Journal of Coastal Research	16	3	816–822	West Palm Beach, Florida	Summer 2000

Holocene Sedimentation in Lagoa dos Patos Lagoon, Rio Grande do Sul, Brazil

Elírio E. Toldo Jr., Sergio R. Dillenburg, Iran C. S. Corrêa, and Luiz E.S.B. Almeida

Universidade Federal do Rio Grande do Sul - UFRGS
Centro de Estudos de Geologia Costeira e Oceânica - CECO
CP. 15001
CEP 91509-900 - Porto Alegre, RS, Brazil

ABSTRACT

TOLDO, E.E., Jr.; DILLENBURG, S.R.; CORRÊA, I.C.S., and ALMEIDA, L.E.S.B., 2000. Holocene sedimentation in Lagoa dos Patos Lagoon, Rio Grande do Sul, Brazil. *Journal of Coastal Research,* 16(3), 816–822. West Palm Beach (Florida), ISSN 0749-0208.

Lagoa dos Patos in southern Brazil is part of the largest lagoonal system in South America. The Holocene lagoonal sediments of the Lagoa dos Patos, mostly muds, have an average thickness of about 6 m as determined by 297 km of 7.0 kHz echograms. Holocene muddy sedimentation developed over a probable Upper Pleistocene coastal plain, whose surface has a sub-bottom reflector that could not be penetrated by the energy of a 7.0 kHz seismic wave. The characteristics of this reflecting surface suggest indurated Pleistocene muds and/or sediments that are coarser than the overlying muddy deposits of Holocene lagoon. Based on stratigraphic correlation and the local sea level curve, we estimate that Holocene sedimentation started about 8.0 ka ago. This yields an average deposition rate of 0.75 mm/yr. A broadly comparable average rate of 0.52 ± mm/yr was obtained for cored intervals between ^{14}C samples from the upper part of these muddy Holocene lagoon deposits.

ADDITIONAL INDEX WORDS: *Muddy lagoonal sedimentation and rates, southern Brazil.*

INTRODUCTION

A seismic cruise was carried out in the Lagoa dos Patos in the State of Rio Grande do Sul southern Brazil in 1993. This cruise was part of an on going study of the paleogeographic evolution of Brazil's continental margin. The present knowledge about the lagoon is almost entirely the result of interpretations of surface characteristics of the coastal plain of Rio Grande do Sul and its bordering continental platform (morphological features, sediment composition and distribution). Exceptions are the studies on the general aspects of shallow structure of the continental platform (Butler, 1970 and Alves, 1977), inferred from the evolution of the South Atlantic Ocean (Urien and Martins, 1985). Based mainly on the concept that morphological features and sediment texture distributions are palimpset, many authors have presented sketches of the Upper Pleistocene and Holocene evolution of the continental shelf (Martins *et al.,* 1972; Urien *et al.,* 1980; Kowsmann and Costa, 1979). Recently, Corrêa (1996) published interpretations of the subsurface structure of the continental shelf, based on a morphostructural analysis.

The distribution of surface sediment in the Lagoa dos Patos and its Upper Holocene evolution have been studied by Alvarez *et al.* (1981), Martins *et al.* (1989), and Toldo (1989). Recently, Toldo (1994) showed how Pleistocene surface morphology affected the Holocene development of the lagoon.

This paper reports on the shallow subsurface geology of Lagoa dos Patos, using the 297 km of 7.0 kHz seismic records (Figure 1), cores and radiocarbon dating to determine the onset of Holocene sedimentation and estimate Holocene sedimentation rates. A description of the sub-bottom morphology and general sediment composition of the Pleistocene surface, over which the lagoonal sequence was deposited, is also presented.

95016 received and accepted in revision 4 October 1999.

METHODOLOGY

A high-frequency seismic reflection data survey was performed on the Lagoa dos Patos using a shallow seismic system RTT 1000, from Raytheon. The equipment consisted of a 719 C RTT recorder, a 3.5/7.0 kHz transducer, and a PTR 106 C transceiver (Geophysical Equipment Bank of the Marine Geology and Geophysics Program—PGGM). The positioning of the lines was determined by two marine radars (DECCA, and FURUNO M-1720). During the field work, it was found that the 7.0 kHz frequency provided a better resolution than the 3.5 kHz frequency, although neither frequency penetrated more than 14 m of sediments.

