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Variation of coastal dynamics during the last 7000 years recorded in beach-ridge plains associated with river mouths: example from the central Brazilian coast

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ABSTRACT

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The reconstruction of relative sea-level changes, during the last 7000 years, has shown that the central Brazilian coast was been subjected to submergence until approximately 5100 yr. B.P. However, the emergence after 5100 yr. B.P. was interrupted by two important fluctuations with an amplitude of approximately 2–3 m and a duration of 200–300 yr. This evolutionary history, which is quite different from that of several other regions in the world, played an essential role in the development of the central Brazilian coastal plains, whether or not they are associated with important river mouths. The periods of submergence, characterized by erosional phases, introduced noticeable changes in the geometry of the coastal deposits. The periods of emergence gave rise to sandy terraces covered by beach-ridges whose orientation is determined by the longshore drift. Elsewhere on a low sandy coast, the direction of longshore sand transport depends on the orientation of the swell. In a coast subjected to various swell patterns the efficient swells are defined as those which determine the resulting longshore transport direction. Such swells are not necessarily the most prevalent. For instance, along the central Brazilian coast the southern sector waves, in spite of their infrequent occurrences, are much more powerful than the northern sector waves and therefore generate a longshore sand transport from south to north.

When fossil beach-ridges are present, as is the case on the central Brazilian coast, their geometry reflects the past directions of longshore sand transport. This makes it possible to determine the provenance of past efficient swells and to establish the past wind patterns. A detailed study of the beach-ridge geometry of some sections of the central Brazilian coast, showed a sequence of reversals of the longshore drift during the last 5100 yr, with a duration ranging from 10 to 100 yr. These reversals represent changes in the direction of effective waves, which determine the longshore transportation of sediments, and, consequently, indicate changes in the wind pattern.

Introduction

A submerging coast does not exhibit the same morphological features as an emerging coast because the relative sea-level change determines coastal sedimentation. This occurs in two ways, by partially controlling the supply of sand and by regulating the geometry of the deposits. Independent of the source of the sediments, this shape changes with the direction and intensity of the longshore drift.

Although it is unrealistic to even attempt a reconstruction of the detailed evolutionary history of relative sea-level changes based upon the geometry of the sandy deposits of the coastal plain, it is, however, possible, under favourable conditions, to distinguish between periods of submergence and emergence. Similarly, as the direction of transportation causes sedimentation of coastal sands, a detailed study of the geometry of beach-ridges indicates the direction of longshore drift

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during the past and, consequently, of the wave pattern.

Influence of relative sea-level changes on coastal sedimentation

A sandy coastal zone has a profile in equilibrium, which is determined by the local hydrodynamics and the grain size of the sediments. The hydrodynamics change incessantly due to tides, surges, etc., to such a degree that this profile is constantly being destroyed. However, over a sufficiently long period of time, a standard equilibrium profile will be established. It is quite obvious that a relative sea-level rise or fall destroys this equilibrium.

The rule of Bruun (1962) states that the equilibrium destroyed by a relative sea-level rise would be re-established by a landward displacement of the beach profile. This results in an accelerated erosion of the beach prism and transfer of eroded sands toward the inner shelf (Fig. 1A). This causes the inner shelf bottom to rise by a height equal to that of sea-level rise. Field and laboratory experiments (Schwartz, 1965, 1967; Dubois, 1976, 1977) have demonstrated the validity of Bruun's rule. Even though this rule was established for a rise in sea-level, it is logical to suppose that a fall in sea level would also destroy the equilibrium profile. This is demonstrated by the erosion of the inner shelf bottom and by transfer of the eroded sand toward the beach prism (Fig. 1B). This transfer ends when the original depth has been re-established. This mechanism can be clearly observed during a monthly cycle of tides. During spring tides (corresponding to a "small sea-level rise") there is erosion of the beach prism and accumulation on the inner shelf bottom; on the other hand, during neap tides (corresponding to a "small sea-level lowering") there is erosion of the inner shelf bottom and accumulation on the beach prism. It is clear that, on a gently sloping sandy coast, a relative sea-level fall results in abundant transportation of sand from the inner shelf towards the beach.

Under conditions of a rising sea-level, on a gently sloping sandy coast a barrier island lagoonal system is the dominant mode of sedimentation (Swift, 1975), and beach-ridge plains are virtually absent. In contrast, a sea-level fall creates highly unfavourable conditions for the genesis and maintenance of barrier island/lagoonal systems. Lagoons and bays become emergent and beach-ridge plains rapidly prograde, resulting in regressive sand sheets.

Influence of longshore drift on coastal sedimentation

Approaching the shore, waves break when the depth is insufficient to continue moving. This

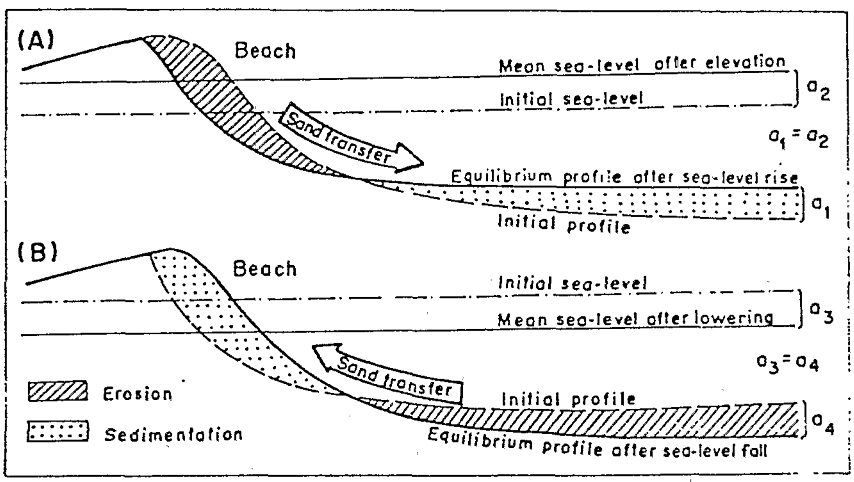

Fig. 1. (A) Behaviour of the littoral zone equilibrium profile as a function of sea-level rise (Bruun, 1962). (B) Behaviour of the littoral zone equilibrium profile as a function of sea-level fall (Dominguez, 1982).

involves the release of a great amount of energy, which is partially absorbed by putting sandy grains into suspension, and by the creation of a current parallel to the coast, known as longshore current. Evidently, this current appears only when the wave fronts strike the coast obliquely. The longshore current is normally slow moving, but because its action takes place in a zone where sand grains have been suspended by breaking waves, the volume of sand transported by this mechanism can be substantial. In addition, breaking waves generate sawtooth pulses of sand transport (shore casting). Obviously, the direction of transport is a function of the angle at which the wave fronts reach the shoreline.

River-borne sediments and sands generated by a fall in sea level will be moved along the beach by the longshore current. This transport can continue until the sand is trapped or blocked by an obstacle. This explains the great differences occasionally found between two regions that have been subjected to the same fall in relative sea level. Sandy deposits are small or even absent in transit regions. They are very large in regions where a trap or an obstacle causes accumulation of sand. Such traps and obstacles can take different forms: such as recesses in the coastline, islands, or shallow bottoms forming low-energy zones, rocky points, river mouths, etc. Obviously, all changes in relative sea-level and in sand transport direction will be accompanied by remarkable changes within the geometry of the deposits, under favourable conditions: that is, on sandy terraces covered by beach-ridges.

Characteristics of the central Brazilian coast

The existence of extensive Quaternary coastal plains is one of the characteristics of the central part of the Brazilian coast (Fig. 2). These plains can be situated at the mouth of a major river but do not have to be related to a present or previous river. A second characteristic of this coast is that, during the Holocene, it was submerging, as opposed to various other regions of the world, until approximately 5100 yr. B.P. Since then there has been a general emergence. Nevertheless, the regular fall in sea level was interrupted by two high frequency sea-level oscillations with an amplitude of 2–3 m during a period of no more than

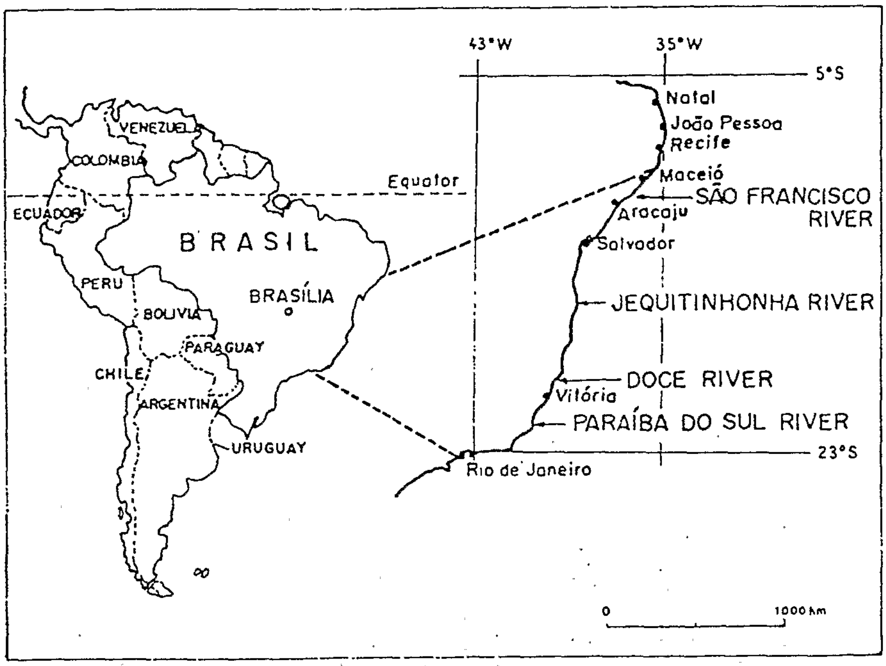

Fig. 2. Location map of major river mouth-associated beach ridge plains along the central part of the Brazilian Coast.

