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Holocene Paleoinlet of the Bojuru Region, Lagoa dos Patos, Southern Brazil

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ABSTRACT

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The Holocene environmental evolution of the Bojuru region, Rio Grande do Sul state, southern Brazil, was inferred from seismic, geochronologic, sedimentologic, and paleontologic data. The absolute ages of two samples, determined by the ^{14}C method, are 9400 ± 140 Cal BP and 7370 ± 150 Cal BP. On the basis of lithology and palynomorph and diatom data, the six stages of paleoenvironmental development of this region were chosen. Layers of muddy sediments characterized by a significant incidence of marine palynomorphs and marine and estuarine diatoms were deposited during the Early and Middle Holocene. Seismic records (3.5 kHz) revealed a prominent buried paleochannel that can be correlated to the present Barra Falsa channel. The main period of the channel incision was related to the last regressive event of the Late Pleistocene. During the last Holocene transgression, this paleochannel was filled up by fluvial, estuarine, and marine sediments. The integrated analysis of data reveals that the Barra Falsa feature resulted from a former channel connecting the Patos lagoon and the Atlantic Ocean. The closure of this inlet channel is attributed to shifts in the sedimentation milieu related to the transgressive maximum and subsequent regression during the Late Holocene.

ADDITIONAL INDEX WORDS: *Coastal evolution, 3.5 kHz seismic, Patos lagoon, Brazil.*

INTRODUCTION

The sedimentary systems of the Brazilian marginal basins have been strongly affected by a multitude of transgressive and regressive sea level oscillations. The present coastal plain and continental shelf physiography of South Brazil is mainly the result of glacio-eustatic sea level changes during the Quaternary. Geomorphologic and sedimentologic studies suggest that the Quaternary evolution of the Rio Grande do Sul (RS) coastal plain and adjacent continental shelf in the southernmost part of Brazil was mainly controlled by sea level changes (CORRÊA, 1996; DILLENBURG, TOMAZELLI, and BARBOZA, 2004; TOMAZELLI and VILLWOCK, 2000; VILLWOCK and TOMAZELLI, 1995; VILLWOCK *et al.,* 1986).

Several studies show that a vast part of the present Brazilian coastal plain was submerged during the Holocene (ANGULO *et al.,* 1999; BARRETO *et al.,* 2002; BEZERRA, BARRETO, and SUGUIO, 2003; MARTIN, DOMINGUEZ, and BITTENCOURT, 2003; SUGUIO, 1999, 2001; SUGUIO *et al.,* 1985; VILLWOCK *et al.,* 1986; YBERT, BISSA, and KUTNER, 2001). The sea level rise identified along the Brazilian coast during the Middle Holocene is similar to sea level rise records from South Africa (RAMSAY and COOPER, 2002). However, these records differ from the concurrent highest relative sea level position at the coast of the southeastern United States and The Netherlands (MARTIN, DOMINGUEZ, and BITTENCOURT, 2003).

Coastal deposits and various associated fossil remains are commonly used to reconstruct the sea level oscillation history. However, as pointed out by MARTIN, DOMINGUEZ, and BITTENCOURT (2003), several indicators of sea level changes should be used to minimize systematic errors associated with the particular nature of an indicator.

The use of palynomorphs for paleoenvironmental reconstruction of the coastal plains influenced by sea level oscillation is important. The application of different types of palynomorphs, found in coastal sediments, mainly cysts of marine palynomorphs (acritarchs, dinoflagellates) and microforaminifera, is useful in estimating sea level oscillations. Usually, an increase in marine palynomorphs in corresponding sediments resulted from the rise in sea level and led to an increase in salinity of the coastal aquatic environments (DOMINGUEZ, 1987; GRILL and QUATROCCIO, 1996; SARJEANT, 1970; TRAVERSE and GINSBURG, 1967; WALL *et al.,* 1977). Another important group of palynomorphs used to re-

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construct the aquatic paleoenvironment comprises the zygospores and colonies of Chlorophyta freshwater coccal green algae. Their wide distribution in coastal sediments could be related to the freshening of the aquatic basin during regressive phases, when freshwater influxes into basin of sedimentation increased (KOMÂREK and JANKOVSKÁ, 2001; MEDEANIC, JANKOVSKÁ, and DILLENBURG, 2003; VAN GEEL and VAN DER HAMMEN, 1978). The pollen and spores of terrestrial and aquatic vascular plants are excellent indicators of paleoenvironment and climate reconstructions and can be used to infer coastal vegetation changes affected by marine influence. A higher incidence of pollen of halophylous plants could indicate an expansion of land as a result of marine influence on the coast. The lower incidence of pollen of terrestrial plants is usually observed in sediments formed during the transgressive stage, when land was far from the sedimentation basin (CORDEIRO and LORSCHEITTER, 1994; LORSCHEITTER, 1983; YBERT, BISSA, and KUTNER, 2001).

Other important microfossils for paleoreconstruction are diatoms and silicoflagellates, whose distribution is strongly determined by ecological characteristics of the environment, including salinity, pH, depth, *etc.* (ABREU *et al.,* 1987; BAPTISTA, 1977; CANTER-LUND, 1995; GUTIÉRREZ TÉLLEZ, 1996; MOREIRA, 1975; MOREIRA, FILHO, and TEIXEIRA, 1963; PALMER and ABBOT, 1986; PRIDDLE and FRYXELL, 1985; RICARD, 1987). The study of diatoms and their use for reconstructing the Holocene on the RS coastal plain was conducted by CALLEGARO and LOBO (1990) and MEYER ROSA (1979). The significant incidence of marine and brackish water diatoms together with the cysts of dinoflagellates, silicoflagellates, and acritarchs in the Holocene coastal samples is evidence of a marine transgressive phase (MEDEANIC, TOLDO, and DILLENBURG, 2000b).

