1985, *apud* Bird, 1986) more than 70% of the world's sandy coastlines have shown net erosion over the past few decades, less than 10% sustained progradation, and the remaining 20 to 30% have been stable or shown no measurable change within this period. This modern prevalence of erosion on sandy coastlines has been documented and discussed in a great number of papers, and the majority of the authors assumes that sea-level rise is presently the most important cause for this phenomenon. Bruun & Schwartz (1985) calculated that sea-level rise would contribute with 10 to 100% for beach erosion around the world.

THE BEACH SEDIMENTARY BUDGET

Coastal dunes, beaches and their adjacent nearshore zones act as buffers to wave energy, therefore they are essential to protect the continent against marine erosion. Consequently, they are dynamic sedimentary environments sensitive to change, over timescales ranging from a few seconds to several years.

Whether erosion or sedimentation will dominate on the shoreline depends on the sedimentary budget in this sector, as summarized by Bird (1986).

The cause-effect relationships of coastal erosion processes have been exhaustively discussed in the literature. Komar (1983) suggested that coastal erosion is the result of a complex interaction of physical processes, as well as of combined movements of waters induced by incident waves, tides, storm surges and nearshore currents interacting on the coast. Short (1979), Wright *et al.* (1979) and Short & Hesp (1982) suggested that beach and surf zone morphodynamic states are also other important forcing factors in erosional processes of local scale and short duration. For Bowen & Inman (1966, *apud* Komar, 1983), Bruun & Schwartz (1985), Bird (1986), and Carter (1988), beach erosion would be a product of a variety of causal mechanisms, like sea-level rise, tectonic instability, isostatic subsidence or uplift, climate change (with particular influence on storminess and sea-level rise) and anthropogenic effects. Bruun & Schwartz (*op. cit.*) present a list of the following seven conditioning factors active in beach erosion:

a) the effects of human impact, such as construction of artificial structures, mining of beach sand, offshore dredging, or building of dams on rivers;

b) losses of sediments offshore, onshore, alongshore and by attrition;

c) reduction in sediment supply from the sea floor;

d) reduction in sediment supply due to decelerating cliff erosion;

e) increased storminess in coastal areas or changes in angle of wave approach;

f) increase in beach saturation due to higher water table or increased precipitation;

g) sea-level rise.

It is not easy to establish the role played by each one of these factors in a beach sedimentary budget. Large scale regional studies are necessary to understand the relative contributions of different processes along a coastline, in order to mitigate erosion and preservation of beaches (management program).

SEA-LEVEL RISE: LAST AND NEXT CENTURIES

The first references on a contemporaneous sea-level rise report back to the 40's and 60's, when some authors used several evidences related to cryologic aspects and from tide gauge stations, to propose rates ranging from more than 5 to 30 cm/century (Barnett, 1983). The most recent studies on sea-level trends during the last 100 years have used data from the projects related to GLOSS

(Global Sea-Level Observing System – Intergovernmental Oceanographic Commission) and PSMSL (Permanent Service for Mean Sea-Level). Long-term series obtained from hundreds of tide gauges around the world revealed that during the last 100 years the sea-level rise ráte was in average 10 to 15 cm or about 1 to 2 mm/year (Gornitz *et al.*, 1982; Barnett, 1983; Hoffman, 1983; Bruun, 1986; Warrick & Oerlemans, 1990, *apud* Gornitz, 1995; Baker, 1993; Pirazzoli, 1993; Gornitz, 1995). For the Brazilian southeastern coast Mesquita (1994), based on tide gauge data, presented an average value of 30 cm/century.

The reason for this sea-level rise, according to the mentioned authors, would be related to geologic and climatic factors. Warrick & Oerlemans (*op. cit.*) quantified these factors with the following proportions: 38% due to thermal expansion of the ocean mass, 38% due to melting of mountain glaciers and small ice caps, and 24% due to enhanced melting of marginal portions of polar and Greenland ice sheets. The recent newspaper notices on melting of large volumes of glaciers and dislocation of enormous icebergs from the Antarctic could be related to these processes. The majority of the researchers believes that the climate change has been the most important factor for the recent sea-level rise. There are countless works on this subject, as well as on the role of the anthropogenic activities enhancing recent climate change (Hoffman, *op. cit.*; Mosetti, 1989; Gornitz, *op. cit.*). The authors are unanimous to assume that changes in the atmospheric composition, due to anthropogenic emissions particularly of the greenhouse gases (CO, CO_2, CH_4, NO_x, and chlorofluorocarbons), have been responsible for global warming, leading to glacial melting and thermal expansion. Numerical models indicate that, if greenhouse gases concentration is doubled, the global warming in the next century will be between 1.5 to 4.5°C (Warrick & Oerlemans, *op. cit.*). On the other hand, Chylek & Kellogg (1982, *apud* Hoffman, *op. cit.*) estimated that 1°C of global temperature rise would produce an estimated sea-level rise of 0.10 to 0.25 m.

Future sea-levels is expected to rise by about 1 m, with a "best-guess" value of 48 cm by the year 2100 (Gornitz, *op. cit.*). Healy (1991) suggested, for coastal planning purposes, rise rates between 0.3-1.15 m by the same year.

OBJECTIVES AND STUDY AREA

It is intended with this paper to provide a general synthesis of recent preliminary results of our study along the whole coast of the state of São Paulo (southeastern Brazil) including its morphodynamic compartimentation and the reconnaissance of sectors where erosional processes are presently active. This study is very important to supply subsidies for appropriate erosion prevention and its future mitigation procedures, and consequently beach preservation.

The 500 km long, the state of São Paulo coast (Fig. 1) has a SW-NE general trend, and about 300 km are occupied by 60 of the most representative beaches, between Ilha Comprida (south) and Fazenda (north) beaches. These beaches are being studied and morphological and sedimentological analyses are in progress since 1991.

Along the São Paulo coastline wave trains approach from SE, S, SW, E and NE quadrants, which can depend of atmospheric systems. Field measurements (1992, 1993, 1994, 1995) and data obtained from aerial photos (1962, 1965, 1973, 1981, 1987, 1994) indicate that the dominant incident waves come from SE sector (Souza, 1994), with about 70% of the measurements ranging between S20-60E. These results are similar to those from CTH/USP (1973) and Bomtempo (1991) obtained in the São Paulo southern littoral, and Souza (1990) in the northern coast. Tidal regime is microtidal (< 2 m) with semidiurnal tides with diurnal inequality.

The distinct geological-geomorphological scenarios of the São Paulo coast (Fig. 1) enables its subdivision into some compartments. Suguio & Martin (1978) proposed its compartimentation into five sectors, based mostly on differences in areal extent of the coastal plains. In this paper, a new compartimentation is proposed, including seven sectors (Fig. 1), based mostly on modal states or the morphodynamics of the present beaches and general coastal physiography. On the other hand, it is known that there is a relationship between these

