Journal of Coastal Research	16	1	71–81	Royal Palm Beach, Florida	Winter 2000

Influence of Antecedent Topography on Coastal Evolution as Tested by the Shoreface Translation-Barrier Model (STM)

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ABSTRACT

DILLENBURG, S.R.; ROY, P.S.; COWELL, P.J., and TOMAZELLI, L.J., 2000. Influence of antecedent topography on coastal evolution as tested by the shoreface translation-barrier model (STM). *Journal of Coastal Research*, 16(1), 71–81. Royal Palm Beach (Florida), ISSN 0749-0208.

This paper demonstrates that antecedent topography played a very important role on the coastal evolution of Rio Grande do Sul (RS) in Brazil during the Holocene. By modeling the last 9 ka of sea level change using the general morphology of the present shelf as the substrate over which barriers have translated a successful reconstruction was obtained showing the position of the coastline at the time of the Post-Glacial Marine Transgression maximum (5 ka). Not only has the antecedent topography played an important role in the definition of the coastal shape of RS, it has also pre-determined the type of coastal barrier: prograded barriers along coastal reentrances, and receded and mainland beach barriers along coastal projections. Analysis of sediment budget indicated that more than half of sediments needed for progradation along coastal reentrances came from the shelf. The Shoreface Translation-Barrier Model (STM) was used to recreate Holocene coastal shorelines and to simulate sediment volumes.

ADDITIONAL INDEX WORDS: *Coastal barriers, sediment budget, sea level change, wave focusing.*

INTRODUCTION

Antecedent topography controls present-day coastal morphologies by providing regional slope, establishing initial coastal orientation with respect to prevailing winds and waves, and through local variations inherited from valleys and interfluves that create embayments and headlands (BELKNAP and KRAFT, 1985). Because of wave refraction and wave focusing effects, protruding coasts are usually subjected to erosion while reentrants (coastal embayments) experience deposition (MAY and TANNER, 1973). Thus prograded barriers typically characterize low-gradient coastal reentrants while retrogradational barriers such as receded barriers and mainland beaches are found on steeper, protruding sectors of coast.

During a marine transgression the rate of shoreface translation is simply a function of the substrate slope and the speed at which sea level is rising, if wave regime and sediment budget are maintained roughly constant. Computer modelling suggests that under these conditions a coastal barrier migrates landward without eroding the substrate and that its basal contact corresponds to the former land surface (ROY *et al.*, 1994). In fact this relationship is broadly true in most continental shelves except at major deltas. Thus in a low-relief autochthonous continental shelf setting such as Rio Grande do Sul (RS), it is reasonable to assume that shelf morphology broadly corresponds to the former land surface. It should therefore be possible to model shoreface translation during the final steps of the Post-Glacial Marine Transgression (PMT) using the present day shelf surface as the substrate over which the barriers translates.

This paper tests the hypothesis that antecedent topography has played a very important role on the coastal evolution of RS during the Holocene by comparing the results of simulation modelling with the area's present-day coastal geology. It will also explore the extent to which the antecedent topography has pre-determined the different styles of barriers that occur in the coast. A computer model (Shoreface Translation-Barrier Model—STM) is used to simulate Holocene coastal shorelines and coastal stratigraphies (sediment volumes).

99024 received and accepted in revision 17 May 1999.