The paleoenvironmental and paleoclimatic characteristics of the RS coastal plain during the Holocene, and inferred from palynologic data, were reported in several articles (LORSCHEITTER and DILLENBURG, 1998; MEDEANIC, MARQUES-TOIGO, and ASHRAF, 2000a; NEVES and LORSCHEITTER, 1991, 1997; TOIGO *et al.,* 2002).

The Bojuru region, located in the eastern central part of the RS coastal plain, was chosen for the study of the paleoenvironmental changes influenced by sea level oscillations during the Holocene. This area is characterized by a narrow and shallow channel called Barra Falsa (Figure 1). TOLDO *et al.* (1991, 2000) suggested that the present Barra Falsa feature originates as a former inlet connecting the Patos lagoon with the Atlantic Ocean.

The first palynologic data on the Holocene paleoenvironmental reconstruction in the Bojuru region were published by MEDEANIC, DILLENBURG, and TOLDO (2001). The marine palynomorphs (acritarchs, dinoflagellates, and microforaminifera), silicoflagellates, and marine diatoms discovered in the thick silty layer (about 2.5 m) from one core are evidence of sediment deposition during marine transgression. The ^{14}C dating of this layer pointed to its deposition during the Middle Holocene, which corresponds to the period of maximum marine transgression.

The new multidisciplinary study of Holocene sediments in the Bojuru region takes into account paleontologic, sedimentologic, seismic, and radiocarbon-age data and use them to reconstruct the paleoenvironmental evolution of the area. The last transgressive drowning of the RS coastal plain and the adjacent continental shelf is discussed.

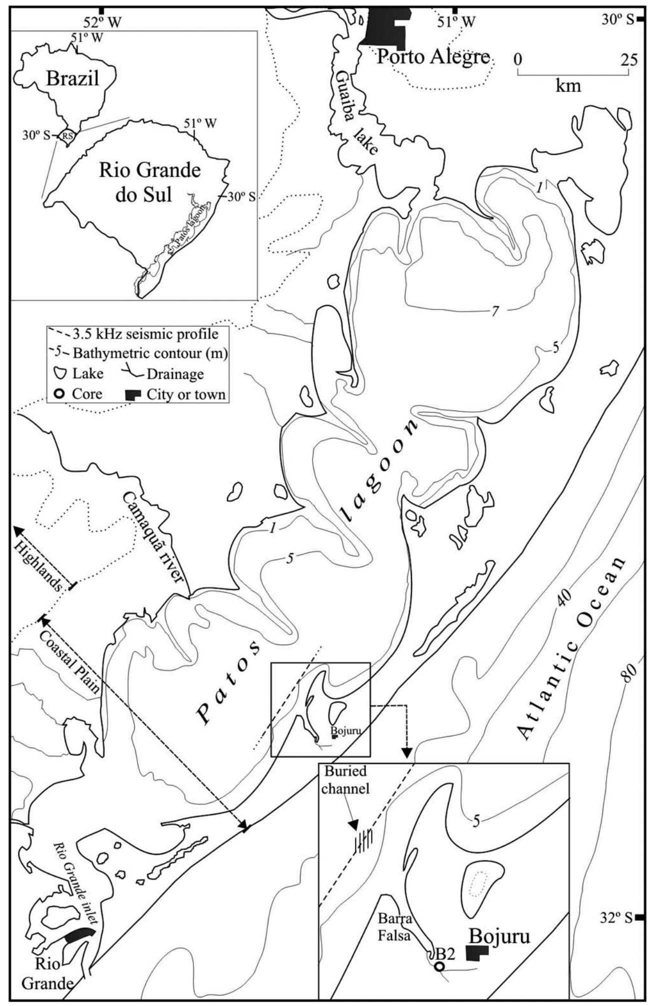

Figure 1. Location of the study area.

COASTAL EVOLUTION OF RIO GRANDE DO SUL

The coastal plain of the state of Rio Grande do Sul represents the upper part of the Pelotas marginal basin. It comprises the juxtaposition of depositional systems formed by processes related to sea level oscillations during the Quaternary period (VILLWOCK *et al.,* 1986). Four lagoon barrier–type depositional systems related to the Upper Quaternary transgressive and regressive events have been identified in the RS coastal plain (TOMAZELLI and VILLWOCK, 2000; VILLWOCK and TOMAZELLI, 1995; VILLWOCK *et al.,* 1986). A correlation between the sea level high stands and major peaks in the oxygen isotope curve of IMBRIE *et al.* (1984) was established by VILLWOCK and TOMAZELLI (1995). This correlation should confirm the idea of close affinity between sea level oscillations and climate changes.

Five marine terraces have been mapped on the continental shelf off the state of Rio Grande do Sul at the depth ranges of 20–25, 32–45, 60–70, 80–90, and 120–130 m (CORRÊA, 1986, 1996; CORRÊA *et al.,* 1992). The origin of these terraces is related to the last glacio-eustatic transgressive event, interrupted by several minor regressive events (CORRÊA *et al.,* 1992). They suggest a temporary, high-energy depositional environment typical of a sea level still stand.