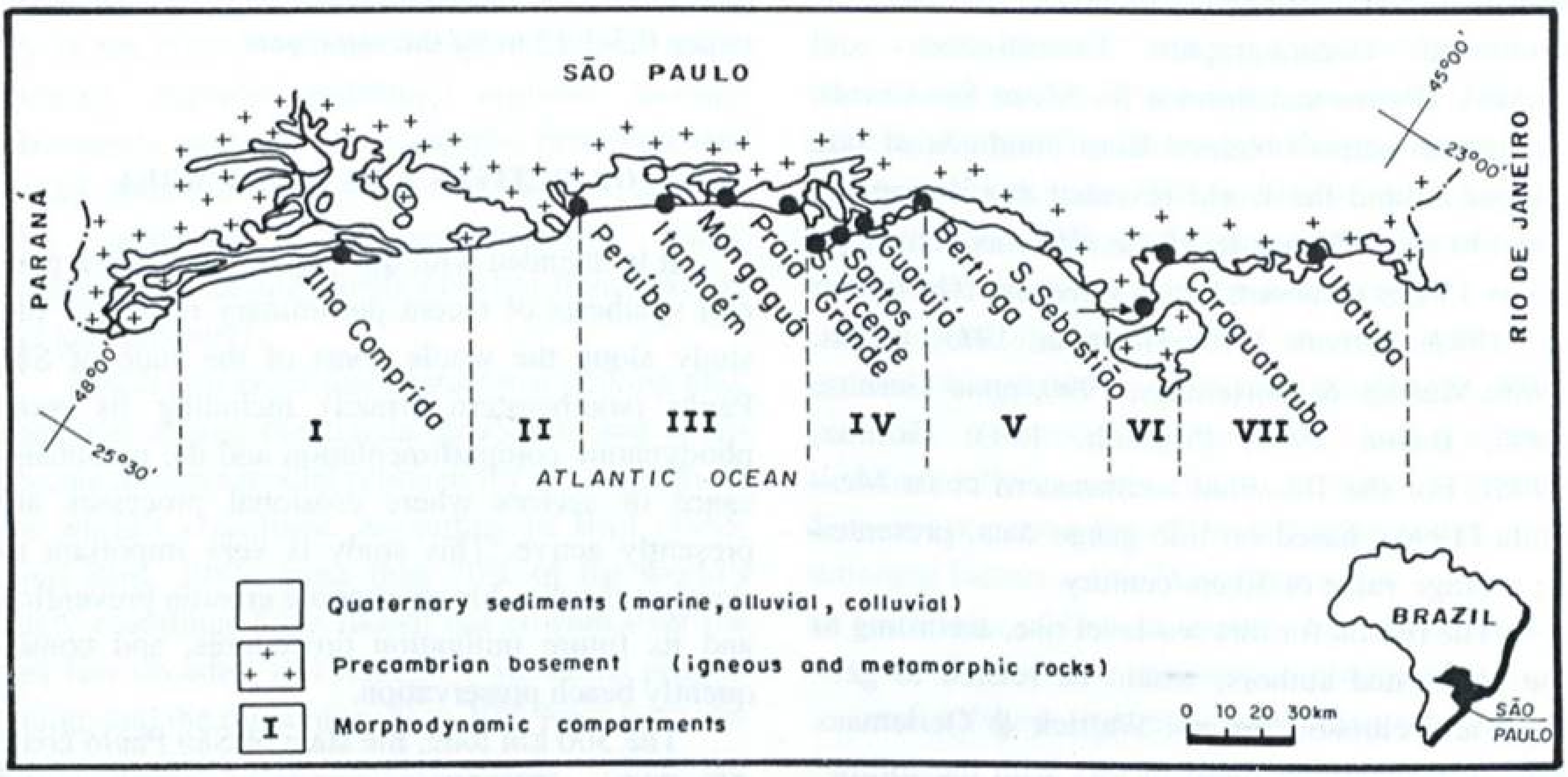

Fig. 1 — The coast of the state of São Paulo and its morphodynamic compartimentation.

beaches and the Quaternary coastal plain (beach ridges plain) evolution, and then the present coastal physiography.

COASTAL MORPHODYNAMIC COMPARTIMENTATION AND GENERAL FEATURES

Beach morphodynamic characterization was made based mainly on: morphological qualitative and quantitative characteristics of beach profiles such as beach (foreshore) and upper surf zone slopes; presence of sandy features (berms, cusps and longshore or crescentic bars); wave characteristics such as the type of wave breaker (spilling, plunging, and collapsing or surging), number of waves in surf zone, wave reflectivity, relative energy level, and approach angle of incident waves; the dominant beach sediments and transport (nearshore currents); and presence or absence of eolian sedimentation in the backshore area. These data were compiled and compared with a table from Sasaki (1980, in Carter, 1988:59), which synthesize the characteristics of coastal domains into dissipative (high and low-energy), transitional or intermediate and reflective, and also based on beach morphodynamic states described in Short (1979), Wright *et al.* (1979) and Short & Hesp (1982).

The mentioned longshore transport directions are preliminary based on geomorphic indicators of longshore currents (Taggart & Schwartz, 1988) obtained from field and aerial photos and satellite images observations and measurements.

Coastal physiography is mainly associated with the distance from the Serra do Mar mountain ridge in relation to the coastline (Fig. 1). In the southern coast it is far way from the sea, but plunges into the sea in the northern coast. Consequently, coastal plains are very extensive in the south and become progressively narrower northward. The same general pattern is observed regarding the beaches.

Human occupation and sand mining activities are also mentioned because they have a very important role in the present coastal erosion processes.

SECTOR I (Figure 2)

The coast between Ilha Comprida and Juréia (Peruíbe) beaches, situated at the southernmost end of the state of São Paulo extends according to a NE-SW trend. It is associated to a barrier-island (Ilha Comprida) and a complex lagoonal-estuarine

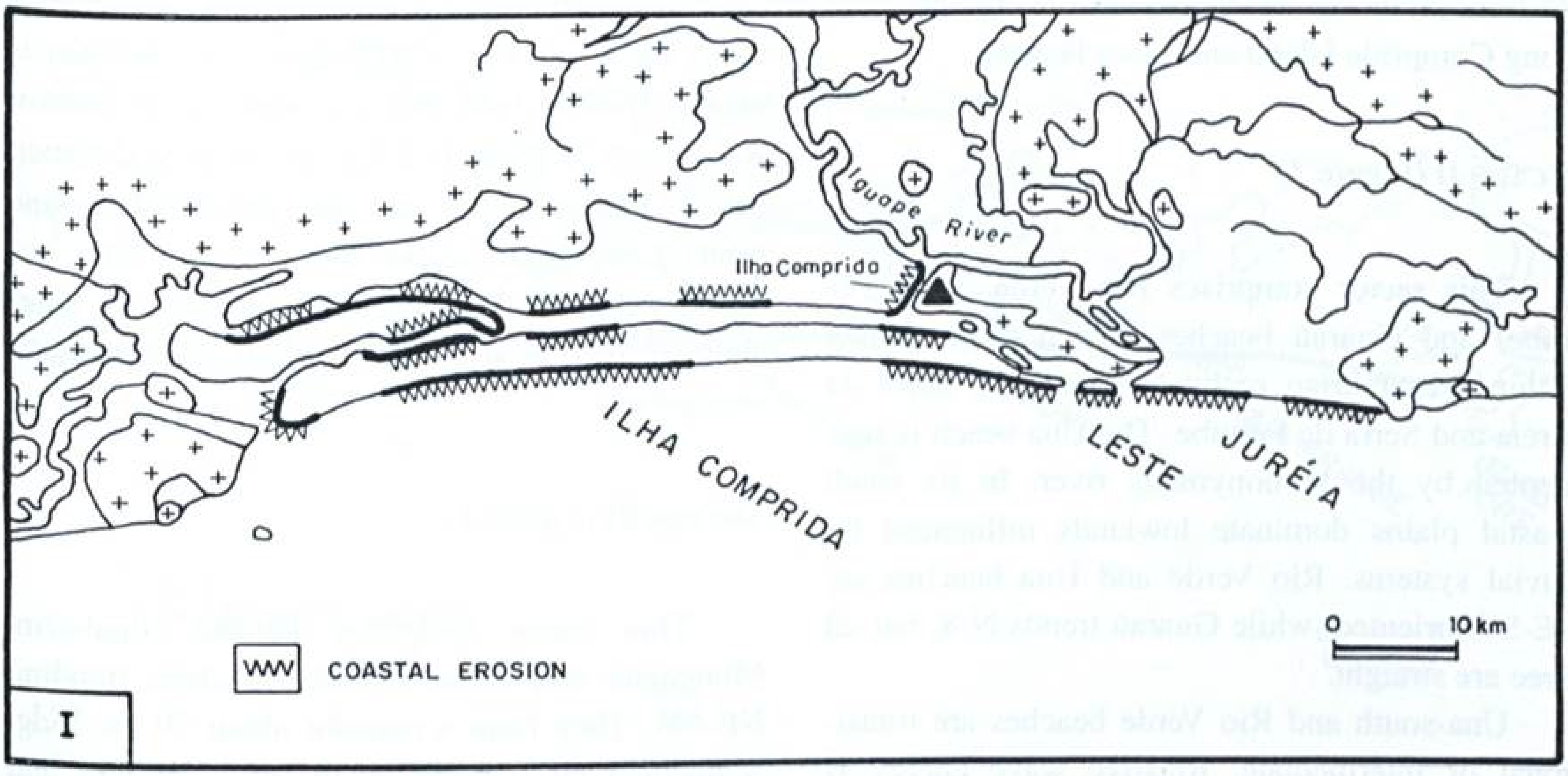

Fig. 2 — Sector I: Ilha Comprida, Leste, and Juréia beaches.

environment under the influence of the biggest river of the São Paulo coast, the Ribeira de Iguape River. Ilha Comprida, with a maximum width of 5 km, is the longest (about 70 km) beach in the state of São Paulo.

This sector is also characterized by a well preserved system of inactive foredunes in Ilha Comprida and Juréia beaches, whose maximum heights are 12 m (Ilha Comprida). These foredunes cover 1.5 to 3 m high Holocene marine terraces and they are the major and best preserved dunes along São Paulo coastline. Present small eolian deposits are also common on backshore zones in Leste, Juréia and the northern portion of Ilha Comprida beaches.

In Ilha Comprida, urban occupation widespreads on Holocene lower marine terraces at the northern sector, while the rest is sparsely occupied, allowing a better preservation of the marine terraces and foredunes. The Leste beach is not occupied because it is completely inundated during high waters of ordinary spring tides. In Juréia beach the urban occupation is growing fast, mostly in its northern and southern extremities, with an intense occupation of the backshore area and even of the upper foreshore zone. This situation is observed where the Holocene beach-ridge terraces are low and reach the shoreline. In the northern part of Juréia beach urbanization is installed on an extensive and flat eolian sand field in the backshore zone, adjacent to 13 m high marine-eolian terraces. In the central portion, human occupation is not favored due to the presence of 3 m-high steep marine terrace covered by a dunefield and a narrow beach which is totally inundated during high spring tides.