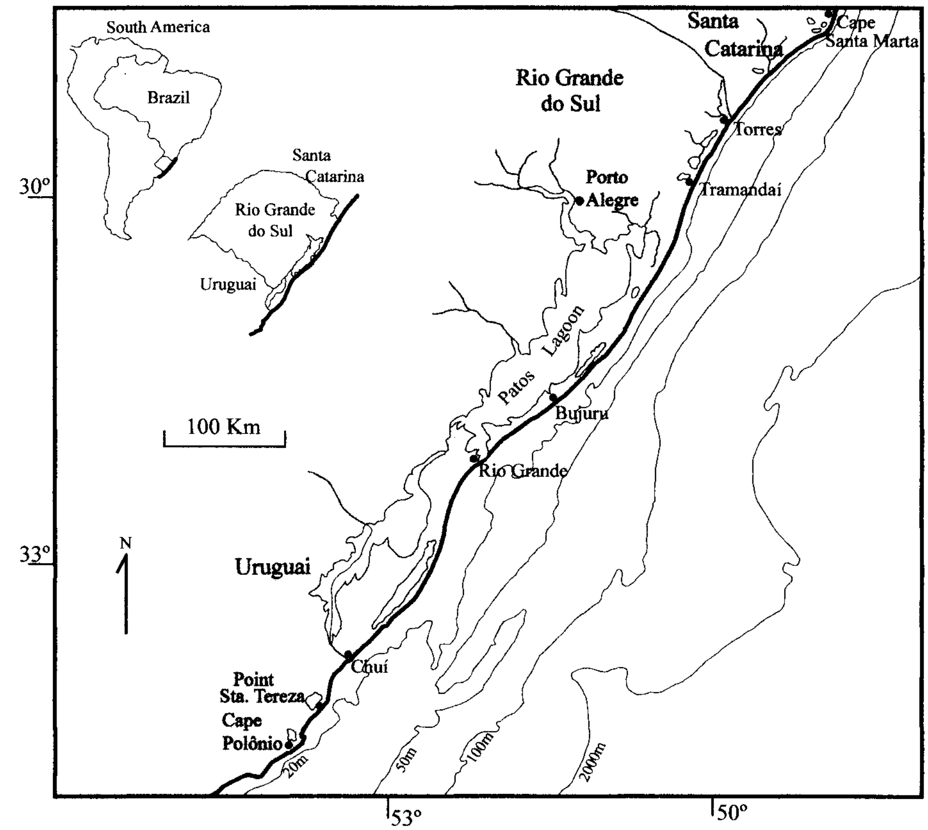

Figure 1. Study area

REGIONAL SETTING

The southern Brazilian continental margin is a rifted plate boundary formed in Early Cretaceous times. In the vicinity of Rio Grande do Sul (29° to 34° south latitudes) deposition of a large amount of post-rift, manly clastic sediments, produced a wide (100 to 200 km), shallow (100 to 140 m) and gently sloping (0.03° to 0.08°) continental shelf. Seismic records of the upper slope reveal a sedimentary thickness of at least 10 km (FONTANA, 1990). On land in central and southern RS a low-relief coastal plain was formed during the Quaternary by justaposition of sedimentary deposits of four barrier/lagoon systems designated I (oldest) to IV by VILLWOCK *et al.* (1986). Here the coastal plain ranges from 60 to 80 km wide and is bordered to landward by a gentle bedrock relief. In contrast, in northern RS, the coastal plain is narrower (20 km), only the two youngest barrier/lagoon systems deposits (III and IV) occur, and it is abruptly bordered landward by bedrock highlands; here relief changes from +20 m to +500 m over a distance of about 500 m. In general the landward border of the coastal plain corresponds to the western margins of a series of lagoons which are large in south and central part of RS and are small in the north (Figure 1). Climate is humid temperate with generally warm to hot temperatures in summer and cool temperatures in winter. Rainfall ranges from 1000 to 1500 mm and is evenly distributed throughout the year.

Rio Grande do Sul is characterized by a monotonous and gentle undulating barrier coast, oriented NE-SW and subject to dominant swell waves generated in southern latitudes, and wind-generated waves produced by strong spring-summer sea breezes from the northeast. The average significant wave height is 1.5 m, measured in 15–20 m water depth (MOTTA, 1969). The coast is microtidal with semidiurnal tides that have a mean range of only 0.5 m. Consequently, sediment transport and deposition along the open coast is primarily dominated by wave action. A net northward littoral drift is evident in coastal geomorphic features (TOMAZELLI and VILLWOCK, 1992), and by field measurements (TOLDO Jr. *et al.*, 1993). The present day beaches of RS receive very little sand from inland because most of the beadload carried by the few streams and rivers that drain to the coast is trapped in lagoons and other coastal plain environments (TOMAZELLI *et al.*, 1998).

The post-glacial sea level history of the Rio Grande do Sul coast extends from about 17.5 ka BP when the sea was positioned at about −120 to −130 m (CORRÊA, 1995). Since that time sea level has risen at an average rate of 1.2 cm/yr until 6.5 ka BP when the rate of sea level rise slowed (Figure 2). There is no reliable data on sea level behaviour during Mid-

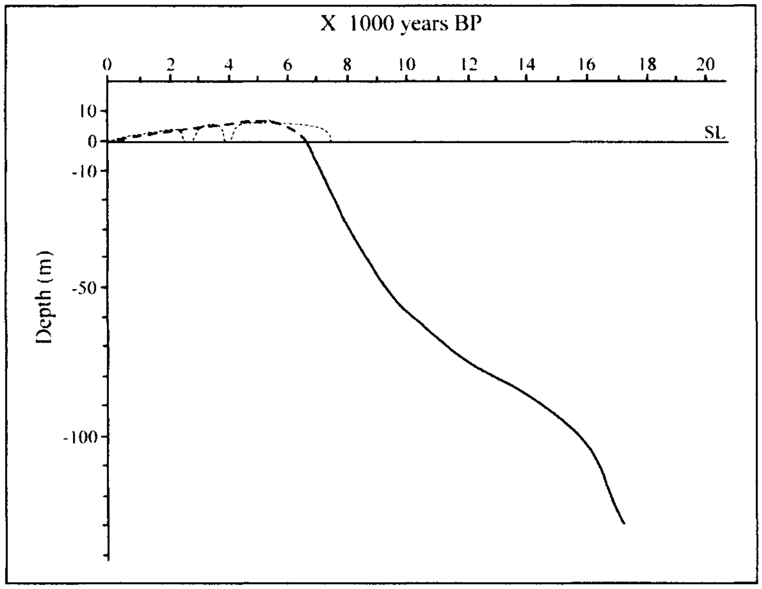

Figure 2. Holocene sea-level curves for the east coast of Brazil. Solid curve after Corrêa (1990). Dotted curve after Martin *et al.* (1979). Dashed curve after Angulo & Lessa (1997).

dle to Late Holocene along the RS coast. Sea level curves for areas further to the north indicate that at the culmination of the PMT (5 ka) sea level reached a few meters above its present level, followed thereafter by a slow sea level fall (MARTIN *et al.,* 1979; ANGULO and LESSA, 1997) (Figure 2). This general sea level behaviour also probably applies to the north coast of Rio Grande do Sul (DILLENBURG, 1996). The sea level curve presented by MARTIN *et al.* (1979) indicates a maximum of +5 m on the coast of Bahia state in NE Brazil, and evidence presented by ANGULO and LESSA (1997) suggests that the maximum was around +3.5 m in the States of São Paulo and Paraná to the north of RS. Finally, ANGULO *et al.* (1996) report new data suggesting a maximum submergence of about +2 m in South Brazil (Santa Catarina State), in a coastal sector distant only 100 km to the north of RS.

THE HOLOCENE BARRIER SYSTEM

The Holocene barrier system of Rio Grande do Sul occupies the entire 625 km length of coast. Discontinuities in the barrier system occur only at two sites: in the south, at Rio Grande, where the inlet of the Patos Lagoon is located, and in the north, at the inlet of Tramandaí Lagoon. Both inlets are permanently open because of a continuous and large discharge of fresh waters through their mouths. The entire coastline is gently undulating and consists of two large subdued seaward projections and two landward reentrances (Figure 1).

Geological mapping of the Coastal Province of Rio Grande do Sul includes early reports by VILLWOCK (1984) and VILLWOCK *et al.* (1986), followed by more detailed local studies by TOMAZELLI (1990), DILLENBURG (1994), REGINATO (1996), TOMAZELLI *et al.* (1995), BUCHMANN (1997) and LUMMERTZ *et al.* (1998). These data plus new interpretations based on aerial photos and satellite images show marked changes in the styles of coastal development during Mid and Late Holocene along the 625 km length of the barrier. Its main characteristics are shown in Figure 3 and described below, from north to south, in five sectors. The nature of the Holocene barriers and their relationships to the deposits to landward are described below. These observations form the basis for interpreting barrier stratigraphies shown in Figure 4.