According to CORRÊA (1986), the last transgressive event began approximately 17,500 Cal BP, when sea level was approximately 120–130 m lower than today. Before this transgression, the present inner shelf surface was subaerial and subject to fluvial processes. Beach ridges consisted predominantly of coarse sands formed along the ancient coastline, whereas fine sands were deposited on the inner shelf. The clayey sands and clays were deposited on the outer shelf and the upper continental slope (CORRÊA *et al.,* 1992). From 17,500 to 16,000 Cal BP, sea level rose quickly, stabilizing at 100–110 m below the present level (CORRÊA, 1986, 1996; CORRÊA *et al.,* 1989). Fine sands deposited on the inner shelf represent the ancient shoreline of that period, interrupted by estuarine and deltaic deposits of medium-grained sands (CORRÊA *et al.,* 1996; MARTINS *et al.,* 1996). The rate of sea level rise decreased from 16,500 to 11,000 Cal BP, resulting in the deposition of muddy sands in the nearshore setting and erosion from the middle to the outer continental shelf. Two minor fluctuations occurred within this period, forming terraces at 80–90 and 60–70 m. Two additional minor regressive events occurred during the long-term transgressive phase (from 11,000 to 5500 Cal BP). They led to terrace forming—the first one at 32–45 m (9000 Cal BP) and the second at 20–25 m (8000 Cal BP). By 5500 Cal BP, sea level reached ~5–6 m above the present position. During this time, drainage channels were displaced landward. The fine sediments were deposited in deeper waters, while transgressive sands were reworked in the coastal zone. Ancient coastline and sea level stabilization periods are marked by the presence of bioclastic gravels and heavy minerals. From 5000 Cal BP until today, sea level fell to the present position.

On the basis of different indicators from the former relative sea level position, MARTIN, DOMINGUEZ, and BITTENCOURT (2003) concluded that the curve of relative sea level oscillations established in Salvador (NE Brazil) by SUGUIO *et al.* (1985) might be used for comparison in the central coast of Brazil. The curve of Salvador shows that the last glacio-eustatic sea level rise (transgressive phase) began in approximately 7800 Cal BP. The maximum of that transgression occurred around 5600 Cal BP, and was characterized by a sea level rise of approximately 5 m above the present position. The following regressive phase led, at last, to the present position of sea level. Furthermore, according to MARTIN, DOMINGUEZ, and BITTENCOURT (2003), this regressive fall of sea level was interrupted by two distinctive high-frequency oscillations of sea level around 4300–3500 and 2700–2100 Cal BP. The secondary oscillations of sea level during the last regressive phase are not confirmed by some authors, who established a smooth decline in sea level during this phase (ANGULO and LESSA, 1997; ANGULO *et al.,* 1999).

The present RS coastal plain is characterized by wide lowlands covering an area of about 33,000 km^2 and bordered on the west by highlands. Geologic evidence for severe storms in the Holocene record have not been related. The tidal influence in the coastal zone is negligible (average amplitude <40 cm). The Patos lagoon, the main physiographic feature, is 240 km long (NE–SW) and has an average width of 40 km, covering approximately 10,000 km^2. The average depth is 6 m. The lagoonal deposits consist of marginal sands and muddy sediments (up to 6 m thick) at the bottom of the lagoon (TOLDO *et al.,* 2000). The lagoon receives fresh water from a huge drainage area and discharges it through the Rio Grande inlet (Figure 1).

MATERIALS AND METHODS

Core Sampling

A core (Bojuru 2-B2; 31°38′ S, 51°26′ W) 25.2 m long was drilled on the prolongation of the Barra Falsa channel (Figure 1). Characterization of sediments involved color (nomenclature according to the GSA rock color chart), texture, structure, and organic matter (OM) content. Organic-rich clay and muddy sediments were collected for the study of palynomorphs and diatoms. Two radiocarbon dates on muddy samples, enriched by organic matter, were performed by Beta Analytic Inc (Miami, Florida). The results are presented as conventional ^{14}C ages, which were obtained after applying ^{13}C/^{12}C corrections.

Seismic Study

A 3.5-kHz seismic reflection data survey was performed in the Patos lagoon on board the research vessel LARUS of the Fundação Universidade Federal do Rio Grande (FURG). The positions of the seismic lines were determined by a differential global positioning system linked to the subbottom profiler system. The seismic equipment used was a GeoAcoustics subbottom profiler, consisting of GeoPulse transmitter (model 5430A), GeoPulse receiver (model 5210A), 132B transducer array (4 mount), graphic recorder EPC GSP 1086, GeoPro processor system, and seismic data acquisition software. Data were saved in analog and digital formats.

Identification of the architectural elements present in the seismic records was based on the general concepts established by the seismic stratigraphy (MITCHUM, VAIL, and SANGREE, 1977). To evaluate the thickness of the sediments, the distance between horizons was calculated converting travel times into meters on the basis of an assumed sound speed of 1700 m/s.

Palynomorph and Diatom Study

The study of palynomorphs and diatoms was conducted on 14 samples from core B2. The chemical treatment of the samples followed FAEGRI and IVERSEN (1975). HCl (10%) and NaOH (5%) were used. A treatment with HF was avoided to preserve siliceous remains, such as diatom valves and silicoflagellate cysts. Separation of inorganic and organic substances was carried out by "heavy liquid," a solution of $ZnCl_2$ in water with a density of 2.2 g/cm^3.

The taxonomic definition of pollen and spores used a palynoteca of recent plants distributed in the state of Rio Grande do Sul, prepared by Medeanic (coauthor of this paper), which is preserved in the Geosciences Institute of Universidade Federal do Rio Grande do Sul. A small concentration of pollen and spores of terrestrial and aquatic plants did not allow us to plot the percentage diagrams of "pollen sum." The taxonomic composition of all pollen and spores found and their incidence (in absolute figures) can be seen in Table 1.