Beaches of sector I are high-energy dissipative. The shoreline is open and straight. The foreshore and upper surf zone are, in general, wide and present gentle slopes (1-3°). Breaker is of the spilling type. In general, the number of waves in the surf zone is > 4. Sands are fine to very fine. Beach berms are absent or very incipient, longshore bars are multiple and parallel. Beach profiles are very homogeneous during the year. Longshore transportation changes along Ilha Comprida, with SW or NE trends forming convergent and divergent longshore currents. A large rip-cell has been observed on aerial photos and satellite images in the central portion of Ilha Comprida beach due to convergent longshore currents. At the northern portion of this beach predominates NE longshore currents, while along Juréia and Leste beaches predominate SW longshore currents. These currents are blockaded by ebb tides and Ribeira de Iguape River flows and a depositional zone is developed. The same process occurs at the southern extremity of Ilha Comprida.

Onshore-offshore transports are also important along Comprida Island and Leste beaches.

SECTOR II (Figure 3)

This sector comprises Rio Verde, Una (Peruíbe) and Guaraú beaches, which are confined within Precambrian rocky headlands of Serra da Juréia and Serra de Peruíbe. The Una beach is segmented by the homonymous river. In its small coastal plains dominate lowlands influenced by fluvial systems. Rio Verde and Una beaches are NE-SW oriented, while Guaraú trends N-S, but all three are straight.

Una-south and Rio Verde beaches are transitional or intermediate. Relative wave energy is moderate. In general, they are narrow and constituted by medium to coarse sands, with foreshore and surf zone slope angles varying from 3° to 10°. Breaker is of the plunging type and the number of waves in the surf zone is, in general, of 2-3. Well developed low berms and crescentic bars are present. Longshore currents trend partially NE, partially SW along Una beach, and SW along Rio Verde_ beaches. On the other hand, Bomtempo (1991) obtained a net longshore transport only southwestward for these beaches. Onshore-offshore transport is also active.

Una-north and Guaraú beaches are respectively high- and low-energy dissipative. Breaker is of the spilling type and the number of breaker waves is ≥ 5. These beaches are wider and flatter, do not present berms and are constituted by fine sands. Longshore transport trends southward.

Una River flows blockade convergent longshore currents near it mouth, where a depositional area occur.

SECTOR III (Figure 4)

This sector comprises Peruíbe, Itanhaém, Mongaguá and Praia Grande beaches, trending NE-SW. They form a corridor about 70 km long, segmented by two rivers, in open, straight and wide intermediate to high-energy dissipative beaches of fine to medium sands. Breaker is plunge-spilling type and the number of waves in the surf zone, in general is 4. Beach profiles are very homogeneous during the year, beach berms are absent, and relative wave energy is high. Beach slopes range mainly between 1° and 3°. Cusps are frequent along all these beaches. About 2 to 4 parallel and continuous longshore bars are always present along them.

Longshore currents trend to SW or NE along these beaches, varying according the wave inci-

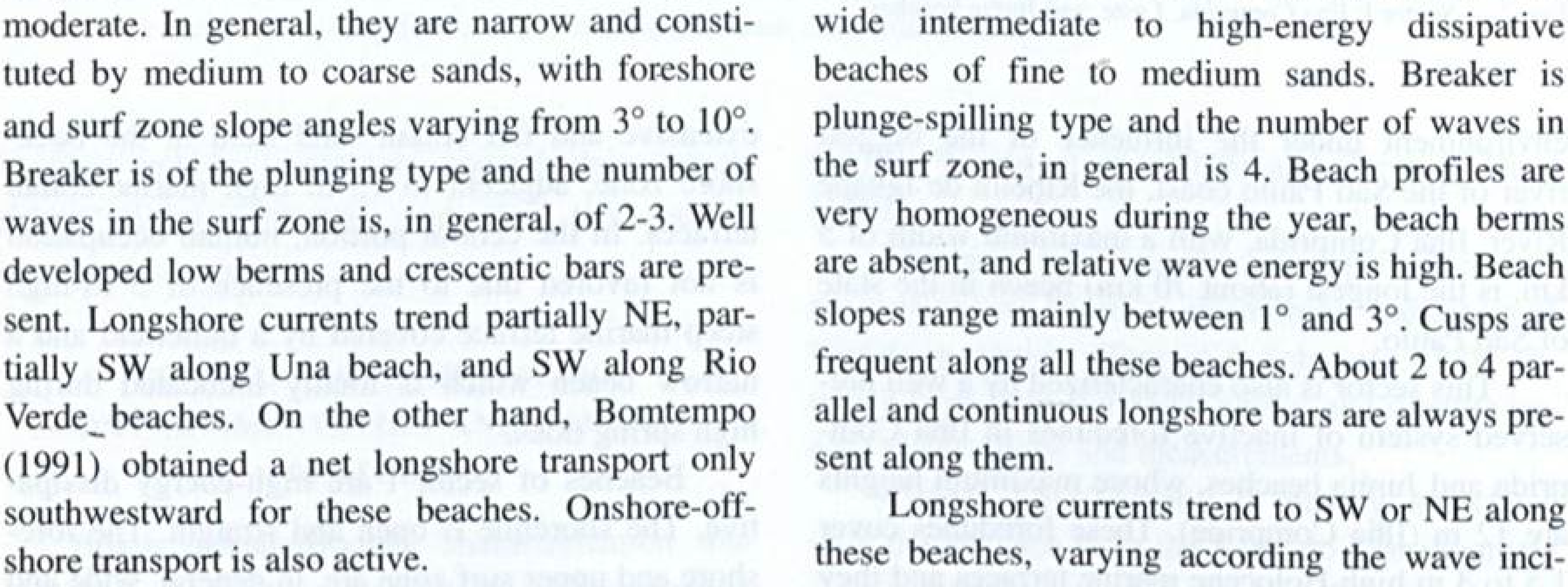

Fig. 3 — Sector II: Rio Verde, Una, and Guaraú beaches.