Eight vibracores were also collected and described from Lagoa dos Patos (Toldo *et al.,* 1991). These cores were taken from lagoon floor (Figure 1), and range in length from 2.02 to 2.14 m (Table 1). Each of the sediment-cores was sliced into 3 cm discs with a diameter of 7.5 cm. The resulting samples were analyzed to obtain grain-size distributions by standard sieving with sieves at intervals of 0.5 phi and pipette analyses. Calculations on grain-size distributions were performed by use of a PC PANCOM-program (Toldo and Medeiros, 1986). Organic content in the samples was determined by loss ignition after 3 hours of burning at 600 °C. Bulk den-

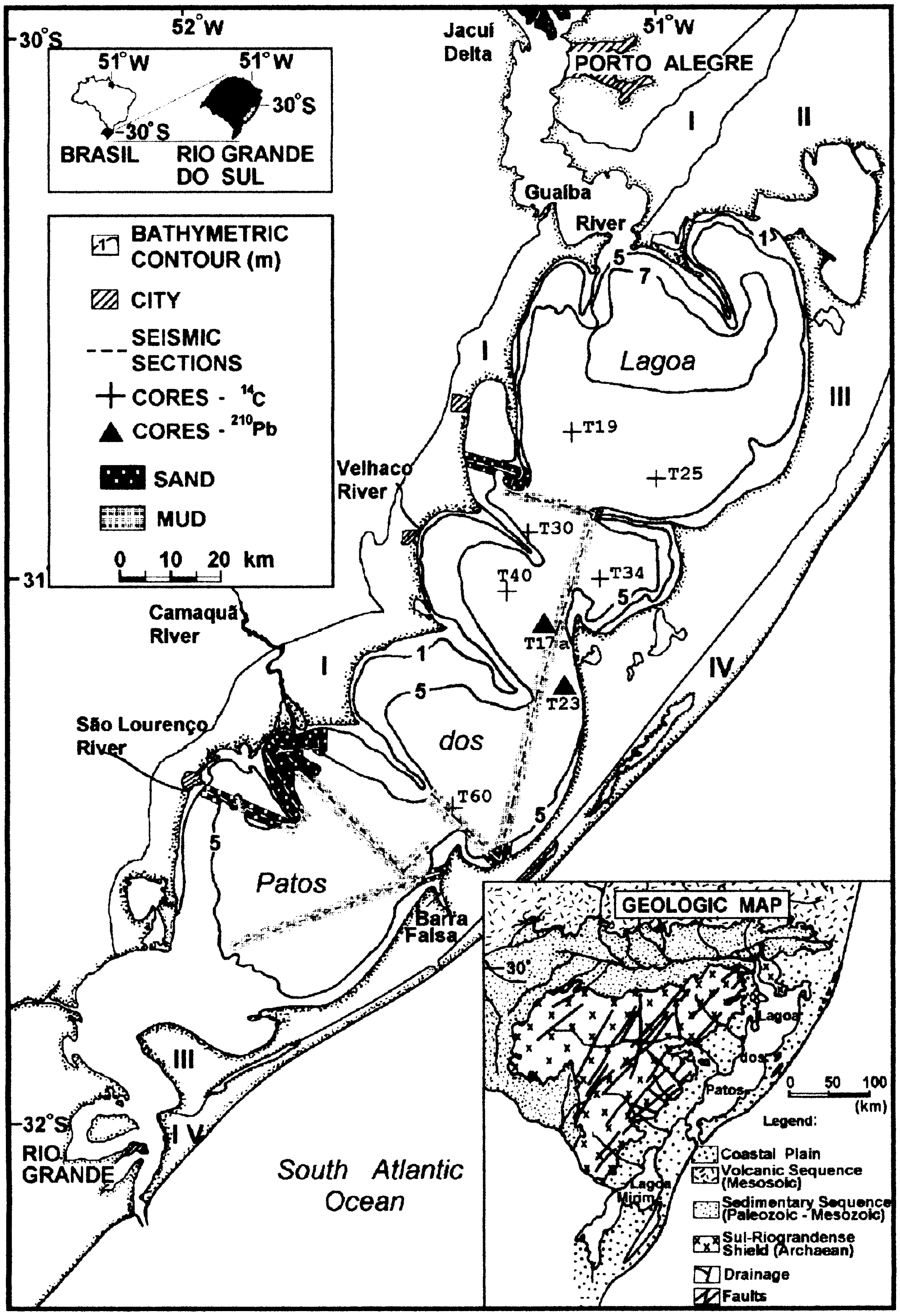

Figure 1. Location map of the study area, including the sites of the cores, the seismic sections, geologic map (Modified from DNPM, 1984 and VILLWOCK *et al.*, 1986), and contours of the barrier/lagoon systems.

sity was determined as the weight of the fresh sample to the volume of the sample. Six radiocarbon dates from shells (*Erodona mactróides and Heleobia australis*), come from the upper parts these cores (TOLDO *et al.,* 1991). Beta Analytic Inc. (T25), Laboratório de Física Nuclear—UFBA (T19, T30, T34, T40, T60), made the determinations of ^{14}C. Florida State University, made two determinations of sedimentation rates by the method of ^{210}Pb, one from each of two cores (T19a, T23).