200–300 yr. A third characteristic of this coast is that it is a high-energy environment, where the longshore current plays an essential role in the transport of coarse sediments.

Quaternary sedimentary deposits

Beach-ridge terraces are the most abundant sedimentary deposits on the Quaternary coastal plains. They can be grouped into two important sets of Pleistocene and Holocene beach-ridges by applying as criteria their differences in morphology, elevation and absolute age (Martin et al., 1981, 1983, 1987, 1988).

The summits of the Pleistocene beach-ridge terraces are 6–10 m above the present high-tide level. They are normally situated inland on the sedimentary plains and lean directly against the pre-Quaternary deposits. Occasionally, the primary sedimentary structures have been completely destroyed by pedogenetic processes. Nevertheless, fossilized burrows of *Callichirus*, associated with tabular and trough cross-bedding, are frequently found. The surface of the Pleistocene terraces are marked by beach-ridge alignments smoothed by erosion and weathering processes. Five fragments of corals, sampled in a reef formation underlying a beach-ridge terrace exhibiting the above mentioned characteristics, were dated using the Io/U method and gave an average age of 123,500 + 5700 years B.P. (Bernat et al., 1983), which correlates with a well known worldwide Upper Pleistocene high sea-level.

The Holocene beach-ridge terraces are located seaward of the Pleistocene terraces and are generally separated from them by a low-lying area filled with lagoonal organic muds, which are frequently covered by freshwater swamps. The surface of the Holocene beach-ridge terraces slopes gently seaward. This suggests that their formation took place during a period of subsiding sea-levels. Primary sedimentary structures in the Holocene terraces are perfectly preserved and are represented almost exclusively by beach-face stratifications. *Callichirus* burrows were also observed, associated with horizontal stratifications at the foot of the terraces. The surface of the Holocene terraces is characterized by perfectly preserved beach-ridge alignments. All radiocarbon ages obtained from these terraces are younger than 5000 yr. B.P.

The Holocene lagoonal deposits consist of blackish or greyish organic-rich muds with abundant fossil wood fragments and shells. The fluvial deposits are represented by coarse-grained natural levee, palaeochannel and point-bar deposits. The areal distribution of fluvial terraces is primarily controlled by the evolutionary history of the Quaternary sedimentary plain.

Relative sea-level changes during the last 7000 yr.

The most recent part of the last transgressive event has been very well studied using numerous reconstructions of ancient shorelines, which have been made using more than 700 radiocarbon ages. This made it possible to establish partial or complete relative sea-level fluctuation curves for several sectors of the central part of the Brazilian Coast (Martin et al., 1979, 1980, 1983, 1987; Suguio et Martin, 1982a; Suguio et al., 1985). These curves (Fig. 3) demonstrated that:

(a) the present mean sea level was overtaken for the first time at approximately 7000 yr. B.P.;

(b) around 5100 yr. B.P. the sea level had risen to 4–5 m above present mean sea level;

(c) between 4000 and 3900 yr. B.P. there was a lowering of the sea level to slightly below present mean sea level;

(d) at 3600 yr. B.P. the sea level rose to 3 m above present mean sea level;

(e) between 2800 and 2700 yr. B.P. the sea level fell again to slightly below the present mean sea level;

(f) at approximately 2500 yr. B.P. a third high sea level occurred. This time, the sea level rose to about 2.5 m above the present mean sea level. Since then it has been progressively subsiding.

In summary, it is possible to recognize along the central part of the Brazilian coast during the last 7000 yr. (Fig. 3), three main events of submergence (7000–5100, 3900–3600 and 2700–2500 yr. B.P.) alternating with three main events of emergence (5100–3900, 3600–2700 and after 2500 yr. B.P.).

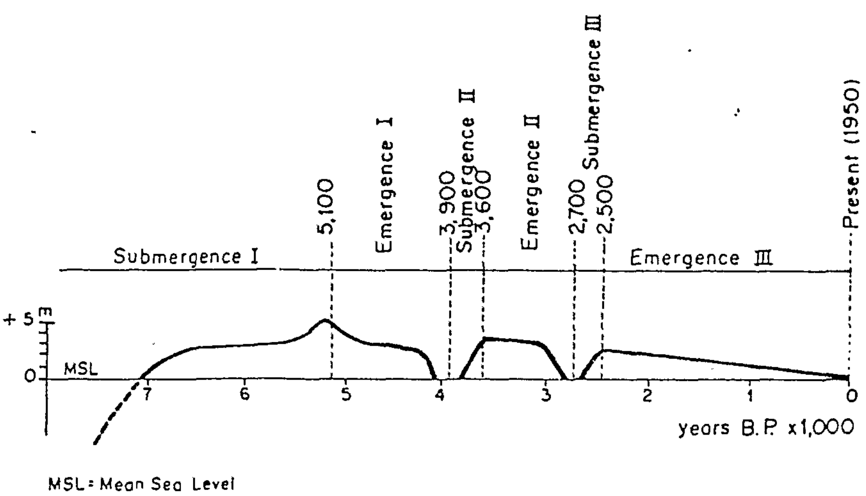

Fig. 3. Sea-level curve valid for the Holocene evolution in the central part of the Brazilian coast showing alternating episodes of submergence and emergence in the last 7000 yr.

Patterns of swell systems

The patterns of swell systems along this stretch of coast are not well known, but there is sufficient data to show that they originated from the northeast and the south-southeast, and that the latter are much less frequent but more effective. Apparently they are generated by two wind directions, from the northeast and the south-southeast, respectively. The winds from the northeast are related to the recurrent trade winds active during the entire year, while those from the south-southeast are related to "cold fronts" which periodically reach the central part of the Brazilian coast, mainly during autumn and winter. In fact, the normal conditions of atmospheric circulation over the South American continent are characterized by the passage, in the middle and high troposphere, of a succession of meridian waves corresponding to frontal systems moving in from the south (Fig. 4A). Over the sea, the latter are followed by winds and swells from the southern sector. These swells, in spite of their low frequency, are much more powerful than those from the northern sector and, in consequence, the predominant longshore transportation of sediments occurs from south to north.

However, this model can be disturbed by a temperature anomaly of the surface waters in the Pacific Ocean, at the latitude of northern Peru, the so-called "El Nino" phenomenon. When this phenomenon is active, as in 1983, the passage of middle and high troposphere wave fronts from the south is blocked by a strong and permanent jet current (Kousky et al., 1984). This blockage extends from the Pacific Ocean to southern Brazil (Fig. 4B). During the blockage period, the frontal zones remain for a long time in southern and southeastern Brazil. Simultaneously, swells from the southern sector, generated by the frontal zones, do not reach the central part of the Brazilian coast. In this case, the northern sector swells become effective, provoking a longshore drift from north to south.

Holocene evolution of coastal plains near some important river mouths

The coastal plains associated with the mouths of the main rivers of the central part of the Brazilian coast, have been described by Bacoccoli (1971), who applies the definition of Fisher (1969), as "highly destructive wave-dominated deltas". This author assigned all these deltas to the Holocene epoch and proposed an evolutionary history to explain the development of these deltaic plains starting with the maximum of the last transgression, passing in some cases through an intermediate estuarine stage, and finally constituting typical deltas, demonstrated by an oceanward advance of the continent. However, numerous "prograded"

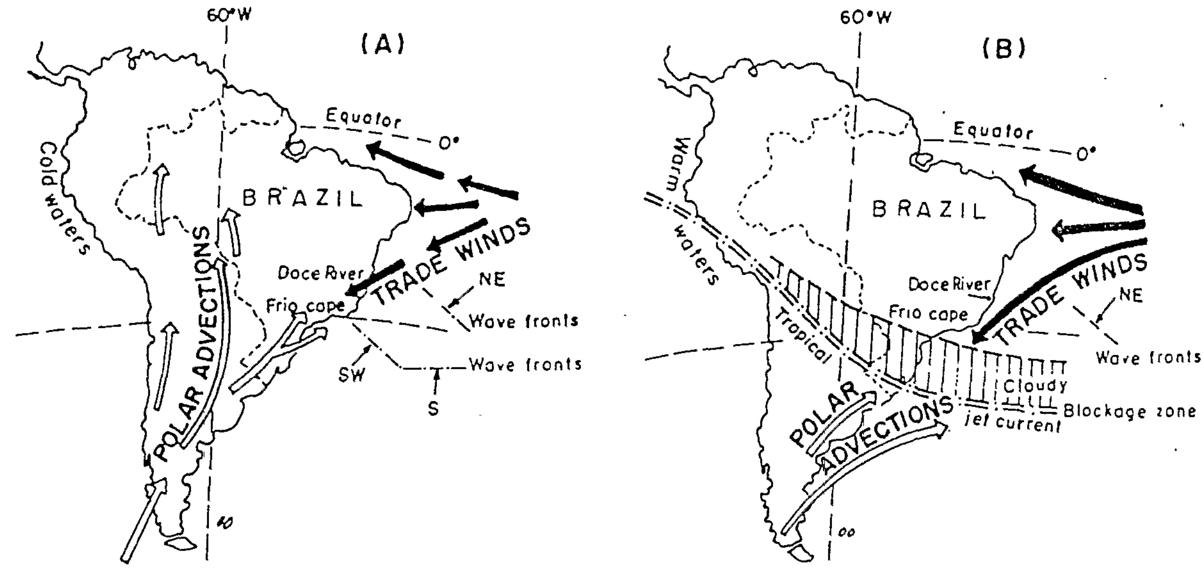

Fig. 4. Directions of wave fronts in the central part of the Brazilian Coast. (A) during normal conditions and (B) during "El Nino" conditions.

coastal plains with no connection to present or past rivers occur along the Brazilian coast. The fact that "progradation zones" could be formed without the presence of a river immediately drew our attention.