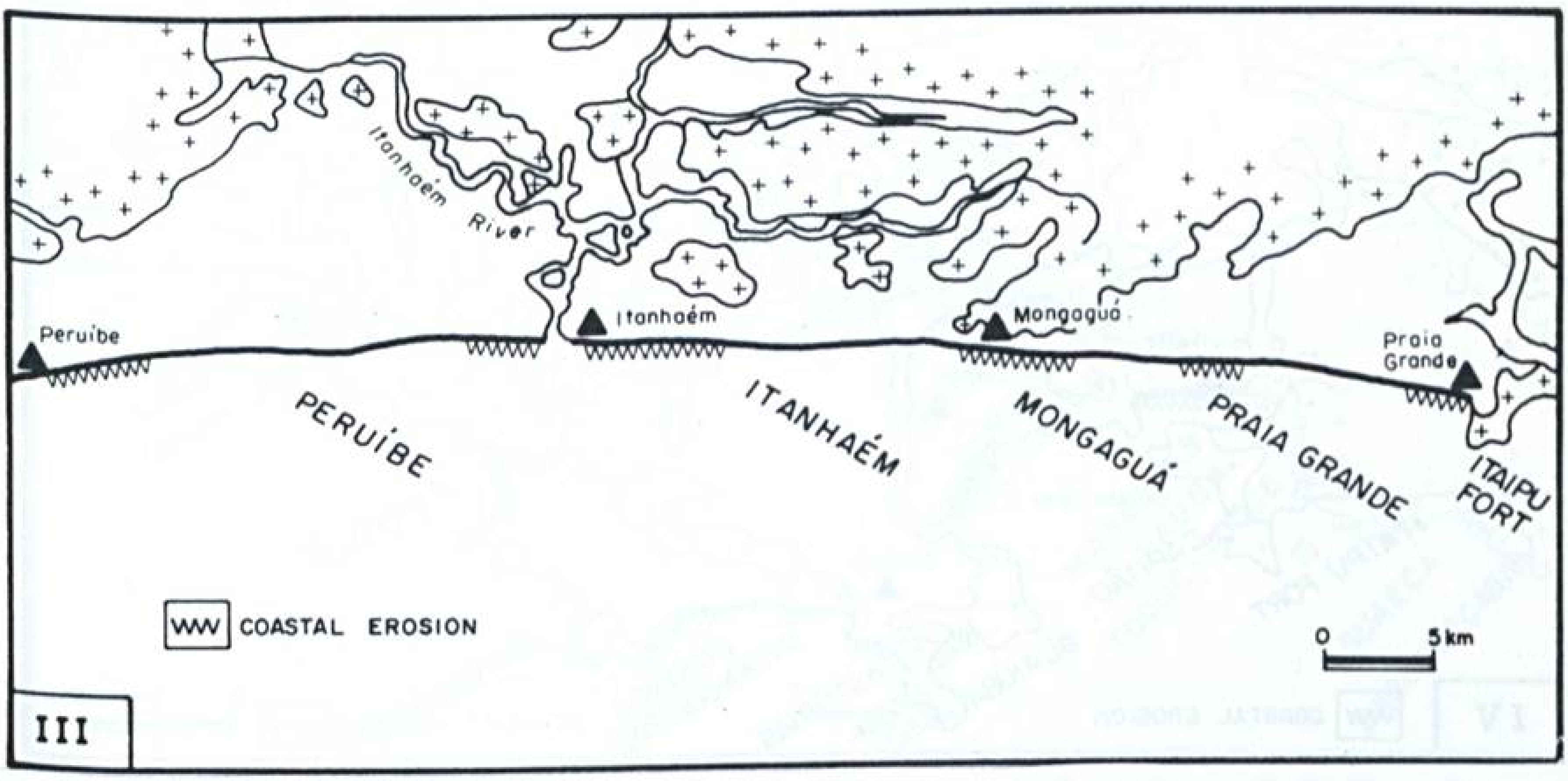

Fig. 4 — Sector III: Peruíbe, Itanhaém, Mongaguá, and Praia Grande beaches.

dence angle. Onshore-offshore transports are also important along these beaches.

This sector differs from sector I in the more limited occurrence of uplifted Holocene marine terraces and dunes near beaches. The coastal ecosystems are mainly influenced by rivers smaller than the Ribeira de Iguape River, being the Itanhaém River the most important among them, although Preto and Mongaguá rivers play locally an important role.

Urbanization is intense in this sector, mainly as cottages. However, between the central and northern sectors of Peruíbe beach there is no urban occupation.

Sector IV (Figure 5)

The long and almost straight coastline trending NE-SW from sectors I to III is suddenly interrupted by the presence of a zone with low coastal mountains advancing seaward. This morphology made the installation of a lagoonal-estuarine complex possible (*Santista* Estuary). The two most important islands constituting this sector, also called *Baixada Santista*, are São Vicente and Santo Amaro. *Baixada Santista* represents the most developed industrial and economical area of the São Paulo coast, with the most important Brazilian petrochemical pole (Cubatão city), and the greater Latin-American harbour (Santos). Then, urban occupation is intense along all this coastline.

The most important and greatest beaches bordering this area are: the E-W oriented beaches situated within sheltered bays, as the beaches of Santos and São Vicente; and E-W and NE-SW oriented beaches situated within wide bights, as those situated at southwestern portion of the Santo Amaro Island. Smaller pocket beaches trending N-S and NE-SW occur at the northern and southern portions, respectively, of the Santo Amaro Island. All these beaches present concave shapes.

The beaches within the Santos Bay could be classified as low-energy dissipative and exhibit very flat and homogenous profiles, with wide foreshore and surf zones composed of fine to very fine sands, and low to very low wave energy level. Breaker is of the spilling type and the number of breaker waves is >3. In general, a discontinuous longshore bar can be present in some locals of São Vicente beaches. Longshore transportation trend is predominantly westward. Onshore-offshore transports can be also important.

The beaches of the wide bights are transitional to high-energy dissipative. They are wide and composed of fine to medium sands. Beach slope ranges between 2° and 4°. Breaker is spill-

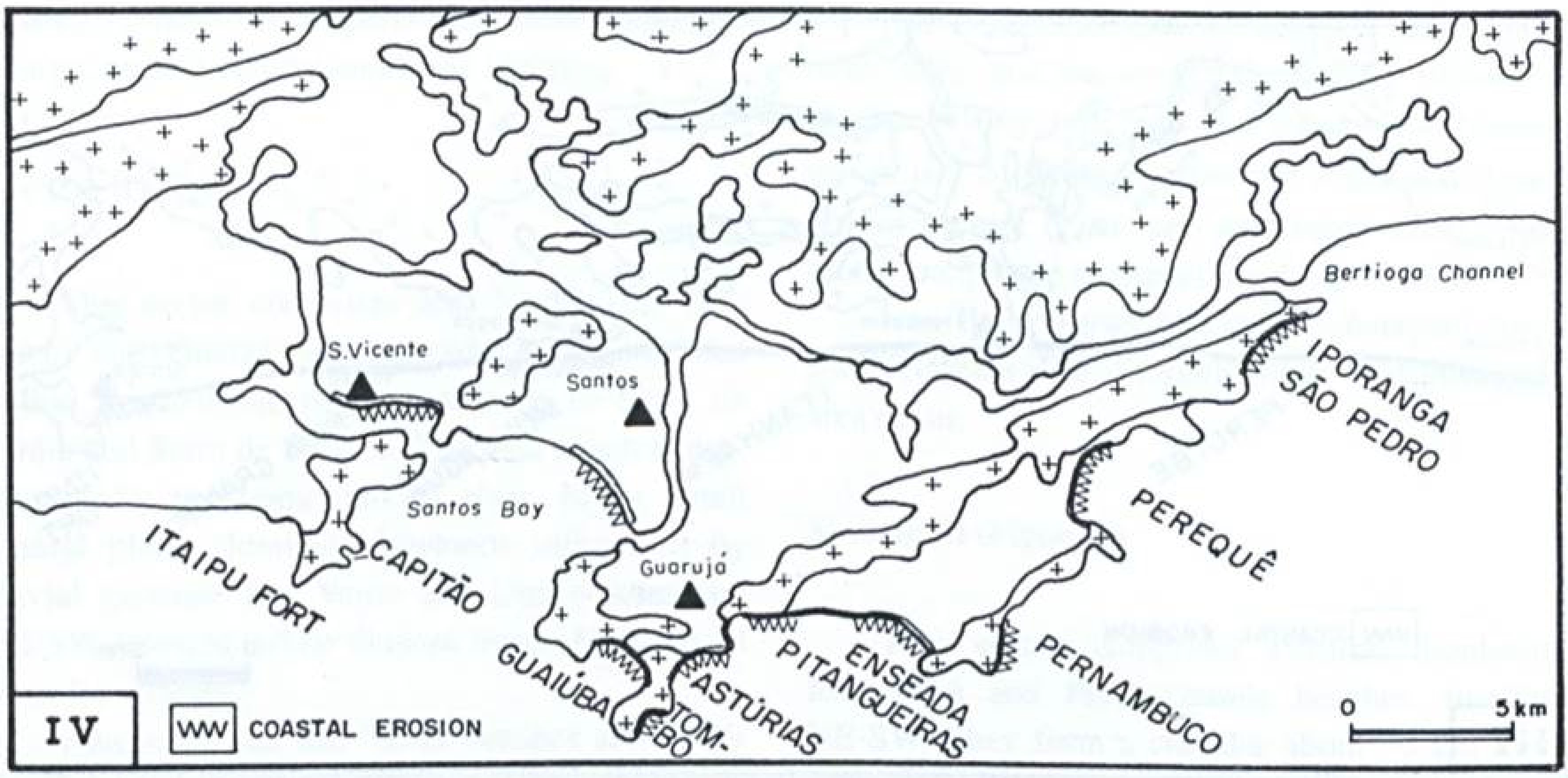

Fig. 5 — Sector IV: São Vicente, Santos, Tombo, Astúrias, Pitangueiras, Enseada, Pernambuco, Perequê, São Pedro, and Iporanga are the most important beaches.

ing-plunging type and the number of breaker waves is 2 to 4. Interrupted longshore bars and crescentic bars can occur along these beaches. In general, longshore currents trend southwards, and there are also rip currents.

The pocket beaches are, in general, transitional to reflective, with medium to coarse sands and slopes commonly varying between 3° to 8°. They present well developed beach berms. Breaker is plunging-collapsing/surging types and the number of waves in the surf zone is 1-2. Longshore currents vary between northward and southward according the beach.

Holocene marine terraces and dunes near beaches are absent in this sector.

SECTOR V (Figure 6)

This sector comprises beaches between Bertioga Channel mouth and São Sebastião Channel, which are limited by isolated crystalline promontories. The Holocene beach-ridge plain becomes again important and continuous, but smaller than the previous sectors. Only locally Holocene marine terraces occur near the shoreline, as in the Itaguaré River mouth. At present, dunes are absent in this sector, but some eolian deposits can occur. Fluvial systems are locally important. Urban occupation is growing fast, mostly during the last five years.

The shoreline shape changes continuously, along this sector because of the more indented character of the coast. Beaches are mainly straight and ENE-WSW oriented at the southern portion of this sector (between Bertioga and Boracéia beaches), but they become concave and E-W oriented at the central portion (between Juréia and Maresias beaches), and NW-SE oriented northward (between Paúba and Barequeçaba beaches). In general, the width, the length and the relative wave energy level decrease, while the declivity, the grain size and the reflectivity increase toward the E-W and NW-SE oriented beaches.

