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ESR dating of pleistocene mammal teeth and its implications for the biostratigraphy and geological evolution of the coastal plain, Rio Grande do Sul, southern Brazil

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ABSTRACT

The fossiliferous deposits in the coastal plain of the Rio Grande do Sul State, Southern Brazil, have been known since the late XIX century; however, the biostratigraphic and chronostratigraphic context is still poorly understood. The present work describes the results of electron spin resonance (ESR) dating in eleven fossil teeth of three extinct taxa (*Toxodon platensis*, *Stegomastodon waringi* and *Hippidion principale*) collected along Chuí Creek and nearshore continental shelf, in an attempt to assess more accurately the ages of the fossils and its deposits. This method is based upon the analysis of paramagnetic defects found in biominerals, produced by ionizing radiation emitted by radioactive elements present in the surrounding sediment and by cosmic rays. Three fossils from Chuí Creek, collected from the same stratigraphic horizon, exhibit ages between (42 ± 3) Ka and (34 ± 7) Ka, using the Combination Uptake model for radioisotopes uptake, while a incisor of *Toxodon platensis* collected from a stratigraphic level below is much older. Fossils from the shelf have ages ranging from $(7 \pm 1)\ 10^5$ Ka to (18 ± 3) Ka, indicating the mixing of fossils of different epochs. The origin of the submarine fossiliferous deposits seems to be the result of multiple reworking and redeposition cycles by sea-level changes caused by the glacial–interglacial cycles during the Quaternary. The ages indicate that the fossiliferous outcrops at Chuí Creek are much younger than previously thought, and that the fossiliferous deposits from the continental shelf encompass Ensenadan to late Lujanian ages (middle to late Pleistocene).

1. Introduction

The coastal plain of the Rio Grande do Sul State (RSCP), in southern Brazil, is the youngest geomorphological unit in the State (Fig. 1). It is a 600 km-long and 100 km-wide unit composed by siliciclastic sediments and characterized by several coastal depositional environments, some of which contain remains of extinct mammals of the Pleistocene megafauna. The fossils are more common in the southern portion of the coast (Buchmann, 1994), and are found mainly in two areas: in a fossiliferous layer exposed along the banks of Chuí Creek (Lopes et al., 2005), and along the coastline, where are thrown by storm waves after being removed from fossiliferous deposits in the adjacent continental shelf (Buchmann, 2002). Although these have been known since the late XIX century, its exact nature and age is still unknown.

The absence of materials suitable for radiometric dating in the sediments of the RSCP has precluded the precise understanding of the regional chronostratigraphy, which in turn has presented difficulties for precise chronological correlation for the fossiliferous deposits. As a result, in the first systematic geological survey of the coastal plain (Delaney, 1965) the fossils were considered Tertiary in

Abbreviations: LGP, Laboratório de Geologia e Paleontologia (Universidade Federal do Rio Grande – FURG); MO, Museu Oceanográfico (FURG).

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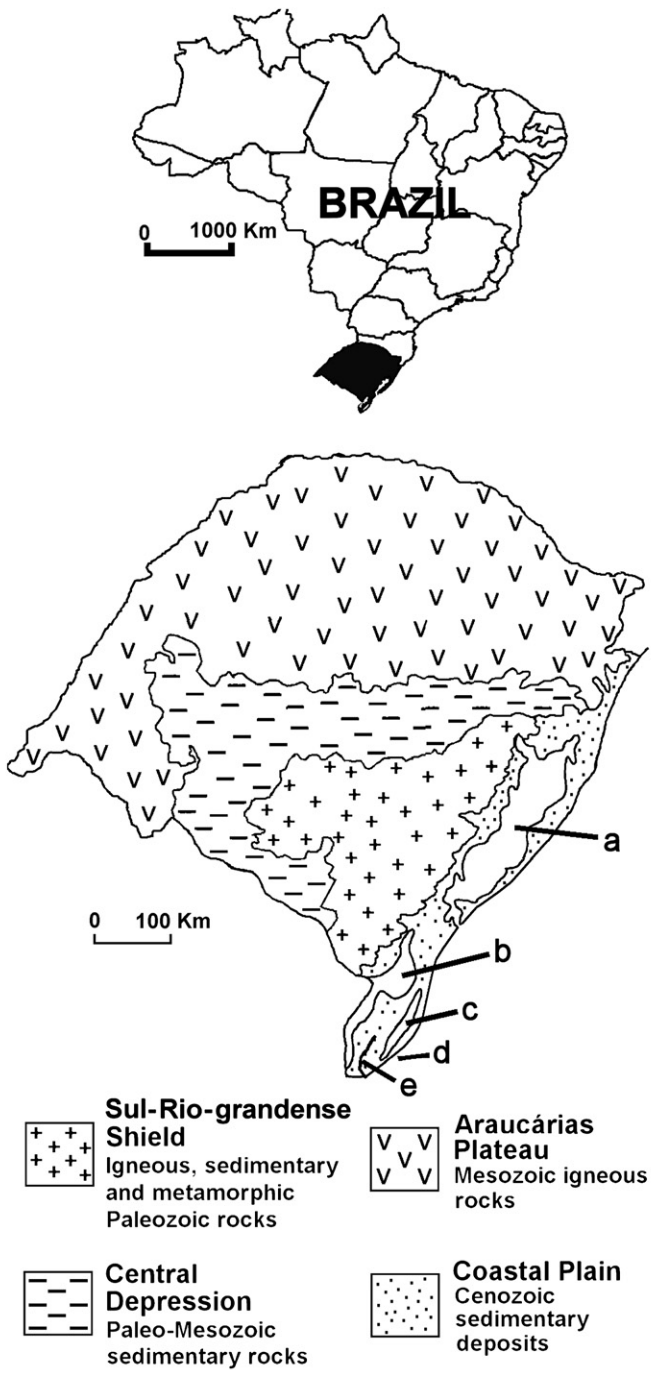