Sector 1

The coast from Torres to Tramandaí is slightly concave with a Holocene barrier formed by a beach/foredune ridge strand plain ranging from 2 to 5 km wide (Figure 3I). The westernmost ridge is highest and was interpreted as a transgressive barrier that records the 5 ka PMT maximum of VILLWOCK and TOMAZELLI (1995). A strip approximately 1 km wide of transgressive dunes occur continuously near the present shoreline from Torres to Xangri-lá; here the transgressive dunes become wider and eventually cover all the barrier surface. Transgressive dunes represent a landward loss of sand from the coast and thus are an indication of coastal retreat. The continuity of the beach ridge is maintained from Cape Santa Marta to Torres but at Torres it is intercepted by rocky headlands. The interpreted stratigraphy corresponds to type B and C respectively in Figure 4.

Sector 2

From Tramandaí to Mostardas the coastline is slightly convex-seaward; the barrier ranges from 2 to 6 km in width and is completely covered by transgressive dunes and in many places the dunes extend onto the Pleistocene barrier (Figures 3I and 3II). There is no evidence of beach/foredune ridge

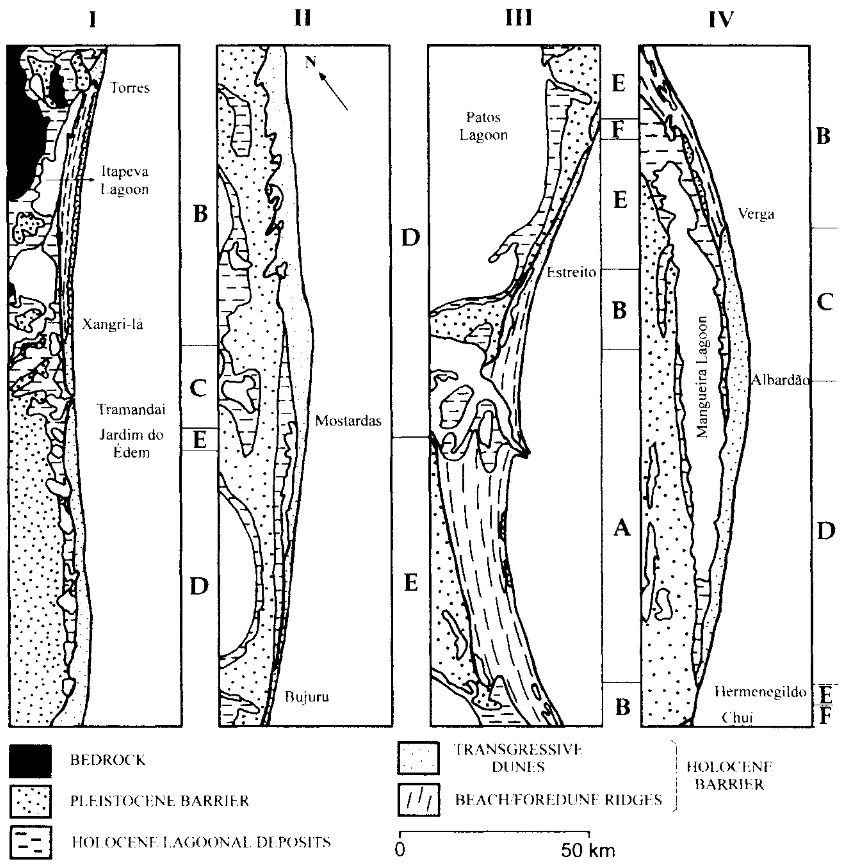

Figure 3. The Holocene Barrier of Rio Grande do Sul. Some important localities mentioned in the text are shown. Capital letters in bold are related with styles of barriers of Figure 4.

strand plain. At Jardim do Édem Beach, located 7 km south of Tramandaí, the receded nature of the barrier is attested by lagoonal muds presently outcropping on the beach face. These muds are at least 1.5 m thick and a ^{14}C date from its base showed an age of 5,760 ± 120 years BP (DILLENBURG, 1994). The interpreted stratigraphy corresponds to type D and E in Figure 4.

Sector 3

Subtle coastal convexity continues from Mostardas to Estreito; here the Holocene barrier is less than 2 km wide and is composed completely of transgressive dunes (Figures 3II and 3III). In the north the barrier dunes transgress into an interbarrier lagoon (Type D in Figure 4), but in the south they onlap the Pleistocene barrier (Type E in Figure 4). Lagoonal muds and peats crop out along the entire beach face and provide clear evidence of a long-term and widespread erosional trend along this coastal sector. A ^{14}C date from the lagoonal muds outcropping near Bujuru showed an age of 3,390 ± 130 BP. In a restricted site located 2 km to the south of Bujuru, Holocene lagoonal deposits were completely eroded and the barrier is onlapping the Pleistocene barrier (mainland beach barrier configuration, type F in Figure 4). This sector is the longest coastal stretch where receded barriers and transgressive dunes coexist.

Sector 4

The coastal sector from Estreito to approximately Verga is concave and has the widest beach/foredune ridge strand plain (2 to 15 km in width) of the RS coast (Figures 3III and 3IV). Transgressive dunes are lacking except for rare occurrences located immediately behind the present beach. Where the strand plain is widest at least 60 beach/foredune ridges have been counted on satellite images. In the north the stratigraphy corresponds to type A in Figure 4, but in the south it corresponds to type B. Yet despite the evidence of long-term progradation, the inlet channel of Patos lagoon has maintained its position.