According to numerous publications concerning classical models of deltaic sedimentation, wave energy, tidal amplitude, fluvial charge, etc., are the crucial factors for this type of sedimentation (Fisher, 1969; Galloway, 1975; Hayes, 1979). Surprisingly, not one author considered the possibility of relative sea-level oscillations. In their classical paper on the subject, Coleman and Wright (1975) analyzed 400 parameters having an effect on the formation of sandy deltaic deposits, but they neglected to pay any attention to the most important aspect: that is, a possible lowering of the relative sea level during the Holocene which, on a sandy coast, supplies a considerable amount of sediment.

Some detailed studies carried out on the coastal plains of the rivers Paraiba do Sul (21 00'S), Doce (19 00'S), Jequitinhonha (16 00'S) and São Francisco (10 00'S) (Fig. 2) showed that their Holocene history had been strongly controlled by relative sea-level changes and the direction of longshore drift (Dominguez, 1982; Suguio et Martin, 1982b; Martin et al., 1983, 1987; Suguio et al., 1985; Dominguez et al., 1987).

Holocene evolution of the Rio Doce coastal plain

The Rio Doce coastal plain, striking almost N–S, is situated between 18°30′ and 19 45′ southern latitude. It is asymmetrical, having the shape of a half-moon curving outwards, with a maximum width in the E–W direction of approximately 38 km and a maximum length in the N–S direction of approximately 130 km (Fig. 5). The inland boundary is represented by a cliff carved in Pliocene continental deposits.

The Rio Doce coastal plain is situated within an area characterized by a rainy season in summer and a dry season during autumn and winter. However, the dry season is attenuated by precipitation caused by polar air masses. The result is that, under normal conditions, the pluvial regime is quite similar to that of the equatorial region with the rains well distributed throughout the year.

Detailed mapping showed the occurrence of sandy deposits associated with the latest two transgressive events which exceeded the present sea level (123,000 and 5100 years B.P.) (Fig. 6 and 7). It was also possible to demonstrate the occurrence

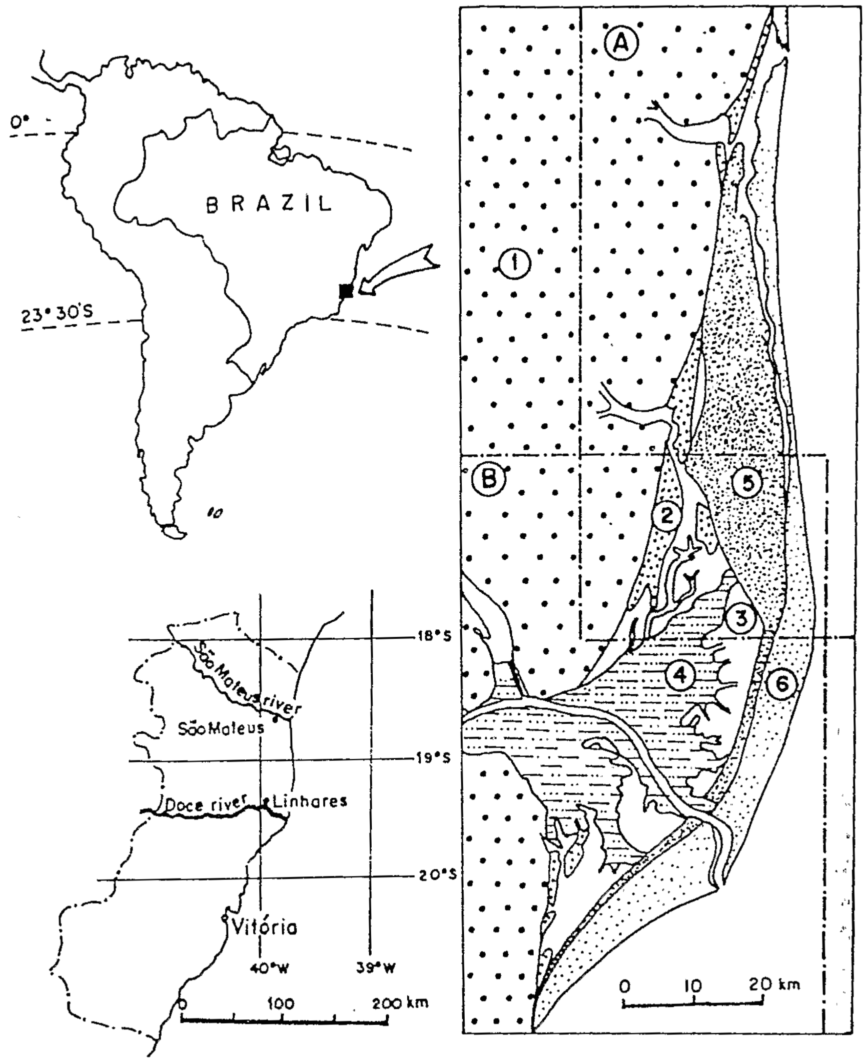

Fig. 5. Schematic geologic map of the Doce River coastal plain. *1* = Barreiras Formation; *2* = Pleistocene marine terrace; *3* = lagoonal deposits; *4* = fluvial sediments of the intralagoonal delta; *5* = Holocene first generation marine terrace; *6* = Holocene second generation marine terrace. See also Figs. 6A and 7B.

of palaeolagoonal deposits partially overlain by fluvial sediments related to the Rio Doce (Fig. 7).

The deposition of the Holocene part of the Rio Doce coastal plain began with the formation of a barrier island lagoonal system (Fig. 8A). Radiocarbon dates of shells and wood fragments sampled from palaeolagoonal deposits indicated that it has existed from at least approximately 7000 yr. B.P., when the sea level in the area was higher than today. Obviously, during that time the barrier islands must have been situated more to the exterior and they reached their final position during the transgressive maximum around 5,100 yr. B.P. Soon after the palaeolagoon formation, the huge intralagoonal delta was being formed (Fig. 8). However, until the transgressive maximum, the lagoon must have been dominated by the rising sea level, which could have obstructed the intralagoonal delta development to a certain extent. This explains why the molluscs obtained from palaeolagoonal deposits provided ages between 7000 and 5200 yr. B.P. (ocean-dominated lagoon), while ages between 5000 and 4000 yr. B.P. have been obtained from wood fragments (river-dominated

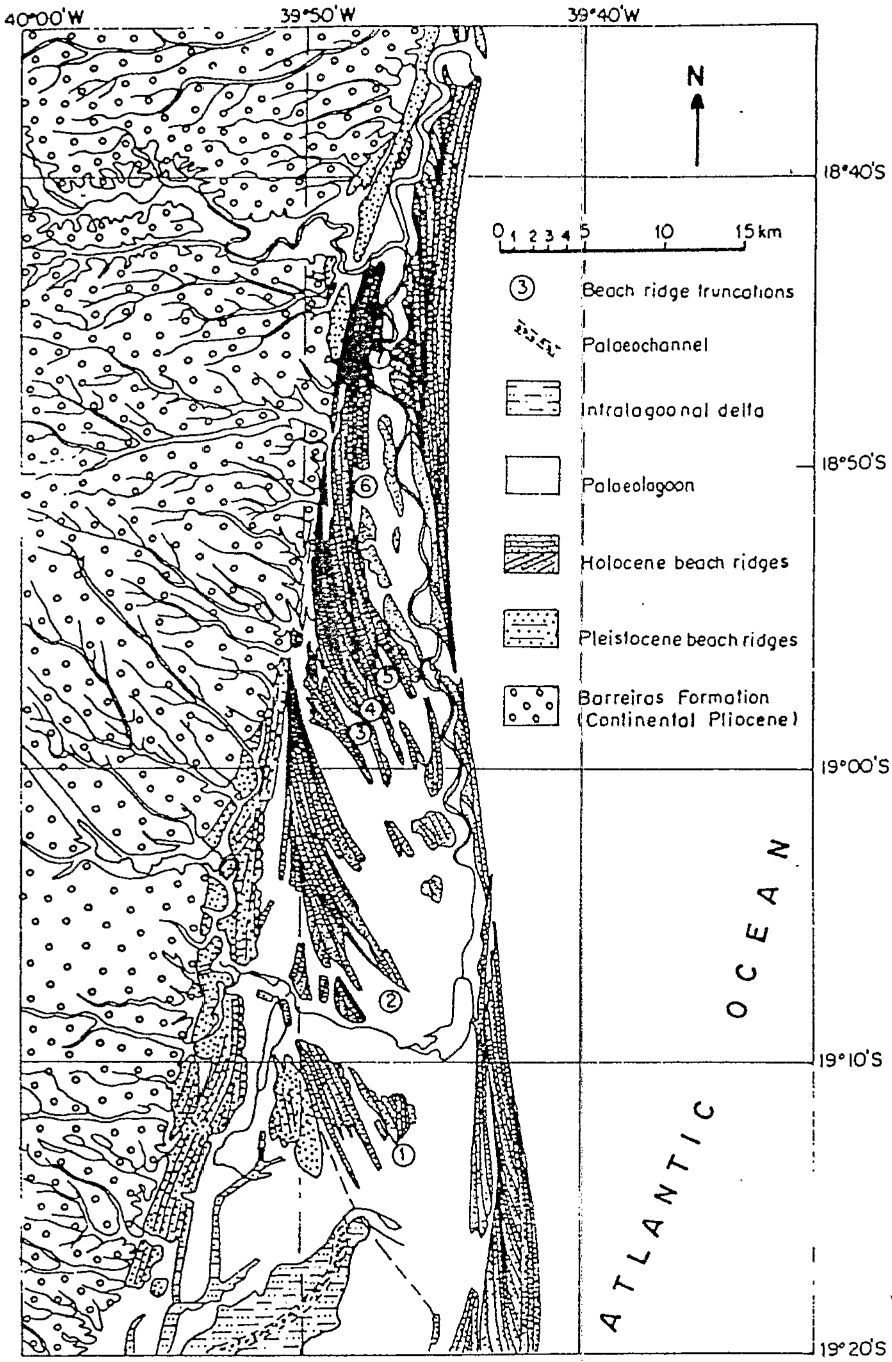

Fig. 6. Schematic geologic map of the northern part of the Doce River coastal plain. Note the unconformities in beach ridge alignments of the first generation marine terrace.