PHYSICAL SETTING

Hydrology

The lagoon has a length of 240 km, an average width of 40 km, and covers a surface of 10,000 km^2, almost one third of the area of the Coastal Plain of the State of Rio Grande do Sul. The lagoon runs roughly NE-SW and its average depth is almost 6 m (Figure 1), and its mean tidal amplitude is 0.45

Table 1. *Bulk density (g/cm³) and porosity of lagoon cores.*

	T19	T25	T30	T34	T40	T60
Core Length (m)	2.05	2.11	2.05	2.14	2.13	2.02
Bulk Density	1.38	1.25	1.46	1.28	1.36	1.41
S.D.	± 0.05	± 0.19	± 0.25	± 0.13	± 0.12	± 0.26
Porosity	0.77	0.85	0.72	0.83	0.78	0.65
S.D.	± 0.03	± 0.12	± 0.15	± 0.08	± 0.07	± 0.16

m. At its southern extremity, the only inlet of the Lagoa dos Patos has a mean discharge of 4,800 m^3/s. Sea water penetrates the lagoon up to 200 km to the north during exceptional conditions favored by southern winds, low water level in the lagoon, and spring tides (MARTINS *et al.,* 1989; TOLDO 1989).

The lagoon receives freshwater from a drainage area of about 170,000 km^2, mostly from the Guaíba River System whose mouth, the Jacuí Delta, is at the city of Porto Alegre at the northwestern end of the lagoon (Figure 1). As a result, much of the lagoon has a lower salinity, of about 3 ‰. A much smaller contributor of freshwater to the lagoon is the Camaquã River. The combined watersheds of these two rivers cover almost half the area of the state of Rio Grande do Sul. The water in the Lagoa dos Patos has a residence time of about 108 days as estimated by TOLDO (1994). Whereas the Guaíba River contributes principally mud to the lagoon, the Camaquã contributes principally sand.

Geology

The coastal plain bordering the lagoon typically has elevations that range up 6 m and consists mostly of sandy deposits interrupted by small streams (DELANEY, 1965). These sandy marginal deposits of the lagoon are all related to four Quaternary transgressive events which developed four depositional systems, mostly consisting of barriers and lagoons: system I (oldest), II and III were formed during the Pleistocene, whereas system IV (youngest) started during the Holocene (VILLWOCK *et al.,* 1986).

The Lagoa dos Patos is almost totally confined within these four depositional sequences (Figure 1). System I is only exposed along the inner western shore of the lagoon and consists mostly of small coalescing alluvial fans, whereas the long barrier that separates Lagoa dos Patos from the ocean is composite and includes both a Pleistocene part (System III) and a Holocene part (System IV). During the Holocene the earlier deposits of systems I, II and III were in part reworked by waves and currents within the lagoon. Sand spits are the most important products of reworking in the Holocene. These spits have an average height of 1 m above the mean water level of the lagoon; on the west side of the lagoon the submerged part of these spits extends about 15 km into the lagoon proper. Earlier there may have also been another outlet, located about 65 km northeast of the present inlet at Rio Grande (Figure 1) (TOLDO *et al.,* 1991).

Lagoa dos Patos itself has two distinct morphological and sedimentological parts: the first part consists of the sandy margins of the lagoon and the second larger part is the muddy, nearly flat interior of the lagoon. Depths of five to six meters typically separate these two parts of the lagoon. On the west side of the lagoon the sandy margin generally has slopes of about 1/1500, but on east oceanic side sandy slopes are much steeper 1/200. The sandy margins form about 40% of the lagoon. Sands along the inner western side of the lagoon are poorly sorted (fine to coarse) whereas those of the eastern oceanic side are fine grained and well sorted (MARTINS *et al.,* 1989).

Sediments of the lagoon floor have less than 4% sand, and consist mainly of the silt and clayey silt in the northern half of the lagoon and silty clay in its southern half. Greenish gray colors predominate. Terrigenous organic matter is exceptionally abundant, as much as 30% occurs in some cores; lagoonal muds are structureless because of intense bioturbation (MARTINS *et al.,* 1989). Present day deposition of the muds occurs in water depths below normal wave base, which rarely exceeds 4 m (TOLDO, 1994). The muds of the lagoon are believed to be largely derived from the Guaíba River, chiefly because its large estuary traps most of the river's sand.

ECHO CHARACTERISTICS

Based on the classification presented by DAMUTH and HAYES (1977), two types of echoes were distinguished: type IA, distinct echoes that are continuous, well defined and lack sub-bottom echoes, and type IIA echoes that are indistinct, semi-prolonged, intermittent, discontinuous and have parallel patterns. Type IA echoes are believed to be characteristic of coarse-grained sediments (sand and/or gravel), which provide excellent echoes of acoustic signals and, consequently, little or no sound penetrates underlying sediments. Some reflectors belong to neither type IA nor IIA echoes and are believed to be mixtures of muds and silts with sands and gravel (DAMUTH and HAYES, 1977).