Fig. 1. Major geomorphologic units of the Rio Grande do Sul State, Brazil, and some landmarks of the Coastal Plain: a) Patos Lagoon; b) Mirim Lake; c) Mangueira Lake; d) Concheiros; e) Chuí Creek.

age. Ten years later, these fossils were biostratigraphically correlated to those of the western portion of Rio Grande do Sul (the Campanha Region) and the Pampean Region of Argentina, of late Pleistocene age (Bombin, 1975), thus giving the remains a Lujanian age, according to the biostratigraphic scale for the Pampean Region, which is the basis for the South American mammalian biostratigraphy (Fig. 2). Given the faunal similarity observed among the fossils from Chuí Creek and the continental shelf, a similar age of ca. 120 ka has been attributed to both (Lopes et al., 2001, 2005), as this is the estimated age for the deposits of Chuí Creek (Buchmann, 2002). In an attempt to establish the chronology more accurately,

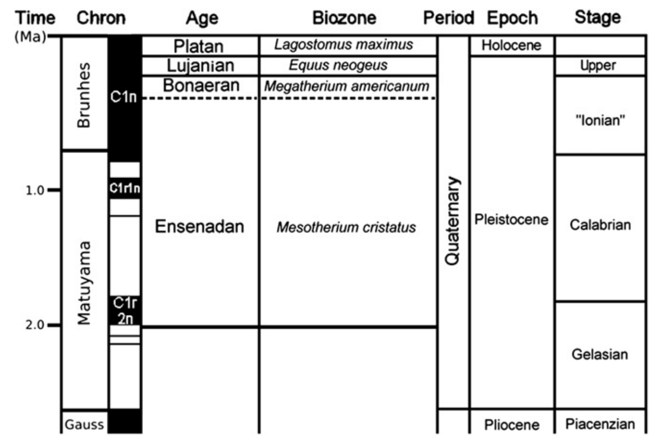

Fig. 2. Biostratigraphic and chronostratigraphic subdivisions of the Pampean Region of Argentine (Modified from Tonni, 2007).

teeth of extinct mammals from both deposits have been selected for dating by electron spin resonance (ESR) spectroscopy, also known as electron paramagnetic resonance (EPR).

Fossils of terrestrial mammals in submarine environments are not new to science. They have been reported on the continental shelf of the United States (Whitmore et al., 1967), the North Sea (van Kolfschoten and Laban, 1995; Mol et al., 2006), Argentina (Cione et al., 2005) and Uruguay (Rinderknecht, 2006). Fossils of terrestrial vertebrates associated with marine fossils have also been described from marine outcrops in Argentina (Pardiñas et al., 1996) and the United States (Cutler, 1998). The presence of remains of terrestrial mammals in submarine deposits is attributed to their preservation on areas of the continental shelf that were exposed to subaerial environments during sea-level lowstands, correlated to glacial maxima.