lagoon). At the outside of the barrier islands, the sandy terraces are covered by beach-ridge alignments. Detailed mapping of these alignments shows the existence of well-established unconformities (Figs. 6 and 7). They are related to a sequence of alternating erosional and depositional periods, which indicate changes in coastal hydrodynamics as a consequence of relative sea-level

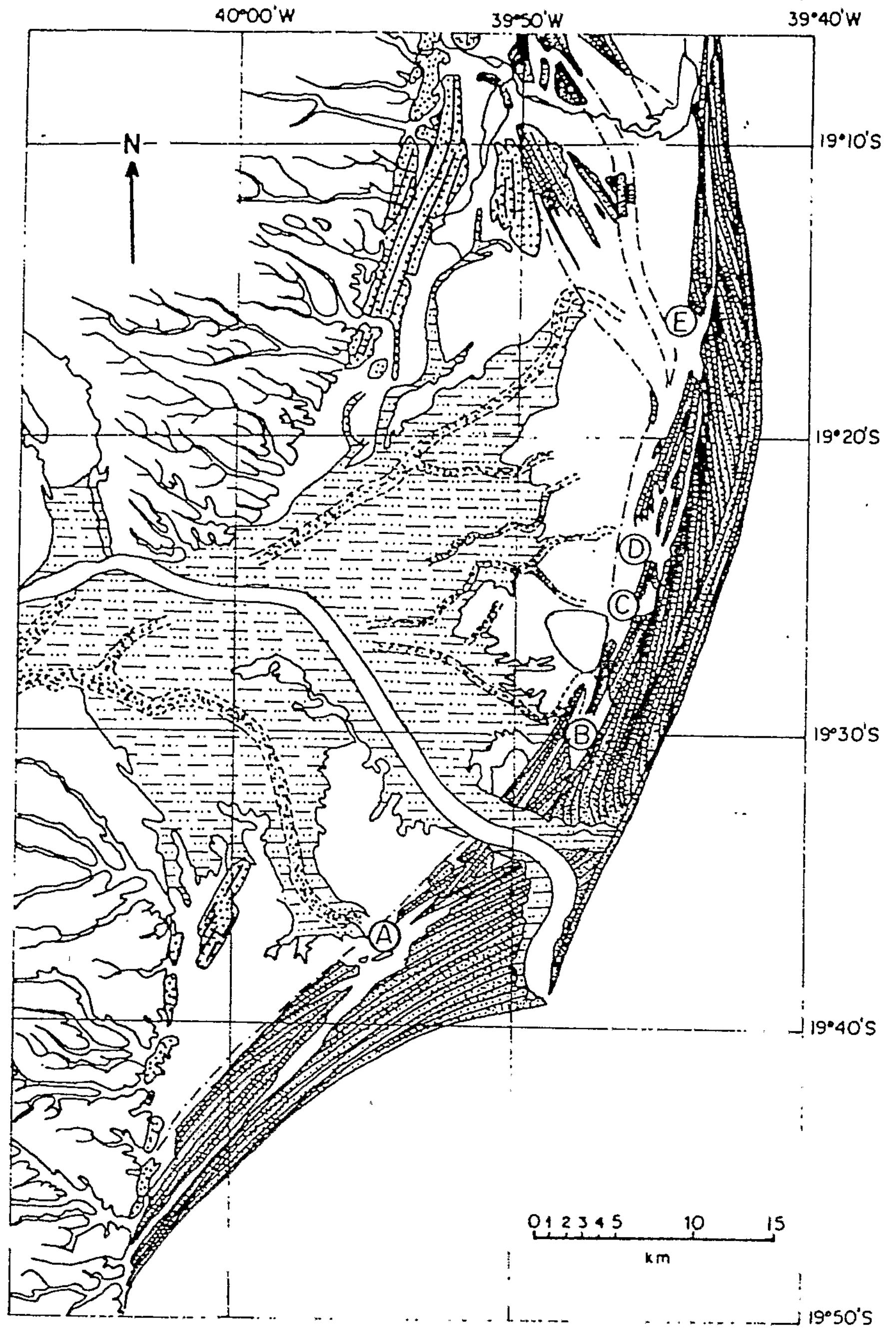

Fig. 7. Schematic geologic map of the southern part of the Doce River coastal plain, showing the intralagoonal delta and the second generation beach ridges. Note the locations of the ancient mouths (A, B, C, D and E).

oscillations or reversals of longshore transportation. The evolution of the Rio Doce coastal plain during the Holocene can be divided into several stages and substages.

Stage A: before 5100 yr. B.P.

This phase corresponds with the formation of the barrier island lagoonal system (Fig. 8A) which,

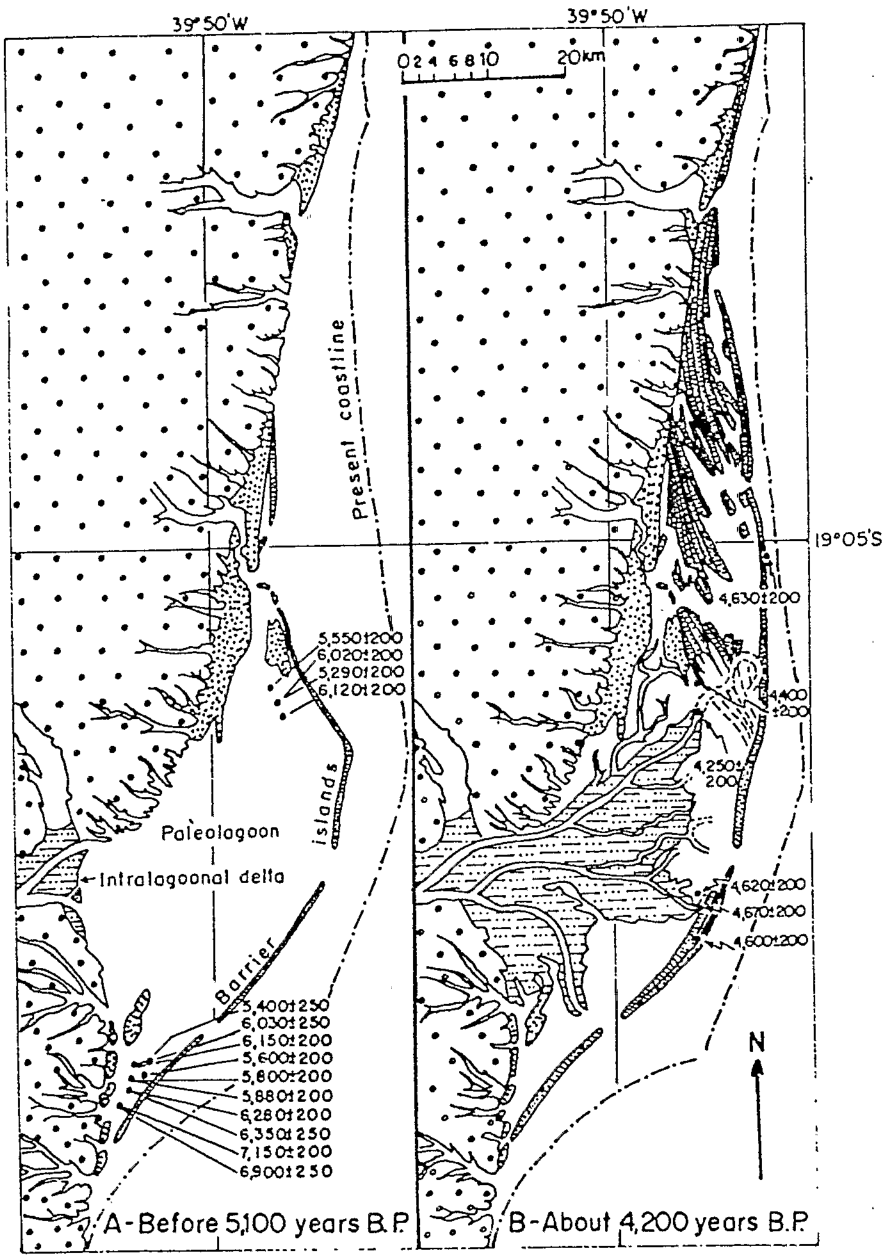

Fig. 8. Palaeogeographic map of the Doce River coastal plain (A) before 5100 yr. B.P. and (B) 4200 years B.P. showing formation of the Holocene first generation beach ridges.

as has been previously shown, existed from around 7000 yr. B.P. In spite of the absence of data necessary to reconstruct the geometry of these barrier islands before 5100 yr. B.P., their final position at the time of the maximum sea level is very well known. It has also been shown that, after the palaeolagoon was created, it became a trap for the sediments supplied by the Rio Doce. There are no data available to follow the first steps in the development of the intralagoonal delta. It is important to determine the moment the Rio Doce began to flow directly into the ocean, thus contributing its discharge to the formation of sandy terraces covered by beach-ridges. There are two possibilities : (a) the intralagoonal delta filled the lagoon rapidly and a few distributaries could attain the ocean very early (Dominguez, 1989); or (b) the abrupt fall in sea level, between about 4200 and 3900 yr. B.P., provoked an almost simultaneous oceanward exit of several still active distributaries of the intralagoonal delta. Based on various sources of data, which will be discussed later, it is possible to visualize that the intralagoonal delta developed within the lagoon until about 4200 yr. B.P., when a phase of a very rapid relative sea-level fall began. This difference in interpretation, in spite of its importance in relation to the source of the sands used for the formation of the first generation of Holocene beach-ridges, does not affect the geometry of the beach-ridges. This geometry will be affected by the direction of longshore transportation, and the angle at which the waves reach the coast. When there are several wave systems in the same general area, the denomination *effective waves* is used for waves having sufficient force to cause longshore transportation in a given direction.