RESULTS AND DISCUSSION

Type IA echoes dominate the lagoonal margins and represent the sandy domain of the lagoon (Figure 2), whereas IIA echoes are typical of lagoonal floor and represent its muddy domain (Figure 3).

The sub-bottom reflectors present on type IIA echoes are interpreted as being an ancient coastal plain surface composed of indurated Pleistocene muds and/or by coarser materials than the sediments of the present Holocene lagoonal sequence. This ancient surface, here considered to represent system III (Figure 1), reflects all the acoustic signal of the 7.0 kHz seismic wave. This reflector at 12 m bellow water level can be traced the length of the Lagoa dos Patos from the mouth of the Guaíba River to the mouth of the lagoon at Rio Grande (Figure 1). It defines the structural strike of the coastal plain sequence; it has, however, a very slight but uniform and consistent seaward dip of about 1/23000.

The seismically transparent layer between the sediment-water interface and the sub-bottom reflector contains the Holocene lagoonal sequence (Figure 4). From the transition between the margins and lagoon floor of the lagoon, this transparent layer increases in thickness to about 6 m, which it maintains across the floor of the lagoon. Texturally, this transparent layer, as yet not totally penetrated by the vibra-

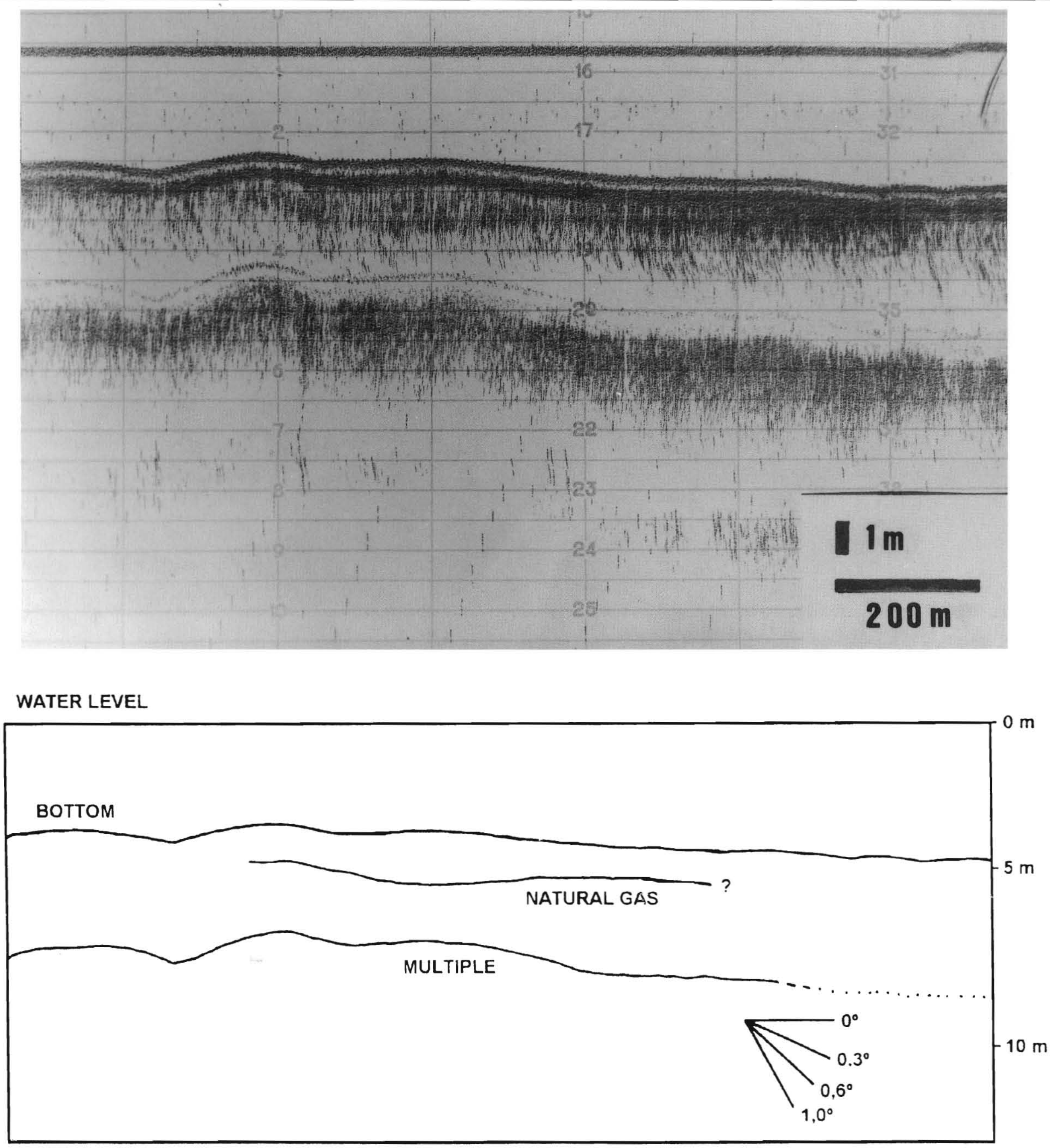

Figure 2. Record of a 7.0 kHz, type IA, continuous echo showing well defined bottom without sub-bottom reflectors.

core, is believed to consist mostly of almost pure muds, whose depositional environment was the low energy bottom of the lagoon.

The regional sea level oscillation curve and the depth of the sub-bottom reflector described above show that sea level reached the sub-bottom reflector in the lagoon about 8,000 years ago (CORRÉA, 1996, Figure 6). Since that time 6 m of Holocene lagoonal sediments were deposited. Thus we can estimate the Holocene rate of sedimentation as about 0.75 ± mm/yr (6 m/8.0 ka).

The six ^{14}C age determinations, all in the upper 2 m of the Holocene mud, have an uncompacted sedimentation rate average of 0.52 ± mm/yr, which compares broadly with the rate of 0.75 ± mm/yr based on stratigraphic projection. To evaluate whether compaction has taken place in the sediment core, the variation of bulk density and porosity with depth