Sector 5

From Verga to Chuí the coast is strongly convex-seaward. The barrier ranges from 2 to 5 km wide and is composed of transgressive dunes as far south as Hermenegildo (Figure 3IV). At Hermenegildo and for 10 km to the south estuarine-lagoonal sediments dated at 4,330 ± 60 years BP outcrop on the beach (TOMAZELLI *et al.*, 1998), and indicate recession of

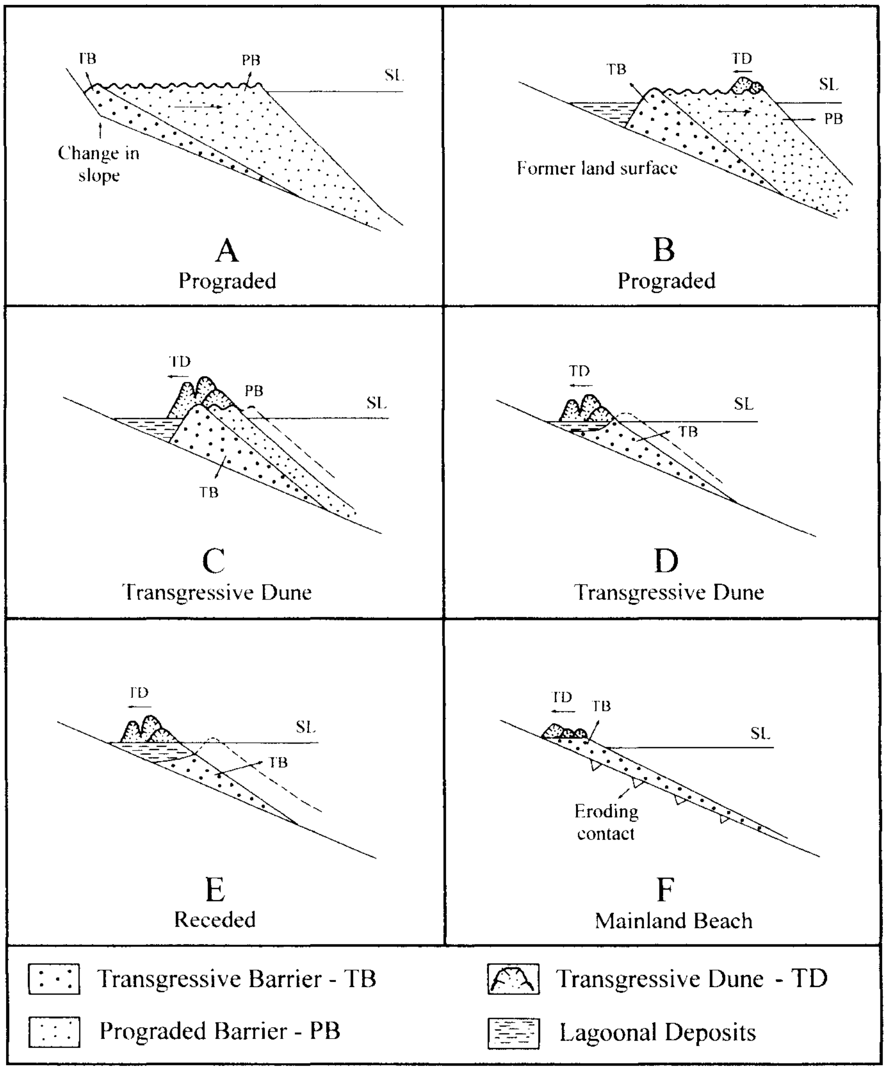

Figure 4. Schematic morphology and stratigraphy of Holocene barriers of Rio Grande do Sul.

the barrier. Near Chuí, the barrier becomes progressively narrower and finally becomes a mainland beach barrier near Chuí. Rocky headlands (Point Santa Tereza and Cape Polônio) occur approximately 40 km south of Chuí (Figure 1). The interpreted stratigraphy corresponds to a variation from type C to F in Figure 4.

In summary, there is a correlation between coastal configuration in plan-view and the nature of the coastal barriers. Coastal reentrances (concave sectors of coast) are dominated by prograded barriers whereas protruding sectors of coast typically have retrogradational capped with transgressive dunes barriers. A correlation also exists between the coastal configuration and the morphology of the continental shelf. Along coastal reentrances the shelf is wider and more gently sloping, whereas along coastal projections it is narrower and steeper (see Figure 1).

PROCEDURES

In order to evaluate the role of the former land topography in the evolution of the RS coast, computer simulations using the Shoreface Translation-Barrier Model (STM), of COWELL *et al.* (1991) were carried out. The model is designed to simulate the horizontal and vertical translation of coastal sand bodies over a pre-existing substrate during a progressive sea-level change. The STM is based on principles of sand-mass conservation and geometric rules which govern shoreface and barrier behaviour. The rules were derived from empirical, analytical and/or numerical process studies, together with stratigraphic and surface-morphology data from well known case studies in SE Australia and elsewhere (COWELL *et al.*, 1992 and ROY *et al.*, 1994). The most important and sensitive variables of the model are rate of sea level change (whose imputs may be rising or falling at different rates, or a sta-

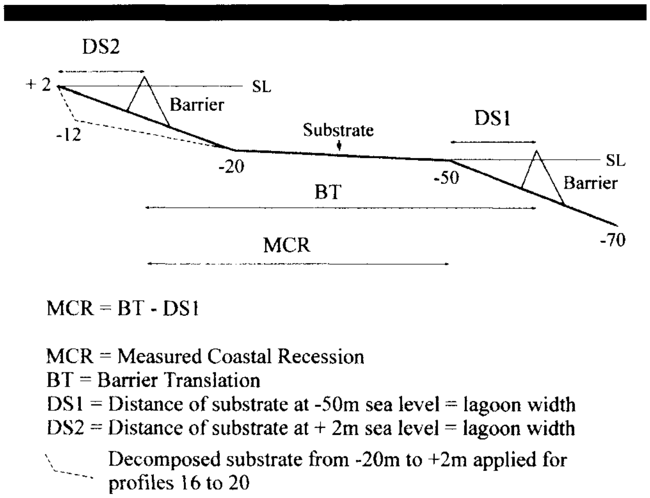

Figure 5. Definition sketch of major parameters used in the modelling sea-level rise from −50 to +2 m.

bilised sea-level), substrate slope, nearshore sediment budget, and mud deposition rate in the backbarrier (estuarine/lagoonal) environment. See COWELL and THOM (1994), and COWELL *et al.* (1995) for more details.