Zygospores and colonies of green algae, acritarch and dinoflagellate cysts, and diatoms were identified following papers of Canter-Lund (1995), Dale (1976, 1978), Meyer Rosa (1979), Moreira (1975), Moreira, Filho, and Teixeira (1963), Sournia (1986), and Van Geel and Van Der Hammen (1978). Microforaminifera were used to estimate salinity changes and their paleoecologic significance following Thunell and Williams (1983).

A sum of palynomorphs (100% by definition) was calculated and included arboreal pollen, nonarboreal pollen, pollen of aquatic plants, spores (Bryophyta and Pteridophyta), Chlorophyta colonies and zygospores, and acritarch and dinoflagellate cysts. The diatoms were counted in the "palynomorph sum." Furthermore, the "algae sum"—diatoms and green coccal algae—was conducted according to their tolerance to salinity. The TILIA Program (Grimm, 1987) was used to plot diagrams.

RESULTS

Seismic Records

A 3.5-kHz seismic profile was acquired roughly parallel to the eastern border of the Patos lagoon. It runs near the lagoon margin and roughly perpendicular to the longitudinal axis of the Barra Falsa channel (Figure 1). For the purpose of this study, the analysis of the seismic records was focused on the identification of former channels that have dissected the area, taking into account the configuration of the seismic reflectors.

Part of the seismic section recorded next to the Barra Falsa channel shows the existence of a large paleochannel. The buried channel is about 1.5 km wide, and the sedimentary filling is at least 20 m thick (Figure 2a). The channel morphology is well marked by fill facies units filling a negative relief in the underlying strata. The underlying reflections are mainly parallel and subparallel, showing erosional truncation along the basal surface of the channel (Figure 2b). The fill facies units are related to sedimentary deposits filling up the Barra Falsa channel (Figure 2c).

The lowermost channel fill seismic facies is basically composed of lateral accreting facies, present along the entire channel. Discontinuous weak and strong reflectors delineate mounded onlap, prograded, and complex fill reflection patterns onlapping the underlying unconformity. This facies is interpreted as fluvial (Figure 2, inset A).

Acoustically laminated channel fill seismic facies delineates a mounded onlap fill reflection pattern (Figure 2, inset B), interpreted as estuarine transgressive sands.

Seismic facies of insets C and D of Figure 2 are similar. However, the upper unit presents a more undulating stronger to opaque reflection. It is correlated to finer sediments (clayey) than the underlying unit, composed of coarser sediments represented by muds and a few fine sands. These sediments of estuarine and marine origin were deposited during sea level rise.

The final episode of sedimentation is marked by acoustically laminated deposits onlapping at very low angle the underlying unit (Figure 2, inset E). The reflectors are continuous and parallel, dipping gentle to the lagoon interior. This facies is interpreted as lagoonal deposits during the regression.

Acoustic anomalies from gassy sediments are present in some parts of the seismic records, sometimes masking the reflectors. Fortunately, this acoustic phenomenon has not hindered the analysis conducted on the seismic data.

Lithostratigraphy of Core B2

Only a few of all studied samples contained relatively abundant palynomorphs. In some samples, pollen and spores of terrestrial and aquatic vascular plants were rare or poorly preserved. Zygospores and colonies of green coccal algae (Chlorophyta) were found in all samples. Acritarch and dinoflagellate cysts were not abundant. On the other hand, various marine and estuarine diatoms were found in all studied samples. Microforaminifera were present in some samples.

On the basis of the lithologic characteristics of core B2, five units were identified (Figure 3), and their description follows from the bottom to the top of the core.

Unit A

Unit A (22.5–25.0 m) is represented by silty clay, sandy clay and sandy mud layers. Grayish colors are dominant in this unit. Some lenses of black clay (N1) and yellowish gray (5Y7/2) to dark greenish gray (5GY4/1) and fine-grained sand occurs. The finer sediments are rich in organic matter (up to 24%) with plant fragments. Small shell fragments are dispersed throughout the unit. Contact with upper unit B is abrupt.

Palynomorphs, found in two samples, are represented by pollen and spores of terrestrial and aquatic plants, zygospores of coccal Chlorophyta algae, rare acritarchs, and spores of fungi (Figure 3). The pollen of herbaceous plants (nonarboreal pollen) predominates. The most frequent pollen is that of Poaceae, Asteraceae, Chenopodiaceae, and Cyperaceae. Pollen of halophylous plants, such as Juncaginaceae (*cf. Triglochin*), and of *Azolla filiculoides* is present. Arboreous pollen is represented by Palmae, Mimosaceae, Moraceae-Urticaceae, and others (Table 1). The distinctive feature of this unit is the incidence of various and frequent spores and hyphae of fungi. Diatoms are represented by *Terpsinöe cf. muzica* and *Paralia sulcata* (dominant). Rare marine diatoms also occur, as for example *Coscinodiscus* sp.

The absolute age of one sample (organic-rich mud) collected at 23.2 m is 9400 ± 140 Cal BP.