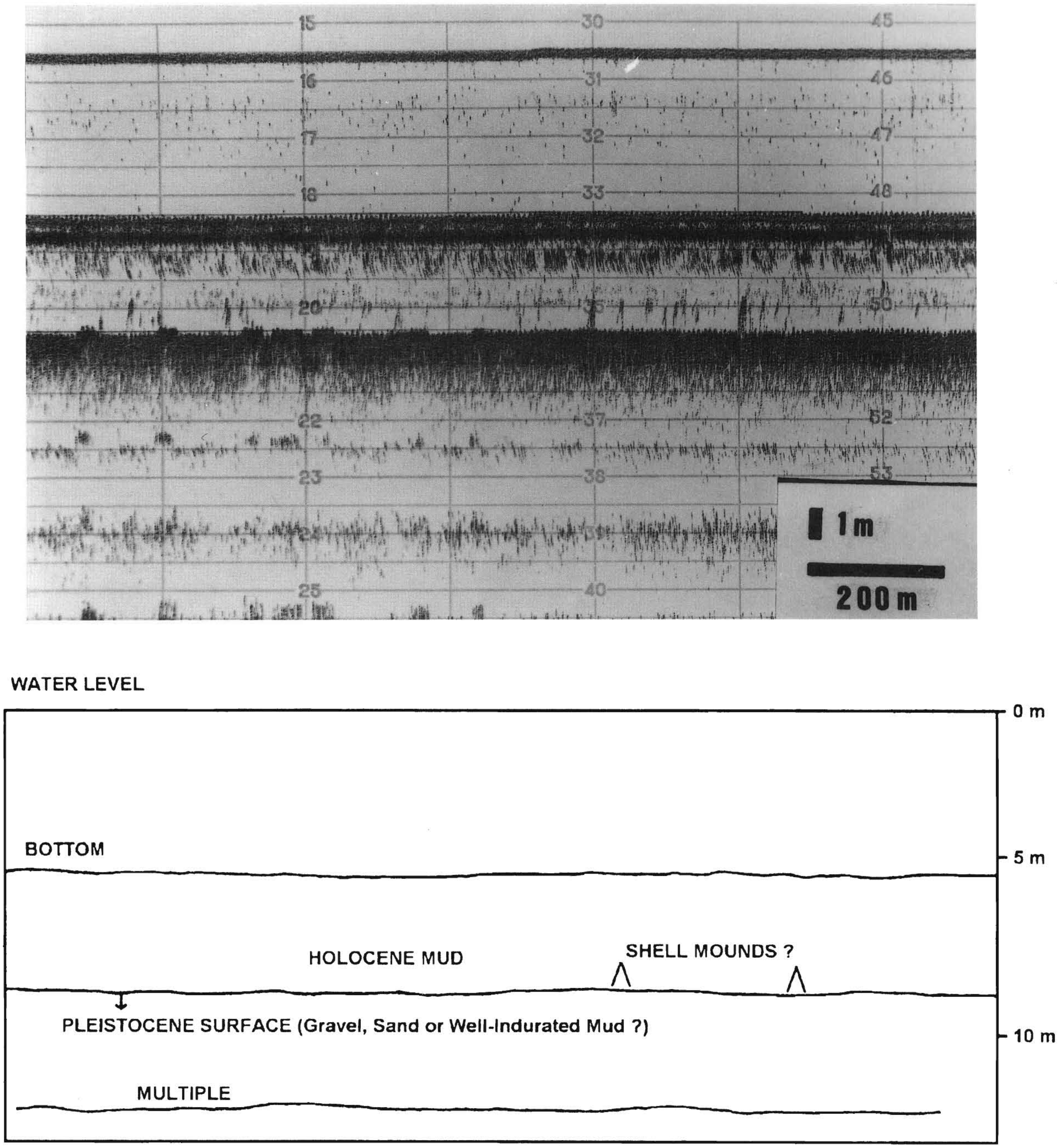

Figure 3. Record of a 7.0 kHz, type IIA, semi-prolonged echo, with parallel sub-bottom reflectors.

were also calculated. The bulk density of a sediment sample is defined in this study (BEHERENS, 1980, In: LUND-HANSEN, 1991) as the ratio between total mass (g) and total volume (cm^3) of the undisturbed sample. The porosity (ϕ) as calculated by:

$$\phi = \frac{\text{bulk density} - 2.65\ (\text{g/cm}^3)}{\text{density of water} - 2.65\ (\text{g/cm}^3)}$$

where the density of the water is 1.0 g/cm^3, and the density of the inorganic part of the sediment is assumed to be 2.65 g/cm^3.

For both calculations of sedimentation rate no correction for compaction was made in the cores and seismic record, because the variations with depth of both bulk density and porosity of the sediment core are quite small as could be observed by values of standard deviation of all cores (see Table 1); hence, compaction in the upper 2 m of the muddy and organic-rich muds of the Lagoa dos Patos appears to be minimal.