Because of the proximity of the region where ANGULO *et al.* (1996) have recently reported a maximum sea level at the end of the PMT of about 2 m, this value was also assumed for the coast of RS. The modelling encompassed the latter part of the PMT with sea level rising from −50 m at 9.5 ka to +2 m at 5 ka (Figure 2). It was assumed as an hypothesis that the present day overall shelf morphology of RS corresponds to the former land surface. This hypothesis is based on the autochthonous nature of RS continental shelf and takes into account a minor reworking of the substrate over which barriers have translated during the course of the PMT. Thus, the slope of 25 simplified cross-shelf bathymetric profiles, spaced approximately 25 km apart were used as a substrate in the modeling. The profiles were constructed using 1:270.000 scale bathymetric charts (D.H.N., 1963a, 1963b and 1964) and on 1:845.000 charts of MARTINS and CORRÊA (1996). Simplified substrates were derived from bathymetric charts for depths ranging from −70 to −50 m and −50 to −20 m. In the absence of subsurface data, slopes above −20 m were interpolated landward up to + 2 m using inferred stratigraphic relationships shown in Figure 4. A definition sketch of major parameters used in the modelling is shown on Figure 5. Together with the simulation results, the locations of the transects are shown in Figure 7. Substrate slopes are listed in Table 1.

A balanced condition for the nearshore sediment budget was initially assumed because of the impossibility of precisely knowing sediment budgets along the coast during the marine transgression. Regarding mud deposition rates, an average value of 1.2 mm/year of mud accumulation was used based on ^{14}C dating of the Patos Lagoon (TOLDO JR. *et al.*, 1991) and Tramandaí Lagoon (DILLENBURG, 1994). Other variables such as transgressive barrier width (600 m) and storm surge elevation (2.0 m) were assumed as general approximations for the whole coast of RS. Using the detailed bathymetric charts of CORRÊA (1990), different shoreface dimensions (Xs = surf base extension and Ys = depth of surf base) were calculated for the coast of RS (Table 1), and were used as the shoreface dimensions of the modeling. A total of 26 steps of

Table 1. *Data of some variables used in the modelling.*

Profiles	Longshore Distance (km)	Shoreface Dimensions Y (m)	X (m)	Slope 1 (degrees) −70 to −50 m	Slope 2 −50 to −20 m	Slope 3 −20 to +2 m	Overall Slope −70 to +2 m
01	0	20	5,000	0.071	0.046	0.128	0.064
02	25	20	5,000	0.064	0.042	0.096	0.057
03	50	20	5,000	0.066	0.045	0.078	0.058
04	75	20	5,000	0.080	0.048	0.109	0.067
05	100	20	5,000	0.093	0.052	0.128	0.075
06	125	20	5,000	0.104	0.099	0.061	0.084
07	150	20	5,000	0.135	0.099	0.090	0.104
08	175	20	5,000	0.127	0.125	0.092	0.113
09	200	20	5,000	0.144	0.114	0.112	0.120
10	225	20	5,000	0.127	0.169	0.092	0.125
11	250	20	5,000	0.088	0.128	0.096	0.104
12	275	17	4,000	0.067	0.099	0.091	0.086
13	300	15	4,000	0.048	0.083	0.086	0.070
14	325	12	3,000	0.042	0.056	0.093	0.057
15	350	12	3,000	0.035	0.045	0.061	0.045
16	375	12	3,000	0.019	0.036	0.054	0.031
17	400	12	3,000	0.019	0.031	0.035	0.027
18	425	12	3,000	0.025	0.032	0.030	0.029
19	450	12	3,000	0.024	0.047	0.029	0.032
20	475	12	3,000	0.025	0.054	0.028	0.034
21	500	12	3,000	0.023	0.074	0.027	0.034
22	525	12	3,000	0.020	0.053	0.029	0.031
23	550	12	3,000	0.025	0.035	0.042	0.033
24	575	12	3,000	0.090	0.020	0.062	0.035
25	600	12	3,000	0.039	0.025	0.048	0.033