Stage B: period between 5100 and 4200 yr. B.P.

At the maximum height of the transgression, the configuration of the barrier island system showed a pronounced recess in the northern part of the coastal plain (Fig. 8A), which served as a trap for sands transported by longshore currents. It will be demonstrated that, before the Rio Doce entered the ocean, this recess would have been filled in and that the coastline has been almost straightened out (Fig. 8B). It is possible that this filling in occurred before the exit of one or several of the distributaries of the Rio Doce into the ocean, since no modification of beach-ridge geometry, an indication of the existence of ancient river mouths, has been observed in these first generation ridges (Figs. 6 and 7). This happened through shoreline progradation from south to north. Therefore, it can be stated that between 5100 and 4200 yr. B.P., a first generation of sandy terraces was formed. These were created by hydrodynamic conditions related to effective waves from the southeast. However, a detailed examination of the geometry of beach-ridge alignments shows that there are seven conspicuous unconformities (Fig. 6), corresponding to seven erosional phases.

Substage 1: First depositional phase (Fig. 9(1)). The concave shoreline, situated to the north of the barrier island system began to be filled by longshore currents from south to north, under the influence of effective waves from the southeast. Sandy spits projected from the shoreline at the cape which marks the beginning of the indentation. Under the influence of wave refraction these spits were reworked and linked up with each other. The initial take-off point formed by the sandy spit favoured the creation of small elongated lagoons. It is possible to reconstruct an ancient lagoonal mouth (outlet) to the north of this first accumulation zone. The presence of beach-ridges curved back towards the interior of the lagoon suggests that this mouth was ocean-dominated and therefore not mouth of the Rio Doce. It is obvious that, if the hydrodynamic conditions had remained stable, the progradation would have persisted without interruption.

Substage 2: First erosional phase (Fig. 9(2)). A pronounced unconformity in beach-ridge alignments shows that the first depositional phase was interrupted by a local and not a general erosional event. This erosional phase, following a depositional phase, could be explained only by a complete change in local hydrodynamics. Being a local erosional event, it could not be the consequence of a rise in sea level, but would result from a reversal of the direction of the effective waves. After this reversal, the ancient shoreline would become unstable and be subject to erosion until a new equilibrium was established. North of the mouth of the lagoon, a sandy spit developed from north to south. This confirms the longshore transportation in this direction, by effective waves from the northeast. It is clear that, during this entire period, waves from the southeast, caused by the passage of cold fronts did not reach the mouth of the Rio Doce. This explains why the normally ineffective waves from the northeast became effective. Simultaneously, the intralagoonal delta continued its development.

Substage 3: Second depositional phase (Fig. 9(3)). The northward progradation, under the influence of longshore transportation from south to north,

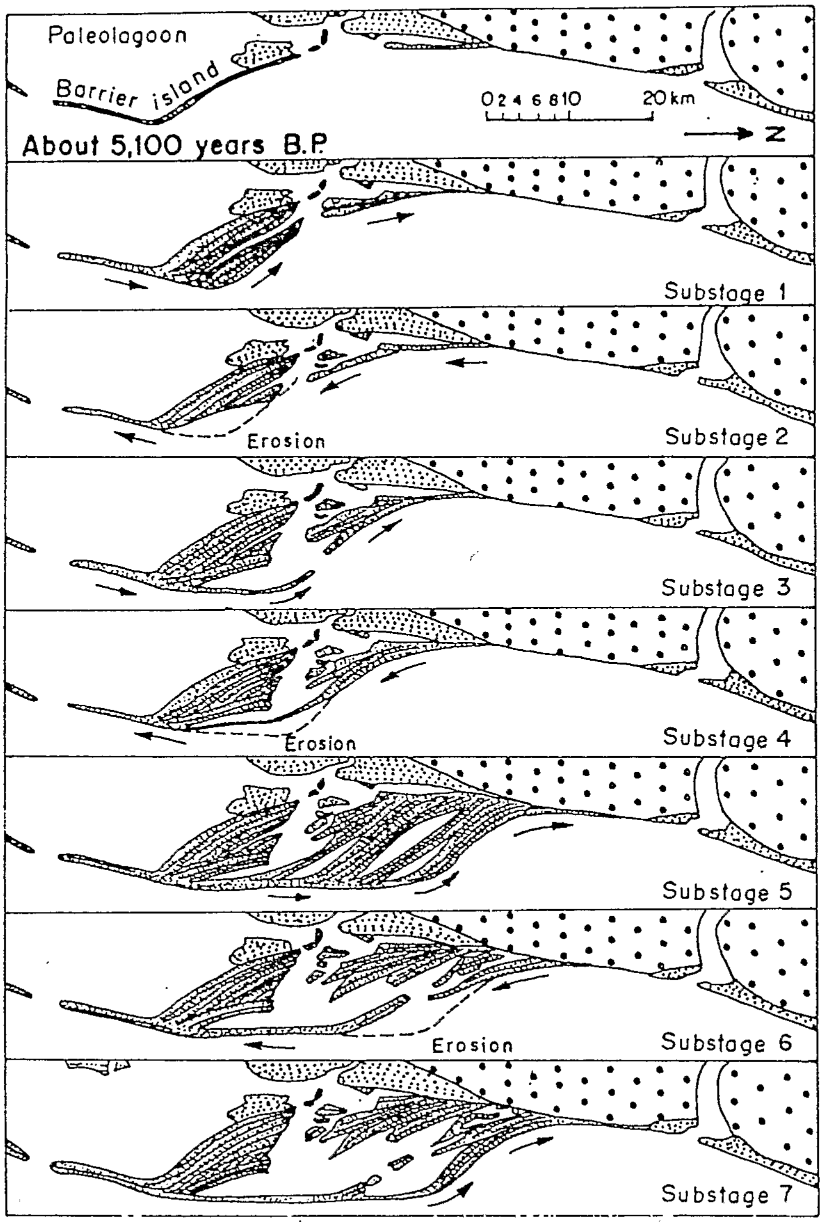

Fig. 9. Substages of the formation of the first generation of beach ridges during the Holocene, showing alternating depositional and erosional phases.

indicates a return to the initial hydrodynamic conditions dominated by waves from the south. This progradation phase is mainly represented by a sandy spit flanked by an approximately 20 km long and 3–4 km wide secondary lagoon. Drill cores, obtained from this elongated lagoon, indicate that it was formed as part of the foreshore by sandy spits (Martin and Dominguez; 1991).

Substages 4–15 (Figs. 9 and 10). Six additional unconformities, clearly distinguishable in the first generation of beach-ridges (Fig. 6), demonstrate the occurrence of a succession of six erosional periods (substages 4, 6, 8, 10, 12 and 14, Figs. 9 and 10), which interrupted the progradation. During these erosional periods, the effective waves always came from the northeast.

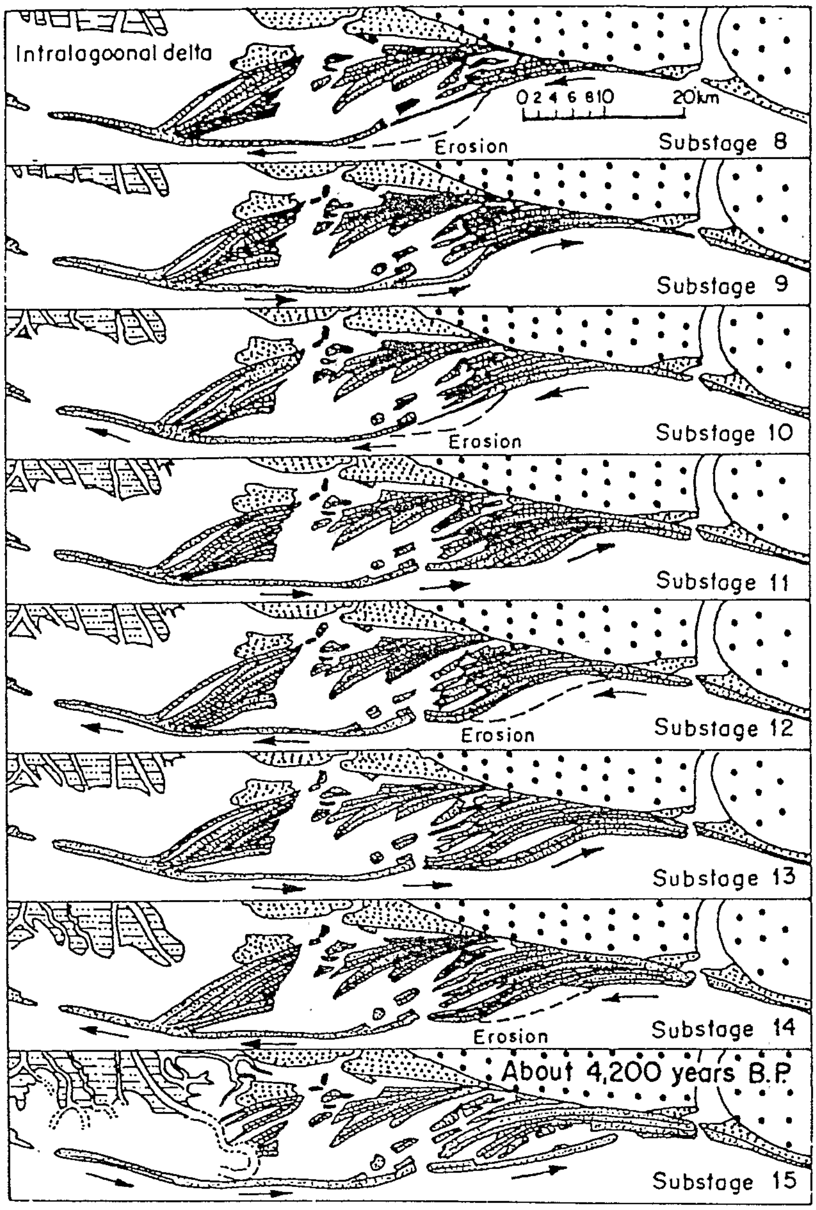

Fig. 10. Substages of the deposition of the first generation of beach ridges during the Holocene, showing alternating depositional and erosional phases (continuation of Fig. 9).