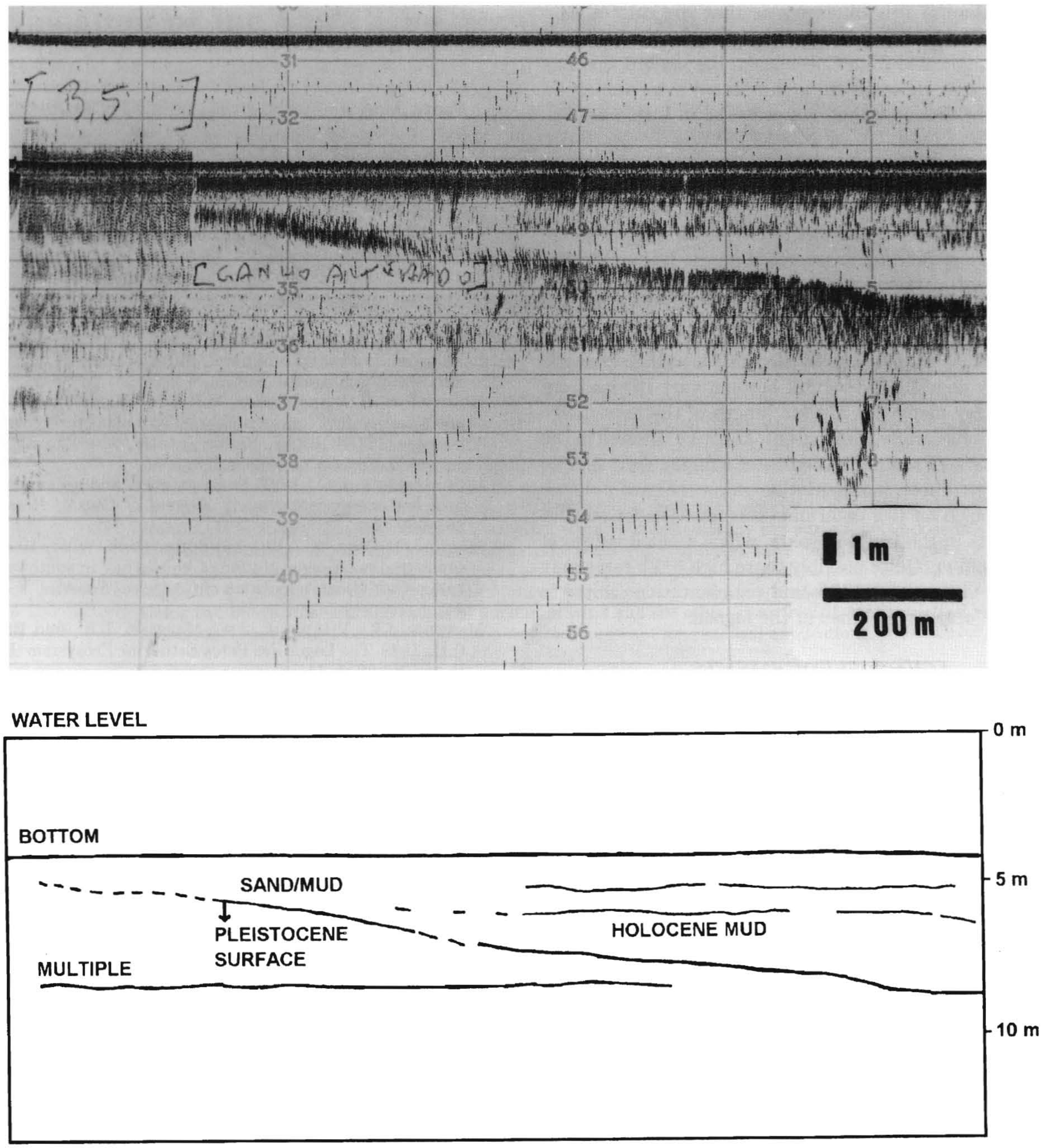

Figure 4. Record of a 7.0 kHz echo in the transition zone between the lagoonal floor and margin.

The short-term rates of sedimentation calculated in two cores by ^{210}Pb measurements (Figure 1), (MARTINS *et al.*, 1989) are quite different. This study used samples from the uppermost 10 cm of the cores and obtained rates of 3.5 and 8.3 mm/yr, which are nearly 10 times more rapid. These high rates could be the result of deforestation in the drainage basin since European colonization, which started about 150 years ago. CHENHALL *et al.* (1995) observed that short-term rates varying between 3 to 16 mm/yr in Lake Illwara Australia, indicate anthropogenic changes in the basin. According to COLMAN *et al.* (1992), another reason for high rates of modern sediment accumulation could be the acceleration in relative sea level rise.

Using the long-term average value of 0.52 ± mm/yr obtained from the ^{14}C dates, what thickness of lagoonal sediment would have accumulated on the lagoon since the inception of Holocene sedimentation 8.0 ka? This average rate of 0.52 ± mm/yr yields a thickness of 4.16 m, about 30% less than the observed average thickness of mud in the lagoon. One explanation of this difference is that the rate of sedimentation was not constant. COLMAN *et al.* (1992) and MARS *et al.* (1992) suggested from Chesapeake Bay and Mobile Bay respectively, that Holocene fill accumulated more rapidly at first than later. Possibly this also occurred in Lagoa dos Patos.

CONCLUSIONS

The base of Holocene sedimentation in the lagoon is defined by a strong reflector interpreted as the Upper Pleistocene surface of a coastal plain, which was drowned by lagoonal waters about 8.0 ka.