The ENE-WSW oriented beaches are the longest and widest in this sector. They are high-energy dissipative to transitional and constituted of fine to medium sands. In general, beach slopes range from 1° to 4°. Breaker is spilling-plunging type and the number of breakers is ≤ 4. These beaches present several continuous and parallel longshore bars.

The E-W oriented beaches are narrow and short, with medium to very coarse sands, and slopes change between 3.5 to 15°. The majority is transitional, but some beaches are reflective (ex.:

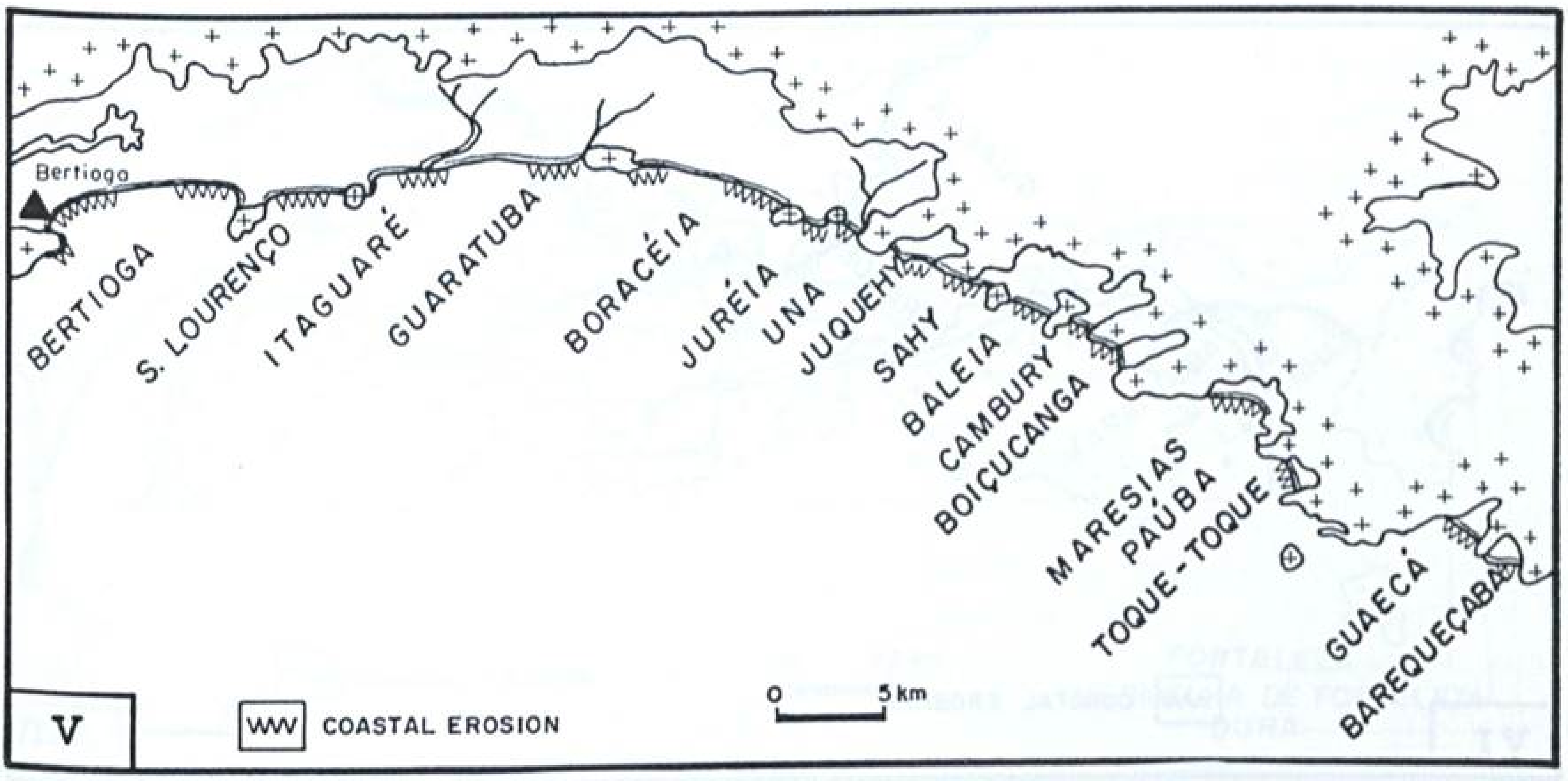

Fig. 6 — Sector V: Bertioga, São Lourenço, Itaguaré, Guaratuba, Boracéia, Juréia, Una, Juquehy, Sahy, Baleia, Cambury, Boiçucanga, Maresias, Paúba, Toque-Toque, Guaecá, and Barequeçaba are the most important beaches.

Camburizinho, Boiçucanga). Breaker is of the plunging to collapsing/surging type, in general with 1 to 2 wave breakers. Transitional beaches present crescentic bars and exhibit low berms. In reflective beaches berms are high and bars do not occur. Well developed cusps are always present along all beaches.

Among the NW-SE oriented beaches there are the reflective at the southernmost and the low-energy dissipative at the northernmost portion. The former have steep slopes, coarse to very coarse sands and present very well developed and high berms and cusps. The number of breakers is 1 and the type is collapsing/surging. Dissipative beaches are very flat and composed by very fine micaceous sands. There are no bars and only one spilling-type wave breaker.

Longshore currents are more effective along this sector, mainly in the southward and central portions, and also have different directions according to the beach orientation. However, we can adopt a general pattern: at the southern/central portions predominate longshore currents oriented southwestward/westward, while at the northern sector they have northwestward trends.

Sector VI (Figure 7)

The beaches along São Sebastião Channel are, in general, very small and have low wave energy. Their modal states are not characteristic because they have emerged profiles similar to transitional and high-energy dissipative beaches, and submerged profiles similar to low-energy dissipative and reflective beaches. These beaches are confined within the channel and therefore submitted to its hydrodynamical regime.

Along the continental side of the channel acts a southward flow which is fed by the Caraguatatuba bight circulation pattern (Souza, 1990, 1994, 1995a). This flow causes southward longshore transports on the beaches. This can be observed as a strong depositional process on the north side of the ferry-boat pier, which has caused the blockage of that flow. Conversely, the northward flow along the island side produces longshore transports in this direction. On the other hand, beaches situated near the channel mouths at the continental side are submitted to wave trains diffracted around the São Sebastião Island extremities and then, they are submitted to a relatively more strong wave energy. Cigarras beach, situated at north mouth of the channel, has N-S orientation