During the last depositional phase (substage 15, Fig. 10), the initial indentation which served as a sedimentary trap was practically filled in. Evidently, during all this time, the intralagoonal delta continued to grow. During substage 15, it was characterized by two main distributary channels and three secondary distributary channels, all of them active. However, none flowed directly into the ocean (Fig. 8B).

Stage C: period between 4200 and 3900 yr. B.P.

It is possible to recognize, from the geometry of beach-ridges, the positions occupied by palaeo-river mouths (Fig. 7) in the central part of the Rio Doce coastal plain in front of the intralagoonal palaeodelta. It is now clear that these palaeo-river mouths (A, B, C, D and E, Fig. 7) were active during the same period of time and that, consequently, they reached the ocean more or less simultaneously (Fig. 11A). Only a global mechanism can explain the contemporaneous exit of five distributaries. It would be very difficult to explain in any other way how they could have reached the ocean simultaneously.

As a consequence of the Rio Doce flowing directly into the ocean, the dynamics of sandy sedimentation changed completely. The Holocene

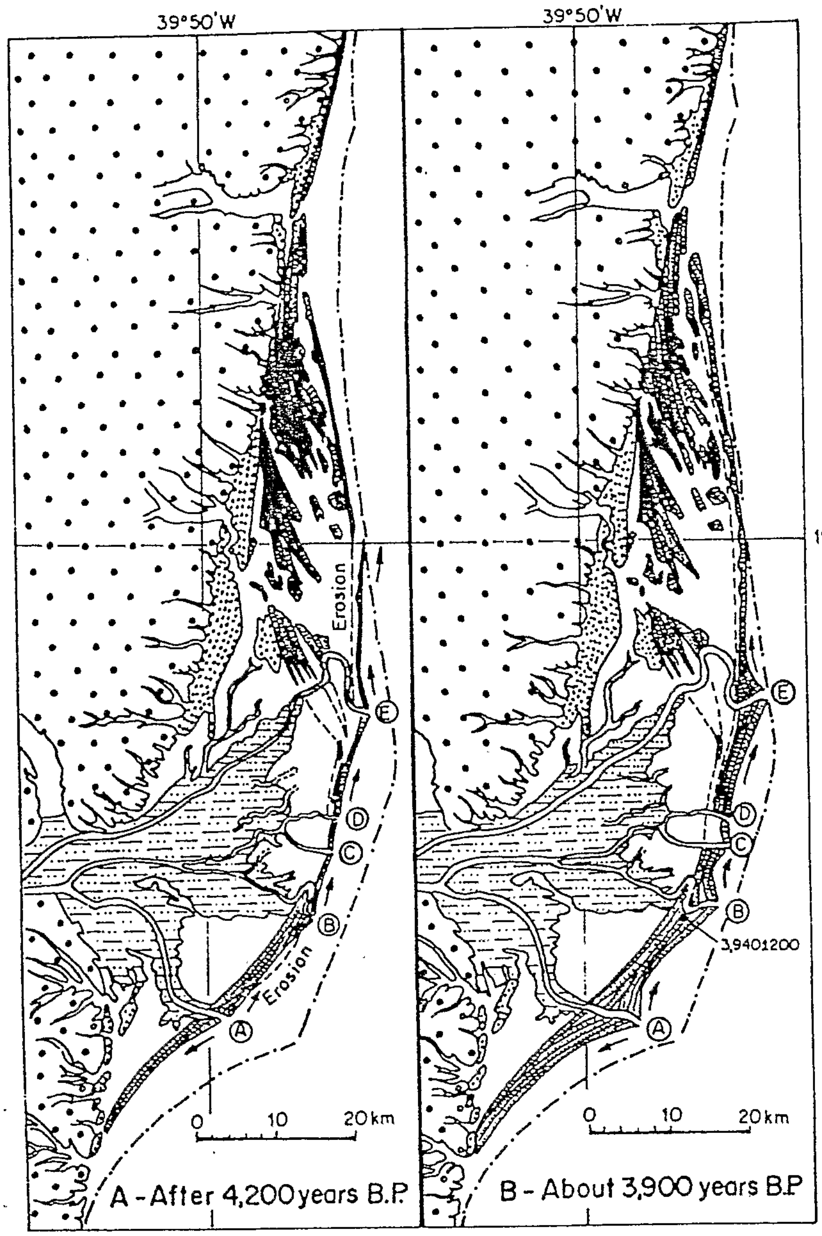

Fig. 11. Palaeogeographic maps of the Doce River coastal plain between 4200 and 3900 years B.P. (A) Direct exit into the ocean of five distributary channels of the intralagoonal delta. (B) Beginning of the deposition of a second generation Holocene beach ridge starting at the five river mouths.

first generation sandy depositional zone, in the north of the coastal plain, was abandoned and sandy sedimentation started in a new area, situated in the south of the coastal plain (Fig. 11A), thereby controlling the geometry of deposition. The sector of the coastal plain, situated between points A and B (Fig. 11A), is not in equilibrium as a consequence of the direct exit into the ocean of several Rio Doce distributaries. This imbalance became manifest through erosional processes in the central part of this sector of the coast (Fig. 11A).

After the Rio Doce distributaries flowed into the ocean, a period of intensive progradation began of sands supplied by the river and, due to relative sea-level subsidence, under hydrodynamic conditions caused by effective waves from the south. (Fig. 11B). A wood fragment, sampled from beach-ridges related to the river mouth at point B, has been dated as 3940 ± 200 yr. B.P. (Bah. 964). This age clearly confirms that a relative fall in sea level was the mechanism that favoured the simultaneous exit to the ocean of the Rio Doce tributaries. The absence of unconformities in beach-ridge alignments formed during this period (Fig. 11B), suggests that no striking changes in hydrodynamic conditions were produced between 4200 and 3900 yr. B.P. and that, consequently, the effective waves were dominantly from the southeast.

Stage D: period between 3900 and 3600 yr. B.P.

A close inspection of Fig. 7 shows that, after the depositional phase following the exit of the five distributaries, the littoral was subjected to intense erosion. This erosion particularly influenced the sandy deposits which were formed on both sides of the five river mouths (Fig. 12A). It would be logical to correlate this general erosional event with the "rapid" relative sea-level rise which took place between 3900 and 3600 yr. B.P. (Fig. 3). At the same time, certain parts of the ancient lagoon of the barrier island/lagoonal system were reoccupied, as well as the elongated lagoons formed during the formation of the first generation beach-ridges (Fig. 12A). A drill core, obtained from an ancient lagoon of the first generation of beach-ridges, shows the existence of two lagoonal sequences separated by fluvial deposits. A radiocarbon dating on shells from sediments of the upper lagoonal sequence gave an age of 3500 ± 150 yr. B.P. (Martin and Dominguez, 1991). No beach-ridges were formed during this period. It is, therefore, impossible to know the hydrodynamic conditions or to reconstruct the direction at which the effective waves reached the coast. However, the possible existence of a period with hydrodynamic conditions caused by effective waves, from the northeast, which would facilitate the erosion, should not be ignored.

As a consequence of a relative rise in sea level, the five river mouths, as well as the lower course of the channels, became unstable and were abandoned, to be replaced by a single mouth independent of the previous ones. The palaeochannels of the ancient distributaries were abandoned and the ancient mouths were partially closed by longshore drift sands (Fig. 12B).

Stage E: period between 3600 and 2700 yr. B.P.

This period was characterized by intense progradation of sands supplied by the new river mouth. The rapid formation of an island in the centre of this river mouth (Fig. 12B) created an eastern (at point H) and a southern (at point G) exit (Fig. 13A). The progradation from these new river mouths continued normally under hydrodynamic conditions generated by the effective waves from the southeast. The absence of any unconformity in the preserved beach-ridge alignments suggests that no changes occurred in the hydrodynamic conditions; that is, no reversal of effective waves took place.

Stage F: period between 2700 and 2500 yr. B.P.