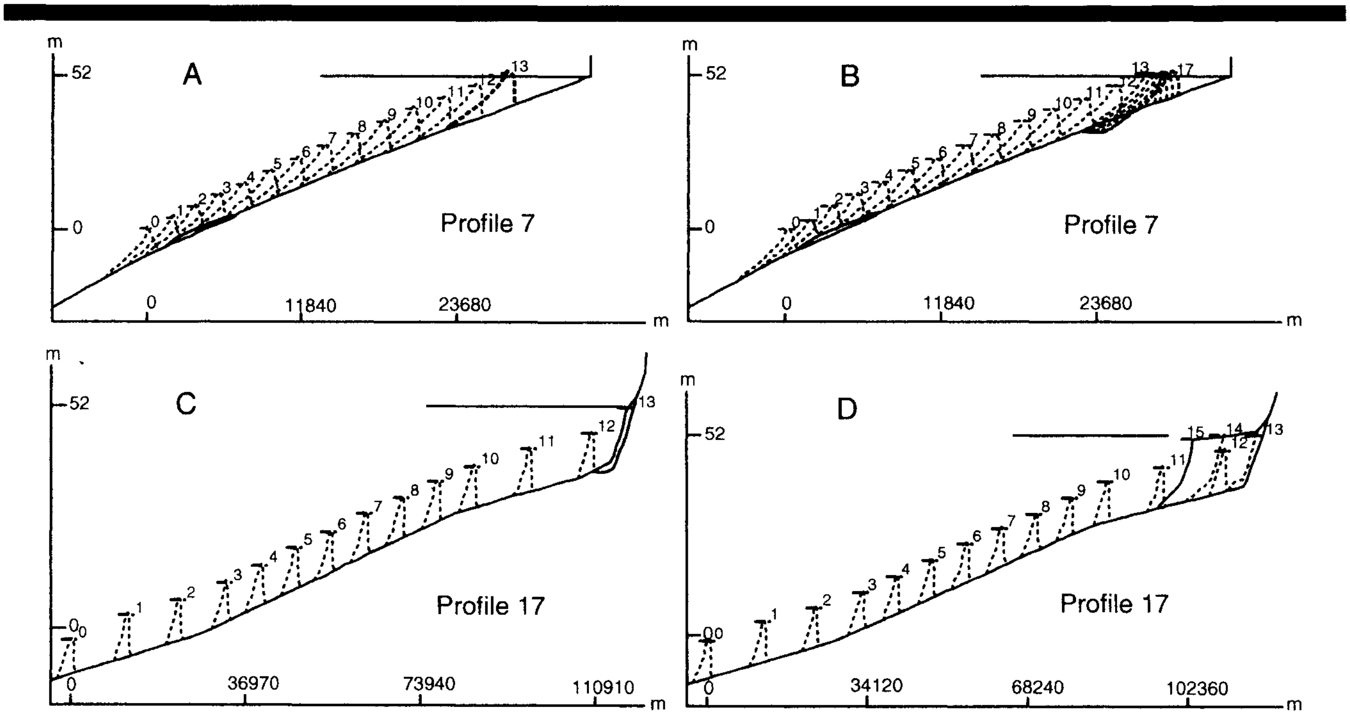

Figure 6. Computer simulation results for profiles 7 and 17. Sea-level rise and barrier translation from −50 to +2 m (a and c). Coastal erosion after 5 ka (b). Coastal progradation after 5 ka (d). Dotted outlines of the shoreface and transgressive barrier are shown for each 4 m increments of sea-level rise as illustration purpose (modelling was in fact performed with 2 m increments).

2 m increments of sea level rise was modeled for a total of 52 m in all. The 50 m isobath was chosen as the starting point because of its almost straight alignment (Figure 1). Modelling of coastal changes after 5 ka was performed for all 25 profiles starting at the predicted coastline position at the time of the PMT maximum.

RESULTS

The overall slope of the inner shelf of RS, calculated for 25 cross-shelf profiles from −70 to +2 m water depth fluctuates in a regular manner from north to south with gradients ranging from 0.027° to 0.125° (Table 1). A correlation exists between the profile slopes, representing the inner continental shelf morphology, and coastal configuration (Figure 7). From profile 1 to 10 and 17 to 21 coastal configuration changes from a reentrance to a projection and the shelf gradients become progressively steeper; from profile 10 to 17 and 21 to 25 the coastal configuration changes from a projection to a reentrance and the shelf slopes become flatter. Thus it is clear that coastal reentrances occur where the inner continental shelf shows gentle gradients and that coastal projections occur where the continental shelf slopes are steeper.

Results of modelling for two profiles (7 and 17) are shown in Figure 6 (see also Table 2). From 9 to 5 ka, sea level rise produced a coastal recession of 24.4 km and 90.4 km along profiles 7 and 17, respectively (Figures 6a and 6c). Despite of a small sea level fall after 5 ka (2 m), the coast in profile 7 was eroded in the order of 1.9 km (Figure 6b), but at the same time the coast in profile 17 has prograded in the order of 14.0 km (Figure 6d). The subtle change of the substrate at −12 m in profile 17 caused the transgressive barrier onlap of Pleistocene barrier at the end of the PMT (Figure 6c).

By integrating results of all profiles the modelling produced a maximum PMT coastline showing the same general configuration as the present one especially in coastal reentrances where the predicted coastline closely matches the inner edge of the prograded barriers (Figure 7). The length of predicted coastal recession from 9 to 5 ka, for each transect, is shown in Table 2. Additional confirmation of the modelling is the close correspondence between widths of predicted lagoons at the end of the PMT, and the widths of the present lagoonal deposits in the coastal reentrances (see Table 3). In contrast, the predicted 5 ka coastline for protruding sectors of coast, with the exceptions of profiles 9 and 11, were all located seaward of the present coast. The only indication of the accuracy of this prediction was provided by the long-term erosional nature of these sectors of coast supported by direct evidence from ^{14}C dates of 5,760 ± 120 BP (DILLENBURG, 1994), 3,390 ± 130 BP, and 4,330 ± 60 BP (TOMAZELLI *et al.*, 1995) on lagoonal muds outcropping at the beach face in Jardim do Édem, near Bujuru and Hermenegildo, respectively.

The modelling of a 2 m sea level fall from 5 ka to the present time shows that, as a consequence of a shoreface adjustment equivalent to 2 m of sea bed erosion along a 5 km length of shoreface (Xs), the overall progradation of the coast of RS would have been in the order of 500 to 1,000 m only (Table 2). By calculating the additional volume of sediments neces-