The lagoonal deposits of Lagoa dos Patos consist of marginal sands that border muddy deposits up to 6 m thick. These muddy deposits have a flat bottom, vary in size from silt to silty clay along the 240 km length of the lagoon, are organic rich, seismically transparent, and accumulated in the last 8,000 years at sedimentation rates ranging from 0.52 to 0.75 ± mm/yr. These sedimentation rates are much slower than rates based on two determinations of ^{210}Pb for surface muds deposits in the last 150 years, which yielded values of 3.5 and 8.3 mm/yr. Quite possibly there high ^{210}Pb rates may be the result of more rapid lagoonal sedimentation related to deforestation of the watershed of the lagoon.

ACKNOWLEDGEMENTS

This work is the result of research sponsored by OSNLR/COMEMIR Program. Support was also received from the Equipment Bank of the PGGM Program. We are grateful to Prof. Gilberto Dias, LAGEMAR/UFF, and Prof. Lauro Calliari, LOG/DEGEO/FURG, for their technical support, and to Prof. Alberto Figueiredo, LAGEMAR/UFF, for the constructive reviews of the manuscript. We also thank Paul E. Potter for his constructive comments and suggestions. Lab. Gilberto S. Santos and Lab. Maribel Nunes kindly performed grain-size analyses and Biol. Beatriz Dehnhardt helped in identify shells. Ana Maciel and Lucia R. Dillenburg assisted with the English text.

LITERATURE CITED

ALVAREZ, J.A.; MARTINS, I.L., and MARTINS, L.R., 1981. Estudo da Lagoa dos Patos. *Pesquisas UFRGS,* 14, 41–66.

ALVES, E.C., 1977. *Estrutura rasa do talude e sopé da margem continental do Rio Grande do Sul e Uruguai.* Dissertação de mestrado. Porto Alegre, Curso de Pós-Graduaçõ em Geociências, UFRGS. 160p.

BUTLER, L.W., 1970. Shallow structure of the continental margin, Southern Brazil and Uruguay. *Geological Society of America Bulletin,* 81, 1079–1096.