The existence of unconformities in beach-ridge alignments, not only around the mouth at point H, but also along the entire shoreline (Fig. 13B), demonstrates a period of general erosion. However, this erosional phase appears to have been less important than the one during stage D, and the mouths were not abandoned. The erosion was balanced by sands supplied by the Rio Doce, which were much more abundant than during stage D. On the other hand, this erosion cannot

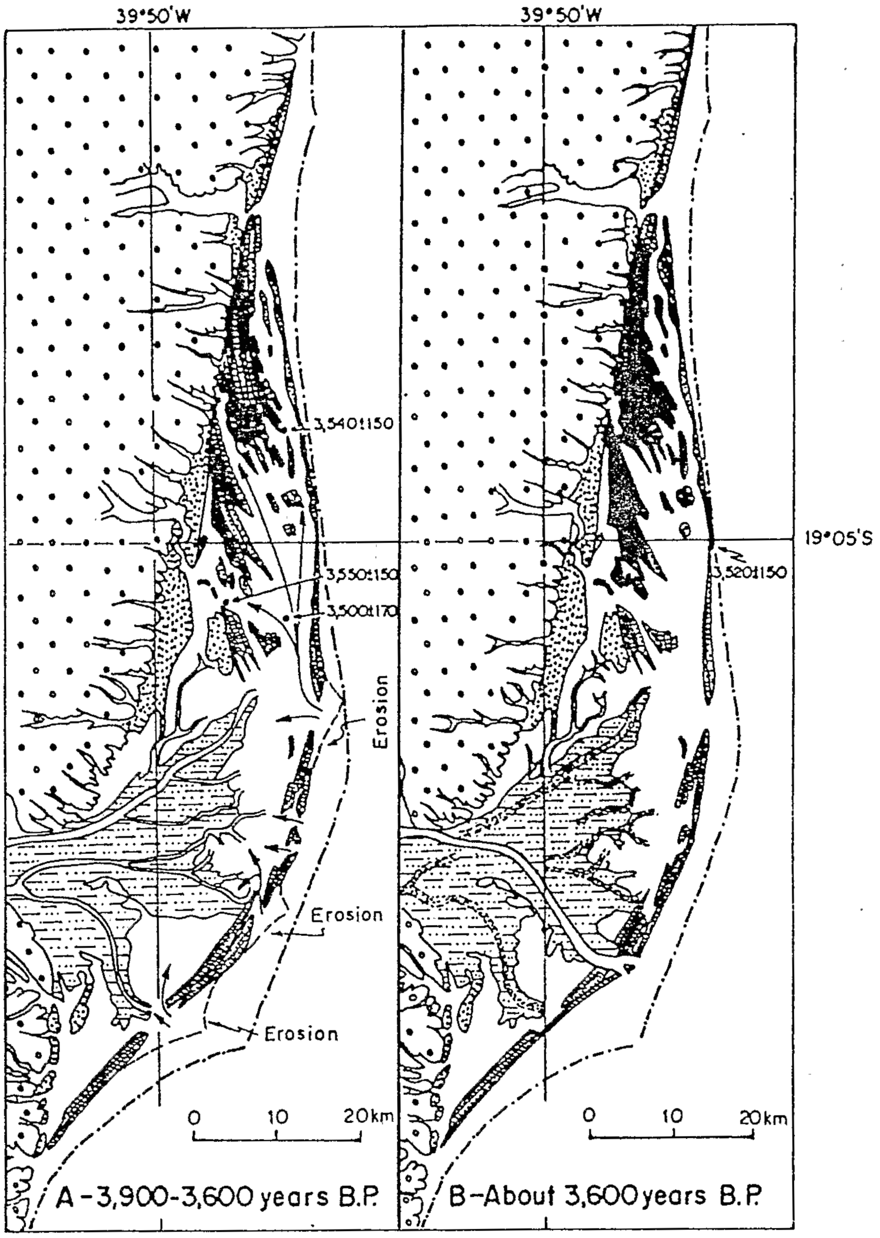

Fig. 12. Palaeogeographic maps of the Doce River coastal plain between 3900 and 3600 years B.P. (A) At the moment of drowning of the five rivermouths. (B) Abandonment of the ancient mouths and opening of a new mouth related to a solitary channel.

be blamed on changes in hydrodynamics as a consequence of a reversal of the direction of the effective waves. In this case, as demonstrated below, only the margins of the northern mouth (at point H) would be eroded, while the southern mouth (at point G) remained protected from the waves from the northeast and, therefore, from erosion. It would appear logical to relate this general erosional phase to the relative rise in sea level which occurred between 2700 and 2500 yr. B.P. (Fig. 3).

There was no formation of beach-ridges during that time interval and it is, therefore, not possible to know the hydrodynamic conditions, nor the direction at which the effective waves reach the shoreline.

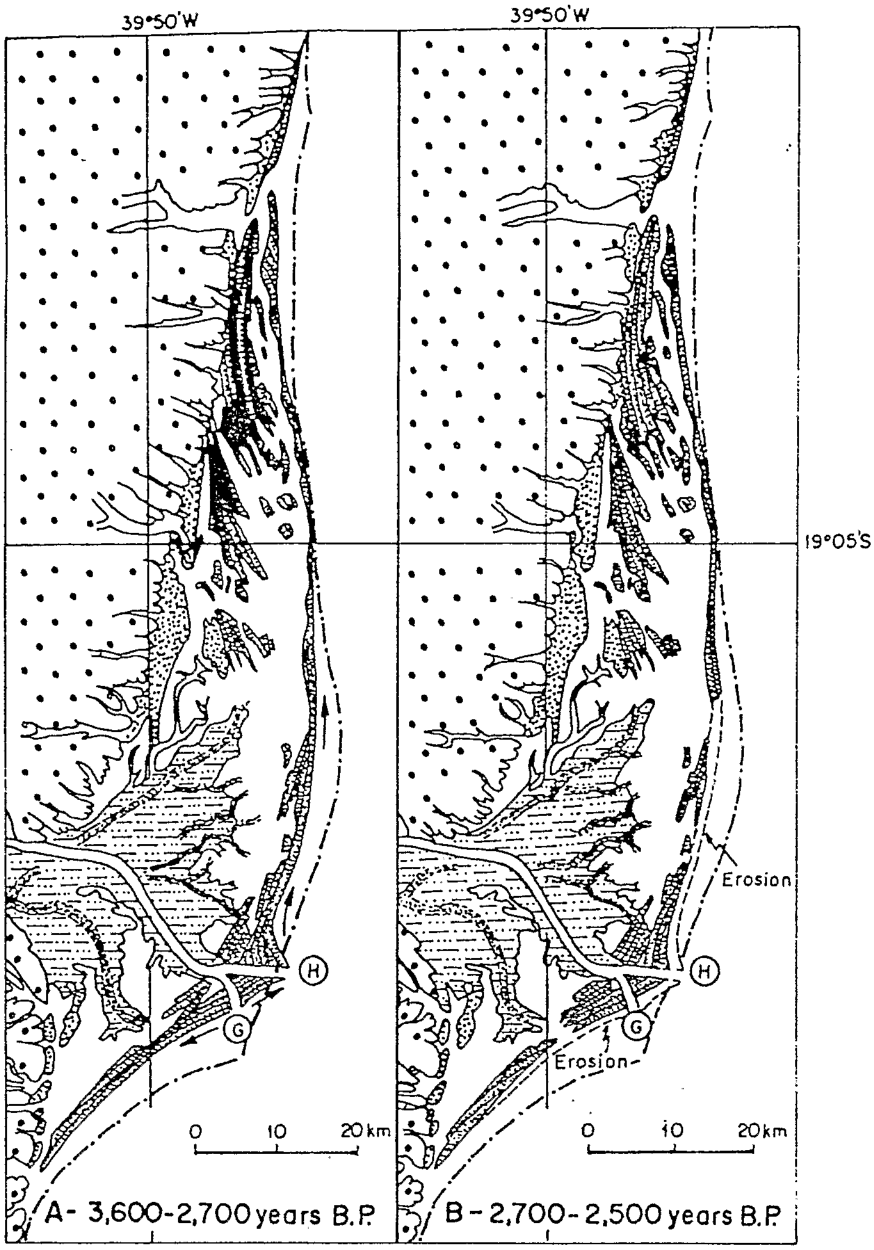

Fig. 13. Palaeogeographic maps of the Doce River coastal plains between 3600 and 2700 years B.P. (A) Progradation starting from the new mouth. (B) Period of general erosion.

Stage G: period between 2500 yr. B.P. and present

A close inspection of Fig. 7 shows the existence of clear unconformities in beach-ridge alignments, which were formed around the mouth at point H after 2500 yr. B.P. (Fig. 7). As in the first generation prograding zone (stage B), this fact demonstrates the existence of several depositional and erosional phases, caused by different hydrodynamic conditions.

Substage 1: First depositional phase (Fig. 14). After the episode of general erosion during stage F (Fig. 13B), the progradation of both margins of