Unit B

Unit B (11.6–22.5 m) is represented by fine-grained sand. In the basal part is a 2-m-thick interval of yellowish gray

Table 1. *Palynologic results on pollen and spore distribution in the samples from core B2 (incidence is given in grains) by stage and depth (m).*

	V		IV				III			I	
Taxa	3.5	3.9	7.8	8.8	9.1	9.5	10.0	10.3	11.0	23.0	24.0
Pinophyta											
Ephedra											1
Podocarpus									1		1
MAGNOLIOPHYTA											
Arboreous pollen											
Alchornea								2	2		
Anacardiaceae								2			
Apocynaceae		1					3	8			5
Boraginaceae								1			
Magnoliaceae											1
Melastomaceae											2
Meliaceae								3			1
Mimosaceae										2	10
Moraceae-Urticaceae											4
Palmae							1	29	1	11	3
Rapanea										4	
Rosaceae											1
Rubiaceae						1					
Thymeleaceae											2
Trema								2			2
Herbaceous pollen											
Amaranthaceae							2			8	
Apiaceae			2			1		1		3	3
Asteaceae			2	6				6	2		32
Brassicaceae									1		
Chenopodiaceae		1						1		5	13
Cyperaceae		3	3	6	6			7		6	85
Ericaceae			1								2
Juncaginaceae		1	1	1				1			10
Fabaceae											1
Liliaceae				1							
Malvaceae			2								
Myriophyllum											14
Onagraceae											4
Poaceae	6	6	77	20	3	20	4	41	5	29	101
Polygonaceae		2					1				
Primulaceae		1							1		4
Scrophulariaceae								4	1		2
Solanaceae		1									
Typhaceae											6
Bryophyta											
Anthoceros			6		2	8		9	1		
Phaeoceros			9	28	20	34	6	60	10	16	9
Pteridophyta											
Azolla filiculoides			4			1					21
Adiantum								1			
Alsophila									1		
Blechnum		6		4		2		4	6	6	
Botrychium				1							
Equisetum		1						10		12	5
Dicksonia											1
Dicranoglossum									11	3	
Dicranopteris							1	1	6		
Dryopteris								6			
Huperzia								1			
Hymenophyllum								18	2	2	
Lophozoria						1		1			
Lycopodiella								1			
Microgramma		1		1				2	12	1	
Polypodiaceae		14	1	6		4		101	12	66	3
Pterideae									1		
Total sum	6	38	108	74	31	72	12	323	76	174	356

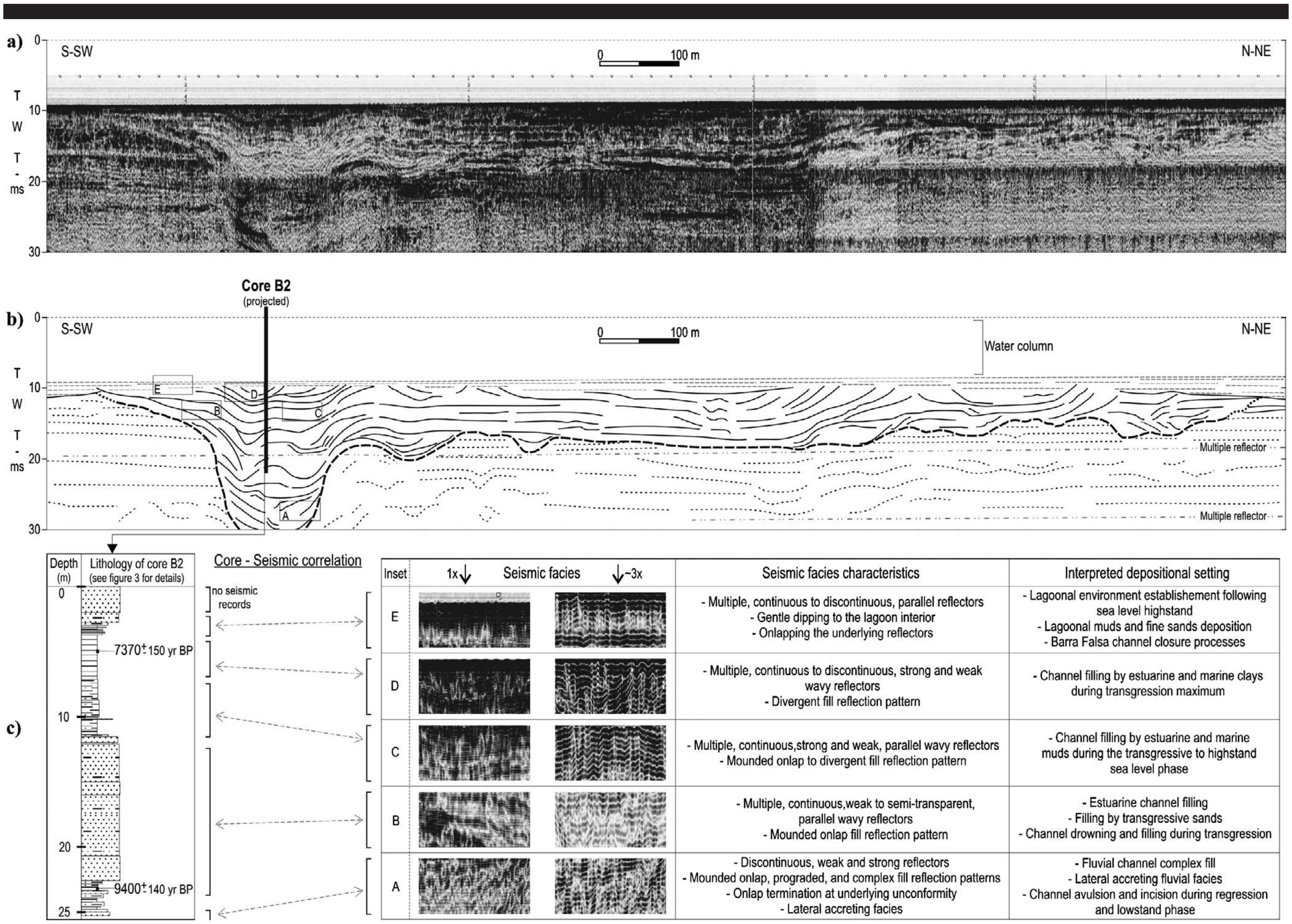

Figure 2. (a) Seismic profile near the Barra Falsa channel; (b) interpretation of channel architecture; (c) seismic correlation and synthesis of results. Location of seismic line is shown in Figure 1. Depths to water surface are in two-way travel time (TWT, ms).