CHENHALL, B.E.; YASSINI, I.; DEPERS, A.M.; CAITCHEON, G.; JONES, B.G.; BATLEY, G.E., and OHMSEN, G.S., 1995. Anthropogenic marker evidence for accelerated sedimentation in Lake Illawarra, New South Wales, Australia. *Environmental geology and water sciences.* 26(2), 124–135.

COLMAN, S.M.; HALKA, J.P., and HOBBS, C.H. III., 1992. Patterns and rates of sediment accumulation in the Chesapeake Bay during the Holocene rise in sea level. *In:* Quaternary Coasts of the United States: Marine and Lacustrine Systems. *SEPM Special Publication* 48, 101–111.

CORRÊA, I.C.S., 1996. Les variations du niveau de la mer durant les derniers 17.500 ans BP: l'exemple de la plate-forme continentale du Rio Grande do Sul—Brésil. *Marine Geology,* 130, 163–178.

DAMUTH, J.E. and HAYES, D.E., 1977. Echo Character of the East Brazilian Continental Margin and its Relationship to Sedimentary Process. *Marine Geology,* 24, 73–95.

DELANEY, P.J.V., 1965. Fisiografia e geologia da superfície da planície costeira do Rio Grande do Sul. *Publicação Especial da Escola de Geologia UFRGS,* 6, 1–195.

DNPM, 1984. Mapa Geológico do Brasil 1:2.500.000. Departamento Nacional de Produção Mineral, Ministério das Minas e Energia, Rio de Janeiro, Brasil.

KOWSMANN, R.O. and COSTA, M.P.A., 1979. Sedimentação quaternária da margem continental brasileira e das áreas oceânicas adjacentes. PETROBRÁS, Rio de Janeiro, *Série Projeto Reconhecimento da Margem Continental,* 8, 9–55.

LUND-HANSEN, L.C., 1991. Sedimentation and accumulation rates in a low-energy embayment. *Journal of Coastal Research,* 7(4), 969–980.

MARS, J.C.; SHULTZ, A.W., and SCHROEDER, W.W., 1992. Stratigraphy and holocene evolution of Mobile bay in southwestern Alabama. *Gulf Coast Association of Geological Societies,* V XLII, 529–542.

MARTINS, I.R.; VILLWOCK, J.A.; MARTINS, L.R., and BENVENUTI, C.E., 1989. The Lagoa dos Patos Estuarine Ecosystem (RS, Brazil). *Pesquisas,* 22, 5–44.

MARTINS, L.R.S.; MELO, U.; FRANÇA, A.M.C.; SANTANA, I., and MARTINS, I., 1972. Distribuição faciológica da margem continental sulriograndense. *XXXVI Congresso Brasileiro de Geologia, SBG, Belém,* 115–132.

TOLDO JR, E.E. and MEDEIROS, R.K., 1986. Programa Interpola em Linguagem Basic para Análise Estatística de Propriedades Texturais de Amostras Sedimentares em Computador. *Pesquisas,* 18(2), 91–100.

TOLDO JR, E.E., 1989. *Os Efeitos do Transporte Sedimentar sobre a Distribuição dos Tamanhos de Grão e Morfodinâmica Lagunar.* Dissertação de Mestrado. Porto Alegre, Curso de Pós-Graduação em GEOCIÊNCIAS, UFRGS, 143P.

TOLDO JR, E.E.; AYUP-ZOUAIN, R.N.; CORRÊA, I.C.S., and DILLENBURG, S.R., 1991. Barra Falsa: Hipótese de um paleocanal Holocênico de comunicação entre a Laguna dos Patos e o Oceano Atlântico. *Pesquisas,* 18(2), 99–103.

TOLDO JR, E.E., 1994. *Sedimentação, Predição do Padrão de Ondas, e Dinâmica Sedimentar da Antepraia e Zona de Surfe do Sistema Lagunar.* Tese de Doutorado. Porto Alegre, Curso de Pós-Graduação em Geociências, UFRGS, 183p.

URIEN, C.M.; MARTINS, L.R., and MARTINS, I.R., 1980. Evolução Geológica do Quaternário do Litoral Atlântico Uruguaio, Plataforma Continental e Regiões Vizinhas. *Notas Técnicas,* 3, 1–43.

URIEN, C.M. and MARTINS, L.R., 1985. Southern South America Continental Margin: Structural Map, South Atlantic Openning Episodes and Basins. *Série Mapas CECO,* 06.

VILLWOCK, J.A.; TOMAZELLI, L.A.; LOSS, E.L.; DEHNHARDT, E.A.; HORN FO, N.O.; BACHI, F.A., and DEHNHARDT, B.A., 1986. Geology of the Rio Grande do Sul Coastal Province. *Quaternary of South America and Antarctic Peninsula,* 4, 79–97.