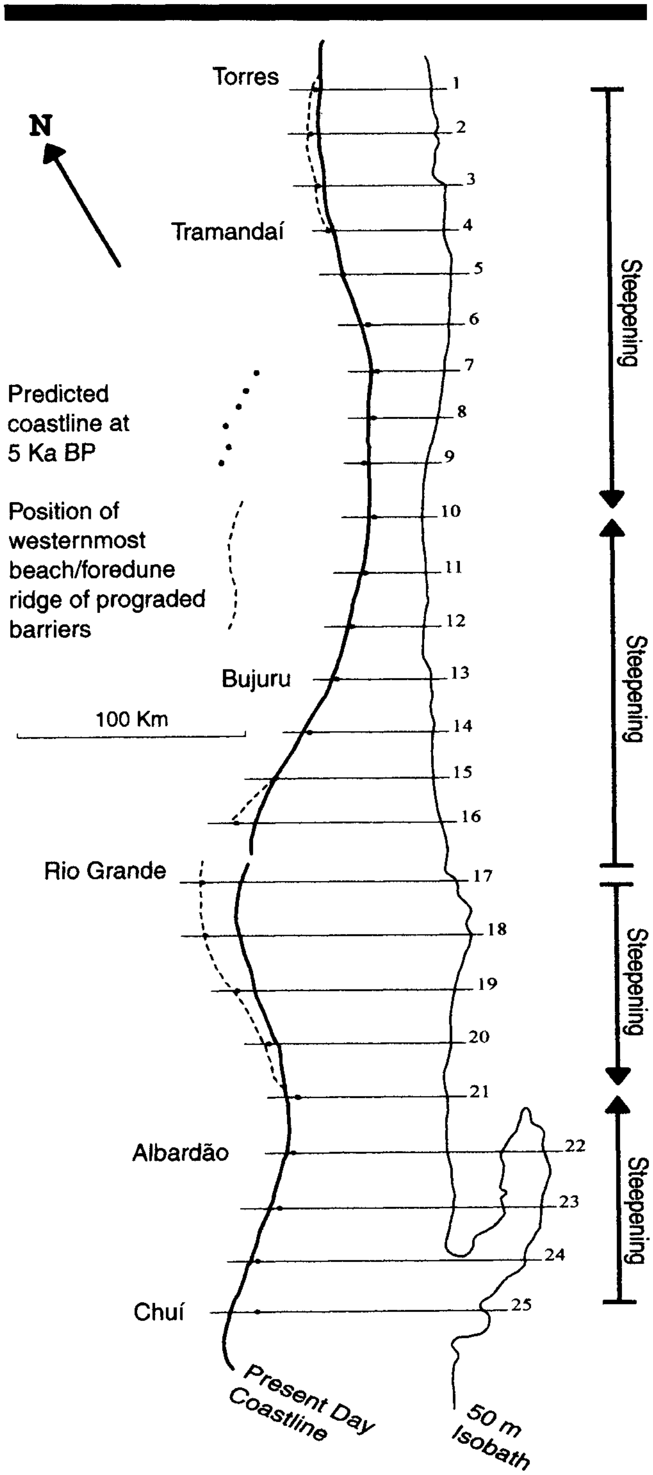

Figure 7. Present coastline of Rio Grande do Sul and the predicted coastline for the end of the Post-Glacial Marine Transgression (PMT). Black dashed curves along coastal reentrances represents the position of the westernmost beach/foredune ridge of prograded barriers, assumed as the coastline position at the maximum of the PMT. Black dotted represents the predicted coastline for the maximum PMT for each profile.

sary to produce real progradation along coastal embayments (Table 2), it was possible to estimate that rates of 940,000 m^3/yr and 2,605,000 m^3/yr (total of 3,545,000 m^3/yr) were required for such progradation along north and south coastal embayments of RS, respectively (Table 2). On the other hand, simulation of coastal erosion along coastal projections indicated the production of a positive imbalance of sediment budget to the littoral drift system of only 1,727,500 m^3/yr, clearly not enough to satisfy the above demand of 3,545,000 m^3/yr (Table 2).

DISCUSSION

The results demonstrate that it is possible to reproduce the coastal configuration of Rio Grande do Sul at the maximum of the PMT by modelling coastal evolution during the last 9 ka using as a substrate the present day general morphology of the continental shelf. This strongly confirms that today's shelf morphology is a geological inheritance from a former land surface.

The modelling shows that very small slope differences on the order of few minutes of substrate slope (see Table 1) can produce appreciable differences in coastal translation rates and distances during a sea level rise (Table 2), and supports the work of EVANS *et al.* (1985) and ROY *et al.* (1994) who reported on the importance of slight variation in antecedent topography on landward barrier migration. Thus, as is the case in RS where these small differences in slope occur along a stretch of coast, the resulting shoreline can be expected to show patterns of gentle undulations (reentrances and projections) after a sea level rise. Because coastal translation was performed over a generalized substrate, some discrepancies can be expected between the predicted 5 ka coastline and its present day position (*e.g.* profiles 1 and 19, Figure 7).

Not only has the antecedent topography played an important role in the definition of the coastal shape of RS, it has also pre-determined the type of coastal barriers that formed. Here the barriers have been subjected, over the long term, to two contrasting coastal processes: deposition in coastal reentrances leading to the formation of prograded barriers, and erosion along protruding stretches of coast leading to the formation of transgressive dunes, receded barriers and mainland beach barriers (Figures 3 and 4). Although other modes of formation of transgressive dunes are possible, including falling sea level and strong onshore winds (see HESP and THOM, 1990; DOMINGUEZ *et al.*, 1987), the simultaneous occurrence of receded barriers and transgressive dunes on sectors of the RS coast exposed to the same environmental parameters suggests a link here between coastal erosion and the formation of transgressive dunes.

As shown in Figure 7, the coast of RS evolved from an almost straight contour at −50 m to a gentle undulating one at +2 m at the end of the PMT (5 ka). The comparison between the predicted coast and the present one indicates that from 5 ka up to the present time coastal reentrances were subjected to appreciable progradation and coastal projections to significant erosion. The long-term erosional trend of coastal projections clearly indicates that any potential for progradation induced by a sea level fall of 2 m after 5 ka was over-

Table 2. *Data regarding behaviour of the coastline of Rio Grande do Sul during the time span of the modelling (9 ka to present).*

Profile	Predicted Coastal Recession (km) from −50 to +2 m (9 to 5 ka)	Predicted Coastline Progradation after 5 ka Due to a 2 m Sea Level Fall Only (m)	Volume of Sediments Required for Progradation Due to a 2 m Sea Level Fall (m³/m/year)	Coastline Change after 5 ka		Additional Volume of Sediments Required for Progradation (Real) in Coastal Reentrances (m³/m/year)	Volume of Sediments (m³/m/year) Produced by Erosion in Coastal Projections
				Progradation (Real) (m)	Erosion (Predicted) (m)		
01	42,449	571	0.6	2,600		9.4	
02	46,682	626	0.6	4,000		17.4	
03	44,084	653	0.7	2,700		9.3	
04	41,014	597	0.6	1,000		1.4	
05	37,112	569	0.6	700		0.1	
06	25,741	685	0.8		4,700		9.0
07	24,434	640	0.6		1,900		4.0
08	21,258	645	0.6		1,750		4.2
09	21,839	611	0.5	750		0.1	
10	18,226	650	0.6		950		2.1
11	20,804	638	0.6		638		3.2
12	25,248	637	0.6		1,850		3.6
13	30,361	712	0.6		2,500		4.5
14	51,755	692	0.5		2,700		4.5
15	54,371	779	0.7		1,050		0.9
16	69,811	635	0.5	5,700		15.5	
17	90,454	737	0.6	1,400		39.4	
18	93,533	806	0.7	11,300		29.3	
19	75,820	921	1.0	6,500		13.0	
20	64,219	913	1.0	4,000		7.0	
21	50,089	893	0.9		7,150		5.0
22	57,554	883	0.9		2,750		1.5
23	64,104	838	0.8		4,850		4.8
24	97,101	777	0.7		3,200		3.8
25	84,499	820	0.8		10,700		18
						3,545,000[1]	1,727,500[2]

[1] Estimated total volume of additional sediments required for progradation in coastal reentrances.