(5Y7/2) sand. Above this interval, a package of sands with minor quantities (<10%) of dispersed mud is found. In this interval, shades of green (5GY5/2, 5GY3/2, 10GY3/2, 10G4/2, 10Y5/4) predominate. Brownish gray (5YR4/1) to yellowish gray (5Y7/2) sand occurs to the top of unit B. The incidence of lenses of organic mud with some plant fragments to the top of unit B indicates a gradual contact with upper unit C. Palynomorphs and diatoms are absent.

Unit C

Unit C (7.2–11.6 m) is represented by silty clay, sandy clay, and sandy mud. The colors vary from black (N1) to medium-gray (N5). Some lenses of fine muddy sand are also present. The lower part of this unit is richer in organic matter (up to 35%) than the upper part (up to 10%). Black plant fragments are abundant in the basal interval. Small shell fragments are common at the top of the unit.

In the lower part of this unit (9.5–11.6 m), spores of ferns and spores and hyphae of fungi predominate (Figure 3; Table 1). *Debarya, Mougeotia* zygospores and *Spirogyra* freshwater algae are also reported. Marine palynomorphs (acritarchs, dinoflagellates) and microforaminifera are found. The incidence of brackish-water diatoms—*Paralia sulcata*—increases (Figure 4). In the upper part of this unit (7.2–9.5 m), pollen and spores of aquatic and terrestrial plants are rare and poorly preserved. Zygospores of freshwater algae are less frequent. Marine palynomorphs are represented by acritarchs and microforaminifera. A major increase in diatoms and, especially, in marine diatoms—*Actinoptychus* sp., *Coscinodiscus* sp., *C. oculus-iridus, C. radiatus,* and *Triceratium favus*—is observed.

Unit D

Unit D (3.5–7.2 m) is represented by medium-dark gray (N4) clay. Some lenses of silty clay are dispersed. To the top of the unit, slightly coarser sediments are observed. The organic matter content reaches 10%. Small shell fragments are scattered. The contact with the upper unit is gradual and characterized by the dominance of marine and brackish-water diatoms. The taxonomic diversity of marine diatoms increases (*Coscinodiscus, C. oculus-iridus, C. radiatus, C. lineatus cf. minor*; Figure 4). The incidence of marine palyno-

Figure 3. Lithology of core B2 and microfossil distribution in the samples. OM = organic matter content.

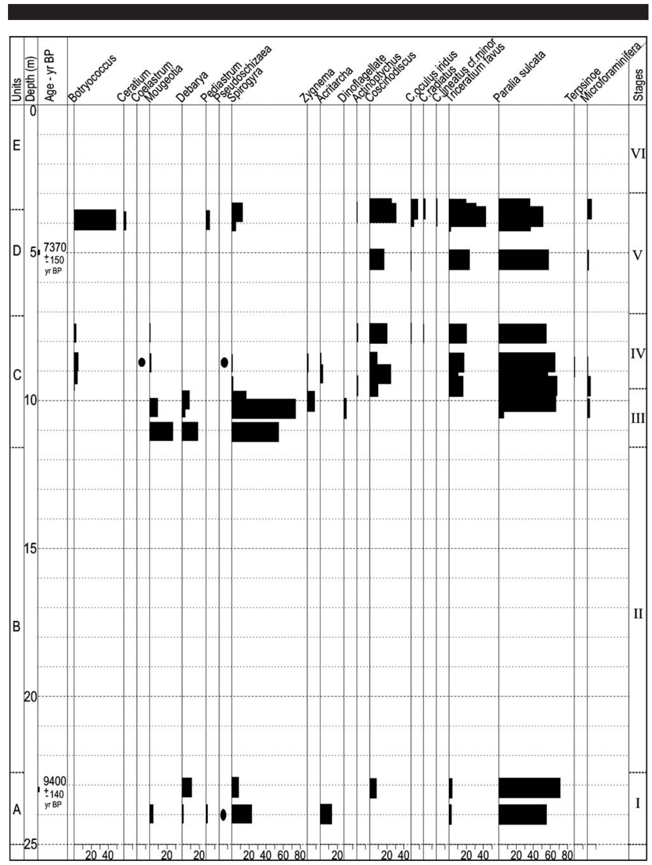

Figure 4. Diagram of algal distribution in core B2.

morphs increases; however, pollen and spores of terrestrial plants decreases considerably. Zygospores and colonies of freshwater algae are found sporadically and are represented mainly by *Botryococcus, Pediastrum* and *Spirogyra.*

The absolute age established for one sample (organic-rich mud) recovered from a depth of 5.0 m is 7370 ± 150 Cal BP.

Unit E

Unit E (0.0–3.5 m) is represented by pale yellowish brown (10Y6/2) to yellowish gray (5Y7/2) fine sand. Lenses of mud are dispersed in the basal part. Dispersed heavy minerals occur predominantly in the upper part of the unit, sometimes concentrated in lenses. Bioturbation structures and roots are common at the top of the unit. There are no palynomorphs or diatoms.