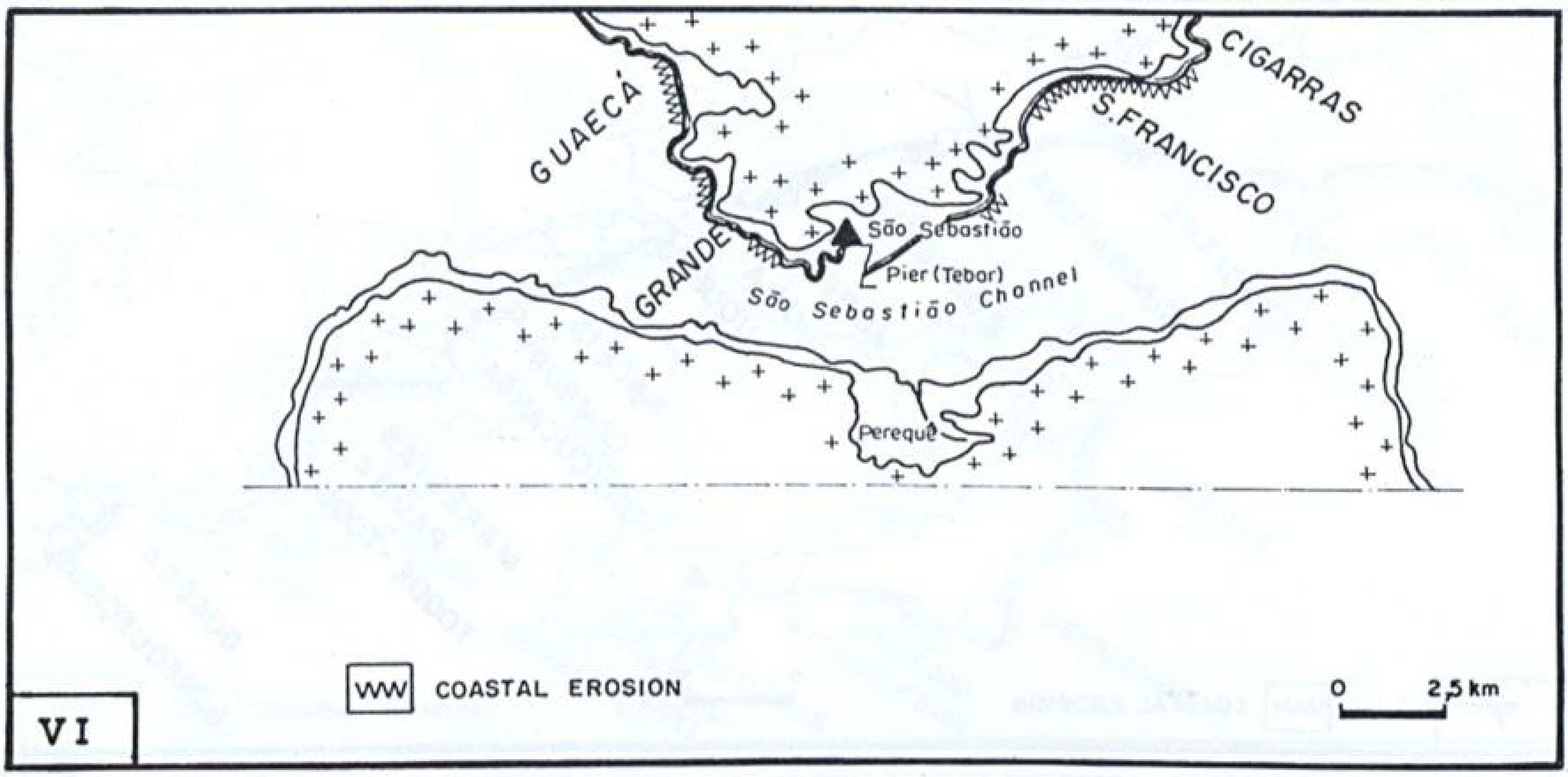

Fig. 7 — Sector VI: Grande, Conchas, Cidade, Pontal da Cruz, São Francisco, and Cigarras are the most important beaches.

and reflective to transitional characteristics. Grande (or Balneário) beach, situated at the opposite mouth has low-energy dissipative characteristics.

As expected, Holocene terraces or dunes are absent in this sector. Urban occupation is intense due to crude oil terminal called TEBAR.

SECTOR VII (Figures 8a, 8b)

This sector is very indented because Serra do Mar plunges into the sea. Coastal plains are very restricted, excepting the Caraguatatuba area. Holocene marine terraces occur near the shoreline only in the Vermelha do Norte beach (Ubatuba). Eolian deposits are not present in this sector.

Beaches always have concave or log-spiral shapes. They are restricted within crystalline rock promontories, but can be either sheltered such as in the Caraguatatuba Bight and the four bays of Ubatuba, or completely opened to the SE waves action as in the north of Ubatuba.

In Caraguatatuba, the beaches have a N-S trend, changing to NE-SW up to south of Ubatuba (Martim de Sá to Vermelha do Sul beaches), reacquiring the previous N-S trend near the urban center of this city (Itaguá to Barra Seca beaches). From Ubatuba northward (Vermelha do Norte to Puruba beaches) the beaches are oriented mostly NE-SW, but at the northern extremity of the state of São Paulo they are deflected to a NW-SE direction (Ubatumirim to Fazenda beaches).

The beaches trending N-S, in general, change from intermediate to low-energy dissipative along a single beach (downdriftward). Breakers vary from plunging to spilling types and the number of breaker waves is between 1 to 4. Sands vary from medium to fine downdriftward and, in general, beach slopes range between 1 to 4.5°. Cusps and interrupted longshore or crescentic bars can occur in these beaches.

At the southern extremity of the Caraguatatuba beach there is a sandy tidal flat (Souza & Furtado, 1987), presenting extremely low-energy dissipative characteristics. It is the sole example of a coastline tidal flat along the state of São Paulo (Souza, 1995b). In Caraguatatuba beach longshore currents have S trend and there is a net-shore transport southward, down to the São Sebastião Channel (Souza, 1990, 1994, 1995a).

The NE-SW oriented beaches are reflective to intermediate. Sands are medium to very coarse. In general, beach slopes range between 6° and 15°. Breakers vary from collapsing/surging to plunging types and the number of breaker waves is frequently 1-2. Beach cusps and well developed high berms are always present. Crescentic bars or inter-

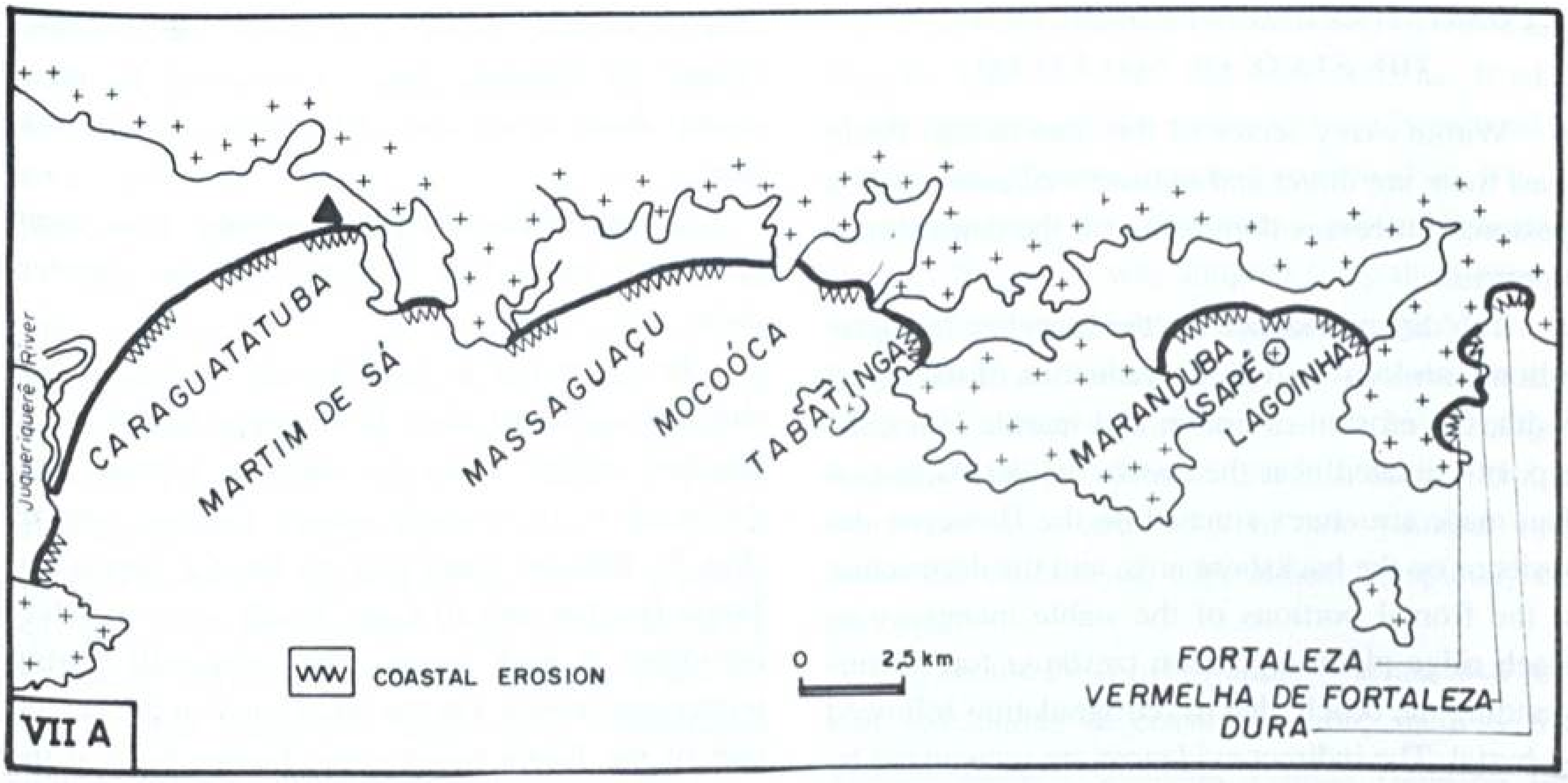

Fig. 8a — Sector VII A: Caraguatatuba, Martim de Sá, Massaguaçu, Mocoóca, Tabatinga, Maranduba, Sapé, Lagoinha, and Fortaleza are the most important beaches.