[2] Estimated total volume of sediments produced by erosion of coastal projections.

whelmed by erosion associated with both the focusing and higher wave energy on protruding (steeper) sections of the coast. A model of wave energy concentration will be discussed later. Regarding progradation in coastal embayments, an important question is: where did the sediments that caused progradation come from? Three hypothesis should be considered: (1) new sediments delivered to the coast by rivers, (2) positive sediment inputs to the littoral drift system from wave erosion of adjacent coastal projections, and (3) onshore transport of sediments from the continental shelf by swell waves.

Table 3. *Comparison of predicted lagoonal width at the maximum of the PMT (5 ka) and after a 2 m sea level fall with the present width of lagoonal deposits for profiles located along coastal reentrances.*

Profile	Predicted Lagoonal Width at 5 ka (km)	Predicted Lagoonal Width after 2 m of Sea Level Fall (km)	Present Width of Lagoonal Deposits (km)
01	4.9	4.5	4
02	7.5	6.7	7
03	9.9	8.8	10
04	6.1	5.5	5.5
05	4.8	4.3	4.5
16	0	0	0
17	0	0	0
18	0	0	0
19	4	3.7	4
20	9.5	9.2	10

The present-day barrier coastline of RS receives no sand from inland sources, as most of the sediment load carried by the few streams and rivers draining the hinterland is trapped in the coastal lagoons shown in Figure 1. The two inlets of the Holocene barrier system at Rio Grande and Tramandaí carry only muddy fluvial sediments to the coast. We can also rule out littoral drift imports from outside the study area. Rio de La Plata river, the second largest river in South America, located 200 km to the south of Chuí, was drowned at the end of the PMT, and at least since that time has delivering no sand to the open coast (URIEN, 1967). Also, rocky headlands that contain compartmented beaches (LABORDE and JACKSON, 1996) on the Uruguayan coast (Cape Polonio and Point Santa Teresa, Figure 1), appear to have acted as physical barriers to the littoral drift towards the north.

The depositional and erosional behaviour of coastal reentrances and projections respectively, has been explained by MAY and TANNER (1973) using a graphical model for littoral sediment transport. In general terms the model explains how an embayed coastline supresses its coastal reentrants and projections by the action of waves. As a consequence of wave refraction, coastal projections tends to concentrate wave energy while in reentrants wave energy is dispersed, with the result that coastal projections erode and their material is transported and deposited in adjacent reentrants. Calculations based on data presented on Table 2 indicate that after 5 ka erosion of the two coastal projections would have added only 1,727,500 m^3/yr to the sediment budget, while the recorded progradation of the two coastal reentrances was at a rate of 3,545,000 m^3/yr. Thus an additional source of sediments is required to account for the total progradation of RS coast.

As mentioned before, an erosion of the sea bed with an onshore transport of the eroded sediments as a result of a shoreface adjustment for a 2m sea level fall after 5 ka, was insufficient to provide enough sand for the progradation (Table 2). However, some authors have reported sand transfer from the shelf to the beach not necessarily under a lowering sea level. In eastern USA, PIERCE (1969) analysed potential sources of sands to nourish an accretional stretch of coast between Cape Hatteras and Cape Lookout and reported that almost half of the required sands (700,000 m^3/yr) come from relict sands and Tertiary outcrops of poorly consolidated sediments on the shelf. In Delmarva Peninsula, in eastern USA, which is undergoing a coastal transgression, material eroded from pre-Holocene units that outcrop on the shoreface is an important supplier of new sediment to the coastal system (DEMAREST and LEATHERMAN, 1985). In southeast Australia, after the maximum PMT, river-borne sands were trapped in estuaries and the compartmented nature of many embayments prevented alongshore bypassing of sands. Here, barriers prograded in response to disequilibrium shoreface conditions with sediment transferred from the inner shelf to the beach thereby steepening the nearshore gradient reestablishing equilibrium conditions (THOM, 1983).

While it is not the aim of this paper to investigate in detail the mechanisms by which sand could be transferred from the shelf to the beach along the coast of RS, there is good sediment budgetary evidence that the sand reservoir of the RS shelf was a source of more than a half of the amount of sand for barrier progradation along coastal embayments of RS after 5 ka. It seems that the lower gradient of the shelf of RS is an important factor controlling onshore high rates of sand transfer from the offshore, specially along coastal reentrances where the shelf gradient is more gentle.

CONCLUSIONS

Modelling coastal evolution of RS during the last 9 ka strongly indicates that the present day shelf morphology is a former land surface that was transgressed by the sea. This inherited former land topography controlled the shape of the present coast: projections occur where the substrate is steeper and reentrances occur where it is gentler. Furthermore these differences in substrate gradient also influence the styles of barriers evolution. Retrogradational barriers such as receded barriers and mainland beach barriers occur along coastal projections whereas progradational barriers occur in coastal reentrances. More than half of the progradation that occurred in coastal reentrances was due to the onshore transfer of sands from the shelf of RS.

The common occurrence of receded barriers and active transgressive dunes on adjacent stretches of coast provides evidence that the transgressive dunes are caused by coastal erosion on the projections/forelands induced by higher wave energy owing to wave focusing and steeper gradients.

ACKNOWLEDGEMENTS

This research was supported in part by a grant from Rio Grande do Sul State Research Foundation (FAPERGS). We thank the Coastal Studies Unit, School of Geosciencies, University of Sydney for all the facilities during the time of the post-doctoral activities of the first author, and for the Comissão Permanente de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the post-doctoral grant (BEX 0703/96-6). We thank Juliano Kuchle for his help with the figures. A special thank to Dr. Paul E. Potter for his thoughtful help with the English text. And finally we thank Dr. Andrew D. Short for a final review of the paper.

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