ANALYSIS AND DISCUSSION

On the basis of the lithologic characteristics of the sedimentary sequence and palynomorph and diatom distributions, six stages of environmental development were detected in the Bojuru region. They are related to sea level changes, climatic oscillations, and coastal barrier and inlet development. The seismic results and the geologic context were also considered.

Stage I

Stage I corresponds to unit A. Palynologic data indicate that sedimentation occurred under conditions of high salinity of marine influence. It was probably a shallow basin influenced by both ocean and freshwater influxes. The relatively abundant pollen and spores of terrestrial plants are indicative of vegetation spreading in this region, distributed not far from the core site. The spreading of brackish and salt marshes in the region is confirmed by relatively frequent spores of *Azolla filiculoides* and pollen of xerophylous and halophylous plants (Chenopodiaceae, Cyperaceae, Juncaginaceae, *etc.*). These plants are well distributed in present salt marshes of the RS coastal plain (Cordazzo and Seeliger, 1995). Dune spreading is confirmed by relatively abundant pollen of Poaceae, Chenopodiaceae, and Asteraceae. A great number of spores and hyphae of fungi and diverse arboreous pollen might have been carried from the land by freshwater fluxes, provided the relatively abundant pollen of terrestrial plants, spores and hyphae of fungi, and zygospores of freshwater algae. The "pure" freshwater algae represented by *Debarya, Pediastrum, Pseudoschizaea,* and *Mougeotia* might have been carried by freshwater influxes, too. The diverse fungal spores and hyphae, especially *Rhizophagites* soil fungi, might justify some periods of dryness at this shallow basin. In that stage, the marine influence was occasional and had an oscillatory character. The rare marine *Coscinodiscus* diatoms and acritarchs (*Micrhystridium*) are evidence of a marine influence.

Stage II

A sand package in unit B represents Stage II and indicates a period of deposition of transgressive coastal sands (beach/shoreface) in the course of sea level rise.

Stage III

Stage III corresponds to the lower part of unit C. The influence by palynomorph and diatom records was weak. The relatively abundant incidence of pollen and spores of terrestrial plants is evidence of wetland spreading with diverse and abundant ferns and mesophylous grasses distributed adjacent to lagoonal areas. The increase in humidity of the subtropical climate caused the expansion of forests in the sheltered lands, whose pollen could have been carried into coastal lagoons by freshwater influxes.

Stage IV

Stage IV corresponds to the upper part of unit C. The significant increase in brackish-water (*Paralia sulcata* and *Terpsinöe*) and marine diatoms (*Actinoptychus, Coscinodiscus, Triceratium favus*) might be indicative of a major sea level rise. The decrease in incidence of pollen and spores could be related to an increase in amplitude of the sea level rise and a distant position of coastal land from the sedimentation basin. The poor preservation of many pollen and spores could be a result of redeposition during marine transgression or of storm effects.

Stage V

Stage V corresponds to unit D. The predominance of marine diatoms and their taxonomic variety could be related to the maximum of marine transgression. Dunes and intertidal marshes spread on the neighboring lands.

Stage VI

Stage VI corresponds to unit E, composed of fine sands. These sands were deposited in the RS coastal plain after maximum transgression of the Holocene during barrier build-up.

These six identified stages delineate the general environmental conditions operating in the Bojuru region during the Holocene. Stages I to III are related to a depositional setting influenced by both ocean and freshwater influxes, representing sea level fluctuations. The occasional and oscillatory marine influence could be indicative of an estuarine channel. In stage IV, the influence of marine water increased, indicating a significant sea level rise and drowning of the estuarine channel. The predominance of marine diatoms and their taxonomic variety in unit D is indicative of sea level high stand. Stage V represents the maximum transgression. Stage VI corresponds to the subsequent regression phase when the inlet channel became closed.

The hypothesis of the existence of a paleoinlet between the Patos lagoon and the Atlantic Ocean in the Bojuru region was proposed by Toldo *et al.* (1991, 2000). According to these authors, the present geomorphologic configuration of the Barra Falsa was inherited from a Holocene inlet. The inlet closure occurred about 2000 Cal BP because of coastal processes related to the development of a coastal barrier (Toldo *et al.,* 1991). This Holocene sandy barrier corresponds to the lagoon-barrier system IV of Villwock *et al.* (1986).

When extending the longitudinal axis of the Barra Falsa channel inside the Patos lagoon, it intercepts the seismic line right at the point of the prominent paleochannel in Figure 2. Therefore, we consider that the paleochannel of the seismic record of Figure 2 corresponds to the former Barra Falsa channel. This seismic record shows that the Barra Falsa feature represents not only a relict feature of a Holocene inlet but also an older (Late Pleistocene) channel that connected the "paleolagoon" to the open ocean.

Core B2 was drilled on the prolongation of the present Barra Falsa channel. The lithostratigraphy of this core reflects the channel infilling sequence throughout the last transgressive-regressive event. The six stages that delineate the Barra Falsa channel infilling sequence might be valid to other past coastal channels incised in the RS coastal plain during the last regressive event of the end of the Pleistocene and filled during the posterior transgression.

A correlation between seismic data and stratigraphic log relates the seismic and depositional facies filling up the former Barra Falsa channel. The basal unit corresponds to the early stage of the sedimentary infilling of the channel by fluvial deposits. The middle units correspond to estuarine and marine deposits related to a transgressive sea level. The upper unit corresponds to marine sediments related to the maximum transgression. The seismic record is topped by a unit related to lagoonal deposition of the subsequent regressive phase since the present Patos lagoon configuration was established. Fine sands of the upper B2 core are related to the modern depositional setting prevailing in the RS coastal plain since the maximum sea level high stand of the Middle Holocene (Figure 2, III).