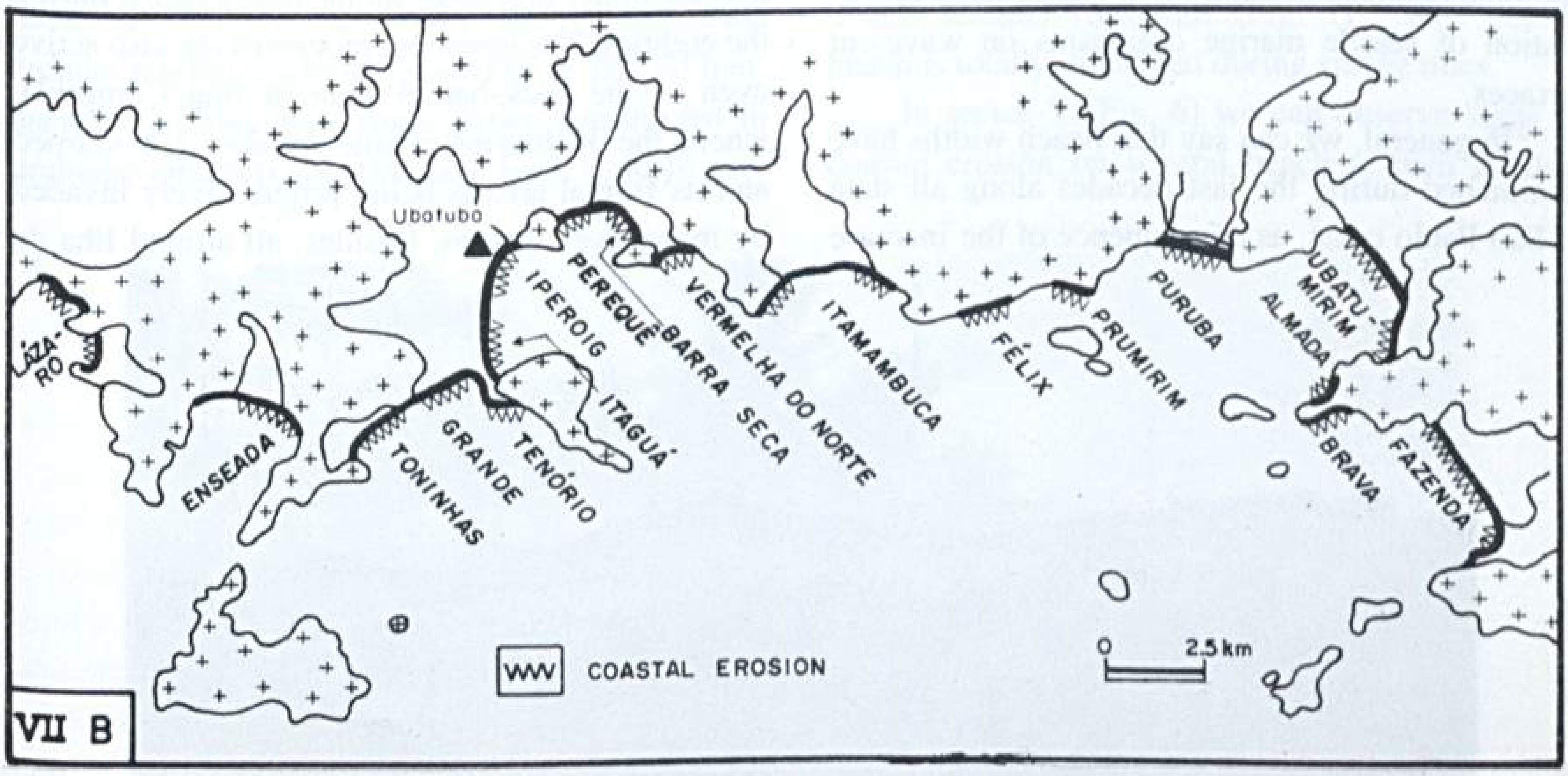

Fig. 8b — Sector VII B: Dura, Lázaro, Domingas Dias, Enseada, Flamengo, Toninhas, Grande, Tenório, Vermelha do Sul, Itaguá, Iperoig, Perequê, Barra Seca, Vermelha do Norte, Itamambuca, Félix, Prumirim, Puruba, Ubatumirim, Almada, Fazenda, and Picinguaba are the most important beaches.

rupted longshore bars can be developed. Longshore currents change either southward or northward according the beach.

The NW-SE oriented beaches are low- to medium-energy dissipative. Beach profiles are flat and sands are fine to very fine. Breaker is spilling type and the number of waves in the surf zone is ≥ 4 or there is no breaker. In general, longshore transports act southward. In general, badly developed cusps can occur, but bars are not present.

COASTAL EROSION EVIDENCES ALONG THE STATE OF SÃO PAULO

Within every sector of the state of São Paulo coast there are direct and indirect evidence that the erosional processes dominated on the depositional processes.

The direct evidence are the shoreline retrogradation with local or regional reduction of the beach width, the erosion of eolian and marine Holocene deposits situated near the beach, the destruction of man-made structures situated on the Holocene deposits or on the backshore area, and the destruction of the frontal portions of the stable mangrove or beach ridge plain vegetation (*restinga* forest) surrounding the beach, due to retrogradation followed by burial. The indirect evidences are recognized by the development of high terraces on Holocene beach ridges, reactivated ancient uplifted wave-cut terraces (2 to 8 m high above present sea-level), subaerial exposition of old peats, mangrove or lagoonal deposits on the beach, and upward proliferation of sessile marine organisms on wave-cut terraces.

In general, we can say that beach widths have diminished during the last decades along all state of São Paulo coast, as consequence of the increase of destructional processes on man-made structures around the beaches. This is supported by aerial photo observations and old inhabitants information.

Some evidence cited here may have been caused or intensified by anthropogenic interferences.

In sector I (Fig. 2), evidence of coastal erosion are visible all along Ilha Comprida and Juréia beaches, where Holocene marine deposits and dunes are being strongly eroded forming terraces (Fig. 9). Besides, some parts of Ilha Comprida and Juréia beaches and all Leste beach are completely inundated at high spring tides, especially during winter and storms. On the other hand, at the central part of the Juréia beach some houses built at the upper foreshore have been destroyed during a high spring tide. Near to the urban center of this beach a recently rocky-groin has been built to retard shore erosion. Bomtempo (1991) observed more effective erosional processes along Juréia beach during the eighties. The erosional processes are also active even in the back-barrier side of Ilha Comprida, where the Holocene marine terraces are scarped and its frontal area is being progressively invaded by mangrove swamps. Besides, all around Ilha de

Fig. 9 — Erosion of Holocene marine terraces and dunes in the central part of Ilha Comprida beach (winter/1992).

Cananéia the Pleistocene marine terraces are also under progressive erosional processes. It is possible to see bordering the island large sandstone-blocks which have fallen down and were detached following N40-55E and N60-80W fracture trends.

In sector II (Fig. 3) coastal erosion occurs in Una-south and Rio Verde beaches, where high spring tides invade the beach eroding and forming terraces over Holocene marine and eolian deposits. Bomtempo (1991) observed also more effective erosional processes along these beaches during the eighties. In the Guaraú beach some houses recently built at lower backshore and upper foreshore zones are being strongly destroyed. Several types of seawalls-like structures have been constructed along this beach, besides a jetty in Guaraú River.

In sector III (Fig. 4) erosional processes are observed along Peruíbe, Itanhaém, Mongaguá, and Praia Grande beaches. In several sites Holocene beach ridges forming terraces or not, streets/avenues, and rough walls of the public promenade around beaches are being eroded (Fig. 10). At Itanhaém and Mongaguá, some jetties constructed in drainage channels mouths have been used to prevent drift from entering channels and to serve as a training wall for river and tidal streams. Rocky-blocks in form of like a seawall have been used to protect these beaches against erosion (Fig. 10). At Mongaguá, near the urban center, artificial nourishment of the beach was adopted for a short time to protect the avenue against erosion. In the Morro do Itaipu (north of Praia Grande beach), there are also several evidence of marine erosion. Two emerged emissary pipelines around this hill, about 1.5-2 m (the older one) and 3-3.5 m (the younger one) above the water level, were almost completely destroyed.

In sector IV (Fig. 5) some beaches also present indications of coastal erosion, such as São Vicente, Santos, Guaiúba, Tombo, Astúrias, Enseada, Pernambuco, Perequê, and São Pedro. In general, evidence are the same of the sector III beaches. In the Capitão beach drastic signs of marine erosion are imprinted on 2 m-high of an abandoned sentinel rock-wall (Fig. 11). This pocket beach is totally inundated during spring tides.

In sector V (Fig. 6) we can observe signs of coastal erosion on several beaches, such as Ber-

Fig. 10 — Erosion of uplifted Holocene marine terraces and street in the Itanhaém beach. Note rock-blocks put around the terrace to try to protect it against erosion (winter/1992).

Fig. 11 — An abandoned sentinel box showing drastic signs of marine erosion in the Capitão beach (summer/1993).

tioga, São Lourenço, Itaguaré, Guaratuba, Juréia, Una, Sahy, Baleia, Juquehy, Cambury, Boiçucanga, Maresias, Toque-Toque Grande, Guaecá and Barequeçaba. In general, the high spring tides reach the top of these beaches, eroding Holocene beach-ridges, trees, houses and other structures situated above them (Fig. 12). In Itaguaré beach, marine terraces occur 3 m high from the present sea-level. Local but uneffective solutions have been adopted to reduce the water impact on the houses, such as mortar-bags (Fig. 12) or rock-blocks put in front of the houses, and construction of walls mainly made of small rocky-blocks. On the other hand, older residences situated at the foot of headlands are also being destroyed by wave impacts.