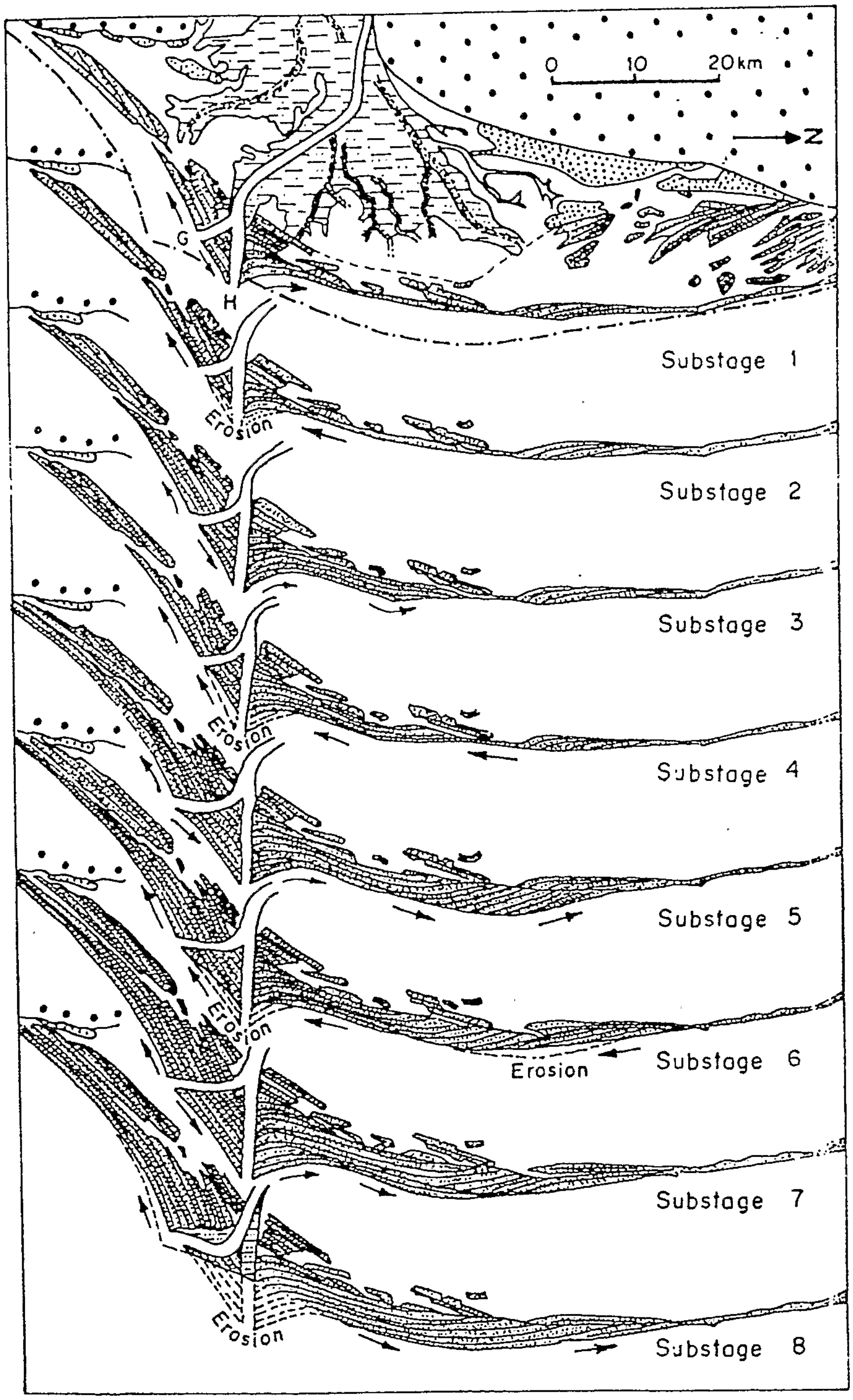

Fig. 14. Substages of the evolution of the southern part of the Doce River coastal plain after 2500 years B.P. Note the alternation of depositional and erosional events is only around the northern mouth.

the mouths at point G and at point H continued (substage 1, Fig. 14). This phase occurred under hydrodynamic conditions created by effective waves from the southeast, when sands supplied by the Rio Doce and deposited in front of the mouth at point H, were transported northwards. On the other hand, sands deposited in front of the mouth at point G, as a consequence of its difference in orientation, were transported both to the north and to the south.

Substage 2: First erosional phase (Fig. 14). Unconformities in beach-ridge alignments around the northern mouth (at point H) enable us to recognize an erosional phase. It is worth noting that this type of unconformity is absent around the mouth at point G. This could possibly be the consequence of local hydrodynamic changes, which were a result of a reverse in the direction of the effective waves. Under these conditions, the northern mouth (at point H) was unstable while the southern mouth (at point G) was sheltered from wave action from the northeast.

Substage 3 : Second depositional phase (Fig. 14). The resumption of northward progradation from the northern mouth (at point H), and to the north and south from the southern mouth (at point G) indicates the return to hydrodynamic conditions caused by effective waves from the southeast.

Substage 4: Second local erosional phase (Fig. 14). Unconformities in beach-ridge alignments, located solely at the northern mouth (at point H), indicate a local erosional phase as a consequence of a change in hydrodynamic regime, characterized by effective waves from the northeast.

Substage 5: Third depositional phase (Fig. 14). The resumption of progradation indicates the return to hydrodynamic conditions caused by southern sector waves. The progradation occurred not only around the mouths but also more northwards within a shallow indentation of the coast situated near the ancient mouth at point E.

Substage 6: Third erosional phase (Fig. 14). As in the substages 2 and 4, unconformities in beach-ridge alignments appear around the northern mouth (at point H), but are absent around the southern mouth (at point G). Moreover, the shoreline subjected to an increased progradation at the proximities of the ancient mouth at point E, during the previous substage, became unbalanced under hydrodynamic conditions dominated by the waves from the northeast, which resulted in erosion.

Substage 7: Fourth depositional phase (Fig. 14). The resumption of progradation indicates the restoration of hydrodynamic conditions dominated by waves from the southeast. The shoreline around the northern mouth (at point H) extended for beyond the present shoreline.

Substage 8: Abandonment of the northern mouth (at point H) (Fig. 14). At present, the Rio Doce has only one active mouth and the existence of beach-ridges between the mouths at points G and H demonstrates that a gradual migration from the mouth at point H to the mouth at point G has not occurred. For some reason, the northern mouth (at point H) became inactive. With the cessation of the sand supply, provided by the Rio Doce, this mouth was in disequilibrium and subjected to erosion, as demonstrated by clear unconformities in both margins of the northern mouth (at point H). However, unlike what occurred during substage 6, the deposits formed to the north of the mouth at point H, which would normally be in disequilibrium under hydrodynamic conditions caused by waves from the northeast, were not eroded. Therefore, the erosion of the northern mouth (at point H) was not caused by a change in direction of effective waves. The occurrence of longshore transportation from south to north, under hydrodynamic conditions caused by waves from the southeast, is confirmed by the existence of an important area of deposition to the north of the coastal plain, immediately to the south of the Rio São Mateus. This deposition took place simultaneously with the erosion of the northern mouth.

Substage 9: Present situation. As a result of the N–S orientation of the present single active river mouth, the sands supplied by the Rio Doce are deposited on both sides of the mouth (Fig. 7), as in typical wave-dominated deltas. This pattern is clearly visible on the terrain as well as on aerial photos. The hydrodynamic conditions are dominated by effective waves from the southeast.

Comparison between the River Doce coastal plain data and other Brazilian coastal plains

The sandy terraces, situated at mouths of the Paraiba do Sul (State of Rio de Janeiro) and the Jequitinhonha (State of Bahia) rivers, indicate changes in local hydrodynamics similar to those observed at the Doce Rio mouth. The abrupt relative sea-level rises between 3900 and 3600 yr. B.P. and between 2700 and 2500 yr. B.P. are reflected by major unconformities. On the other hand, secondary unconformities in beach-ridges alignment similarly show the existence of periodic reversals in the direction of longshore drift. Detailed reconstructions made of the Rio Paraiba do Sul coastal plain demonstrated that, between 5100 and 3900 yr. B.P., reversals were much less numerous than at the Doce Rio mouth. This means that, from time to time, waves from the southeast which reached the Paraiba do Sul Rio mouth continuously, did not reach the Doce Rio mouth. During other periods in time, waves from the southeast reached neither the Paraiba do Sul Rio nor the Doce Rio mouth. Obviously, between 5100 and 3900 yr. B.P., the blockage of effective waves from the southeast was variable. It is not possible to make the same type of palaeogeographic reconstructions for the Jequitinhonha Rio mouth as for the Doce Rio and the Paraiba do Sul Rio coastal plains. However, at first sight, the Holocene sandy terraces show unconformities in beach-ridge alignments which, also in this case, must correspond with changes in the direction of longshore transportation. In contrast, the morphological records show that, at the São Francisco Rio mouth, the longshore currents flowed permanently from north to south, as a consequence of effective waves from the northeast. This corroborates the fact that, in a normal situation, the waves from the southeast rarely reach this region today. The blockage of these waves does not change the littoral dynamics of the São Francisco Rio mouth, which is permanently controlled by waves from the northeast.

Conclusions

On a sandy coast, changes in littoral dynamics generated by relative sea-level oscillations and reversals of littoral transportation, greatly influence the sedimentary deposits. These features can be demonstrated by unconformities in beach-ridge alignments, which are frequently overlapping sandy terraces. It is possible to decipher the nature and the direction of transport of these sandy deposits so that one can recognize, for the same time interval, certain characteristics of the littoral dynamics.

A detailed examination of the geometry of Holocene sandy terraces, situated at the mouths of the Paraiba do Sul, Doce and Jequitinhonha rivers enabled us to identify three generations of sandy terraces which were formed during falls in relative sea level after 5100 yr. B.P., and were interrupted by two episodes of relative sea-level rises between 3900 and 3600 and 2700 and 2500 yr. B.P. In addition, a meticulous analysis of the geometry of beach-ridges of the first and the third generations of Holocene terraces clearly show well-defined unconformities in beach-ridge alignments. These are indicative of several episodes of local erosion, related to periods of reversal in littoral sand transport with durations of 10–100 yr. These reversals can be explained only by changes in the direction of the effective waves and of the wind pattern; such as that which occurred in 1983 on a Salvador (State of Bahia) beach, described by Farias et al. (1985). This disturbance occurred soon after the blockage of polar advections (waves from the southeast), by reinforcement of the subtropical jet current, as a consequence of the "El Nino" phenomenon. This phenomenon is capable of producing indirectly, on a monthly time scale, disturbances in the littoral transportation of sediments in central part of the Brazilian coast. The periods of reversal of littoral transport, accurately recorded in the Rio Doce coastal plain, can, therefore, be correlated with periods of "El Nino-like" conditions of long duration (Martin et al., 1984). However, it has to be stated that these reversals can be explained by a permanent blockage, as well as by discontinuous but very frequent blockages. If this hypothesis is correct, "El Nino-like" conditions with consequences very similar to those produced by the El Nino phenomenon of 1982–1983, may have occurred in the past over South America.

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