In general terms, the sea level fall during the last regressive event of the Late Pleistocene excavated the deep and wide "Barra Falsa incision" and other coastal channels. During this forced regression event (Wisconsin, last glaciation), the channels represented an important shelf bypassing system, linking the continental drainage basin to the Atlantic Ocean. Before the subsequent transgressive event, the present inner shelf surface was subaerial and subject to erosion and fluvial incision (Corrêa *et al.,* 1992).

The Holocene transgressive event in the area of study began about 17,500 Cal BP, when sea level was about 120 m lower than present (Corrêa, 1986). The transgression flooded the wide Pleistocene coastal plain, forming the main features of the present continental shelf off the state of Rio Grande do Sul (Suguio and Martin, 1987).

Throughout the transgression, the fluvial channels were drowned by the rising sea waters. The widespread channel incision was progressively inhibited and then reversed. The decrease in the competence of the streams led to channel infilling by fluvial and paralic sediments. Previous existing rivers were transformed into estuaries. Fine sediments were deposited in deeper waters and transgressive sands on the coastal zone.

In the last transgressive high stand (approximately 5500 Cal BP), sea level reached around 5–6 m above present level, drowning a huge area of the RS coastal plain (CORRÊA, 1996). The coastal and lagoonal dynamics changed. The sediment loading from the fluvial discharges was mainly trapped in intralagoonal deltas. The position of former inlet and confining sandy margins was submerged where deposition of finer sediments occurred. During the initial stages of the regression, the former inlet morphology had changed. The past Barra Falsa inlet was no longer the main way to the lagoonal discharge. New inlets were connecting the Patos lagoon to the open ocean. Presently, the lagoon captures an enormous river discharge and leads it to the ocean through a unique huge inlet near the city of Rio Grande, located about 90 km south of Bojuru.

CONCLUSIONS

The data on the environmental development of the Bojuru region during the Holocene, on the basis of core and seismic records, have a methodological character and show the implication of different analyses integrated for the purposes of paleoreconstructions on coastal zones.

Newly acquired data and analyses of seismic records allow us to conclude that the geomorphologic feature Barra Falsa represents a former inlet channel connecting the Patos lagoon to the Atlantic Ocean in the past. Its evolution was mainly controlled by sea level oscillations. The Barra Falsa channel was incised during the last regressive event of the Late Pleistocene, when sea level was 120 m below present. During the last marine transgression, the Barra Falsa channel was drowned and infilled by fluvial, estuarine, and marine sediments. The paleochannel Barra Falsa was closed after a transgressive peak during the regressive phase.

The five lithologic units identified correspond to six stages of environment development in the course of the last transgression (stage I to V) and the subsequent regression during the Holocene (stage VI). The deposition of the lowest lithologic unit A (stage I) was related to the drowning of the drainage system of the Bojuru region by a rising sea level around 9400 Cal BP. The connection between the sedimentation basin and the ocean was established through a paleochannel. The high salinity is marked by marine palynomorphs (acritarchs, dinoflagellates) and some marine and brackish-water diatoms. The relatively high frequency of terrestrial palynomorphs might indicate the proximity of land, occupied by brackish-water and salt marshes, and dunes. The climate was subtropical and relatively dry. Unit B represents the deposition of transgressive sands in a rising sea level scenario (stage II), which in turn was overlaid by deeper water sediments of unit C (stages III and IV). The unit corresponding to stage IV was formed during a major sea level rise. The deposition of muds was attributed to the deepening of the water column. The clay unit (stage V), characterized by the absolute predominance of marine diatoms and the presence of microforaminifera and dinoflagellates, was deposited in an estuarine to marine setting around the sea level high stand. The low incidence of pollen and spores of terrestrial and aquatic plants was probably related to a farther distance of the shore from the sedimentation basin. The climate during this stage was warmer and more humid than the previous stage IV. The sand unit (stage VI), which closes the depositional sequence in the Bojuru region, was deposited during the subsequent marine regression.

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☐ RESUMO ☐

A evolução ambiental holocênica da região de Bojuru, estado do Rio Grande do Sul, Brasil, é aqui reconstruída tendo como base novos dados paleontológicos, sedimentológicos, sísmicos e de datação radiométrica do carbono. Duas amostras foram datadas por ^{14}C, fornecendo idades absolutas de 7370 ± 150 e 9400 ± 140 anos AP. Dados litológicos, palinológicos e de diatomáceas permitiram o reconhecimento de seis etapas paleoambientais para a região, relacionadas com oscilações do nível do mar e mudanças climáticas. Camadas de argila e lama, caracterizadas pela presença significativa de palinomórfos marinhos e de diatomáceas marinhas e estuarinas, foram depositadas durante o aumento do nível do mar correspondente à última transgressão marinha. Dados sísmicos de 3,5 kHz revelam a existência de um grande paleocanal correlacionável ao canal atual da Barra Falsa. O período principal de formação do canal é relacionado ao último evento regressivo do final do Pleistoceno. No decorrer do último grande evento transgressivo o canal foi sendo progressivamente preenchido por sedimentos fluviais, estuarinos e marinhos. A análise integrada dos dados indica que o canal da Barra Falsa é uma herança morfológica de um antigo canal que conectava a laguna dos Patos ao oceano aberto. O fechamento deste canal é atribuído as mudanças nas condições ambientais ocorridas durante o máximo transgressivo e subseqüente regressão do final do Holoceno.