Into the São Sebastião channel (sector VI – Fig. 7), erosional processes occur mainly in beaches situated northward on the continental side, which are strongly damaged by high spring tides. Beaches became narrower and, consequently, old trees and houses have been destroyed. Large rock-blocks were used to protect the armored concrete walls of the BR-101 highway,against the impact of the tides.

In sector VII (Figs. 8a, b), strong erosional processes are observed in the beaches of the urban center (Fig. 13) and in the tidal flat (Fig. 14) of Caraguatatuba (Souza, 1995a, b). Since 1976, some rock-groins and jetties have been constructed to protect urban center beaches against erosion, but it resulted in increasing erosion rates (Fig. 13). On the other hand, the tidal flat, despite constituting a natural depositional area (downdrift), has been submitted to strong erosion with a reduction in width; the bordering beach and also the backshore forest (mangrove and *restinga*) were destroyed during the last years (Souza, 1995b). In the Martim de Sá beach (central-northern portion), the concrete walls of an emissary pipeline are currently being destroyed. In the central part of the Massaguaçu beach, the waves reach the backshore Holocene high terraces, eroding the BR-101 highway roadside walls, and blocks of rocks have been used like a seawall to try to mitigate erosion. In the Mocoóca beach, despite its high reflectivity, the high spring tides reach the backshore zone, mostly in its central portion. In the Tabatinga beach, Holocene lagoonal deposits overlaid and intertongued

Fig. 12 — Erosion of Holocene beach-ridges, trees and a wall in the Guaecá beach (winter/1992). Mortar-bags were put around the wall to protect it against erosion. Some months later they have been destroyed.

Fig. 13 — Erosion of the beach garden in urban center of Caraguatatuba and the impact due to construction of a new concrete jetty, causing strong erosion downdrift and deposition updrift (neap tide, may/1995).

Fig. 14 — Erosion of a wall of a hotel built in the sixties, in the beach bordering the Caraguatatuba tidal flat (neap tide, may/1995).

Fig. 15 — Holocene lagoonal deposits overlaid and intertongued by Holocene marine sands exposed on the beach face in the Tabatinga beach (summer/1993).

with Holocene marine sands have been eroded and exposed on the beach face (Fig. 15). According to local old dwellers, the shoreline was previously situated about 120 m seaward and there were uplifted terraces similar to those occurring in Itaguaré beach. Presently, luxurious residences have been constructed on the remnants of these terraces, which are about 1.5 m high, and erosional processes are still active and advance on gardens and houses, mostly in the northern and central sectors of that beach. In the Ubatuba municipality, erosional features (destruction of houses, trees, walls, etc.) have been observed in Maranduba, Sapé, Lagoinha, Fortaleza, Vermelha de Fortaleza, Dura, Lázaro, Enseada, Toninhas, Grande, Tenório, Itaguá, Iperoig, Perequê-Açu, Barra Seca, Vermelha do Norte, Itamambuca, Félix, Puruba, Ubatumirim, Almada and Brava do Almada, Picinguaba and Fazenda beaches. In all these beaches the high spring tides are apparently becoming more aggressive, especially in combination with cold atmospheric front incursions. In the Barra Seca beach trees burial by sand occurs along all its present upper foreshore zone (Fig. 16), which results in strong erosion of an ancient backshore forest (*restinga* forest). The same phenomena can be observed in Ubatumirim beach.

In general, three levels of wave-cut terraces (2-3, 4-5, 6-8 m high above present sea-level) found on the rocky promontories, along all the littoral, are devoid of any plant cover and present signs indicative of reinstalled marine erosional processes, mostly in the two lowest terraces (Fig. 17). Sometimes a 9-10 m uplifted wave-cut terrace is observed also devoid of vegetation. Besides, it is possible to observe, in some places, the upward migration of sessile organisms and the destruction of the underlain communities.

DISCUSSION AND CONCLUSIONS

In general, the reflectivity increases northward along the state of São Paulo coast. It is due to the interaction between coastal morphology and preferential wave approach direction. Morphodynamic state changes from dissipative between the southern and central parts, intermediate between the central and northern parts, reflective at the northern portion, and again to dissipative at the northernmost part.

Fig. 16 — Tree burial by sand in the Barra Seca beach (spring tide, summer/1993).

Fig. 17 — Wave-cut terraces on rocky promontories at the Boracéia beach (2, 4-5 and 6-8 m high above present sea-level), are devoid of vegetation cover and present signs indicative of the reactivation of marine erosional processes, mostly in the two lowest terraces.

Erosional processes are active all along São Paulo coast, independently of its morphodynamical state or coastal morphology. Presently, they are the predominant process.

To determine the causes of these erosional processes is not an easy work, because besides natural processes there are several anthropogenic interferences, whose consequences and impacts can be very difficult to determine. These interventions can be very old, having started several decades ago, or young from only some months ago on.

Some local anthropogenic interferences which can result in increasing erosion rates along the state of São Paulo coast are as follow:

1. Houses recently built on upper foreshore areas, such as in Juréia and Guaraú beaches;
2. Artificial structures, perpendicular and parallel to coastline, such as groins, seawalls-like (rocky-blocks or mortar-bags) and jetties, have been made to protect river mouths, inlets and beaches against coastal erosion, without any previous studies, modifying both beach morphology and circulation patterns and, consequently, increasing erosion (examples: Ilha Comprida, Juréia, Guaraú, Mongaguá, São Vicente, São Lourenço, Guaecá, São Sebastião, São Francisco, Caraguatatuba, Massaguaçu, Itaguá, Iperoig, and Ubatumirim beaches);
3. Unjustified and unlawful extraction of beach sands, such as in: Ilha Comprida, Juréia, Peruíbe, Itanhaém, Mongaguá, Praia Grande, São Vicente, Santos, Enseada (Guarujá), Perequê, Bertioga, São Lourenço, Boracéia, Baleia, and Caraguatatuba beaches;
4. Backshore area occupation, with destruction of eolian deposits and marine beach ridges in areas all along the littoral;
5. Dredging of fluvial and tidal channels, and morphological alterations on these channels, mainly in *Baixada Santista* and São Sebastião areas;
6. Alteration and destruction of coastal ecosystems, such as mangrove, *restinga* (beach-ridge plain) and estuarine areas, as waste land or other re-

claimed lands, mainly in *Baixada Santista* and São Sebastião coastal plains;

7. Construction of roads and other structures intercepting and altering the lowland areas drainage (along all the littoral); and
8. Intense occupation of beach ridges coastal plains and hills causing soil erosion and impermeabilization, and sediment filling of the drainage system (mainly in *Baixada Santista* and São Sebastião coastal plains).

Among these interferences, those numbered 1, 2 and 3 seem be the most important to enhance present erosional processes. Destroyed houses on upper foreshore modify the beach profile morphology, acting like small seawalls. On the other hand, the interference of number 2 signs a previously active erosion. The beach sand extraction is not continuous and is very difficult to quantify the volume mined. The cleaning of beach garbage by tractors contributes to this sand withdrawal.

Fluvial and tidal channels dredging has been necessary because sand filling is intense mainly near their mouths, causing problems in navigation and inundation of lowlands. These problems also occur due to interferences 6, 7 and 8. Dredging of channels has a more direct effect on the beach sedimentary budget than interferences 6, 7 and 8.

Areas downdrift of net shore-drift cells and areas of longshore currents convergence, where depositional processes must have been predominant, have also been submitted to increasing erosion.

Reactivated ancient wave-cut terraces (2 to 8 m above present sea-level) and proliferation of sessile marine organisms upward rocky cliffs with erosion of underlain colonies are practically independent phenomena from the beach sedimentary budget.

On the other hand, erosional processes seem to predominate the depositional ones, either along beaches practically untouched by man or where any of these interferences have occurred, for example at Ilha Comprida, Una-south and Fazenda beaches. Bomtempo (1991) calculated the lost by erosion sand volume in Juréia, Rio Verde, and Una beaches during the eighties: 0.67 m^3 by each linear meter in the Juréia beach; 3.5 m^3 by each linear meter in the Rio Verde beach; and 13 m^3 by each linear meter in the Una-south beach.

Despite the fact that our conclusions are preliminary, we believe that the primary cause of the present time increasing erosional processes can be also natural. The confirmation that coastal erosion has been an almost worldwide phenomenon, as well as the fact that tide-gauge records, Brazil included, have shown ascending sea-level curves during the last decades, suggest that at least part of the coastal erosion along the state of São Paulo can be attributable to sea-level rise.

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