Due to its hydroxylapatite crystals, larger and in higher concentration than found on bone or dentin, tooth enamel is much more resistant to physico-chemical alterations during diagenesis (Rink, 1997), thus constituting an excellent archive of paleoecological and paleo-environmental information. Today, tooth enamel has become a major tool for paleoclimatic and paleoecological studies in terrestrial environments (e.g. Fricke and O'Neil, 1996; Koch, 1998; Sharp and Cerling, 1998). Besides stable isotopes, teeth also register the effects of radiation emitted by the surrounding sediment after its final burial.

Electron Spin Resonance (ESR) dating, as well as thermoluminescence (TL) dating, is based on the study of the effects of ionizing radiation on the material. Unpaired electrons or holes are produced by ionizing radiation in solids and are trapped by impurities or lattice defects, originally present on the sample or radiation-induced. The natural radiation is produced by cosmic rays and radiation emitted by radioactive elements such as Uranium (^{238}U), Thorium (^{232}Th) and Potassium (^{40}K) present in the surrounding sediment and in the sample. The age is obtained by dividing the accumulated dose on the material by the annual external (environmental) and internal (from radioactive elements in the sample) radiation rates. The concentration of unpaired electrons is determined by ESR spectroscopy and is called the Archaeological Dose (AD).

To determine the AD, the Additive Dose method (Ikeya, 1993) is used. This method is based on the principle that if the future concentration of defects is known, the time elapsed until the present concentration can be inferred. Thus, a set of known additive doses are applied to the material to produce additional defects, and the intensities of ESR spectra are used to construct the dose–response curve and to obtain the AD. Irradiation given to the

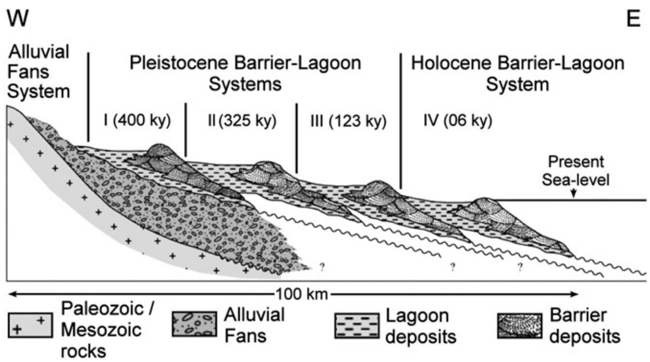

Fig. 3. Transect of the RSCP, showing its main depositional systems (Modified from Tomazelli and Villwock, 2005).

sample in the laboratory (usually employing ^{137}Cs or ^{60}Co sources or a linear accelerator) are used as a "time machine" to assess a future spin concentration. The intensity of the ESR signal increases as a function of the absorbed dose and the AD is determined by the growth of the signal. Assuming a linear relation between the dose and the ESR signal intensity:

$$I(D) = I_0\left(1 + \frac{D}{AD}\right) \tag{1}$$

where I_0 and I refer to the initial and post-additive dose, and D the additive dose. In a general case the dose–response curve can be adjusted by an exponential saturation curve:

$$I(D) = I_0\left(1 - e - \left[\frac{D + AD}{D_0}\right]\right) \tag{2}$$

where I_0 represents the signal intensity of the saturation signal and D_0 the saturation dose.

In the ESR dating technique, the age of the sample is given by the concentration of unpaired electrons in defects. Some events might cancel the unpaired electrons thus affecting the information about the age. Among these, crystallization processes and heat exposition are the most common. In speleothems, the signal intensity is usually zero on the surface, while in its interior the carbonates exhibit an intense signal. This is due to the constant crystallization process, and on the surface the accumulated dose is always lower. A similar behavior is found in biological materials such as shells and corals, where a biomineralization process also happens constantly while the organism is alive.

The action of heat on clay ceramics does also cancel out the defects present in its quartz and feldspar components. As a result, the time is 'zeroed' by heat action and the detected ESR centers are those generated by irradiation after this event. Thus, ESR dating can also be employed in rocks and minerals heated by human action or geothermal events such as volcanic eruptions (Ikeya, 1993). The age is given by:

$$\text{Age} = \frac{\text{AD}}{(D_{\text{int}} + D_{\text{ext}})} \tag{3}$$

where AD is the archaeological dose, obtained through the additive-dose method, D_{ext} and D_{int} are respectively the external and internal dose rates.

The internal and external dose rates produced by radioactive elements found in the sediment and in the material can be calculated through the ^{238}U, ^{232}Th and ^{40}K concentrations. These can be obtained through techniques such as Neutron Activation Analysis (NAA). The annual dose rate from cosmic rays is about 0.25 mGy/year (Watanabe et al., 2003).

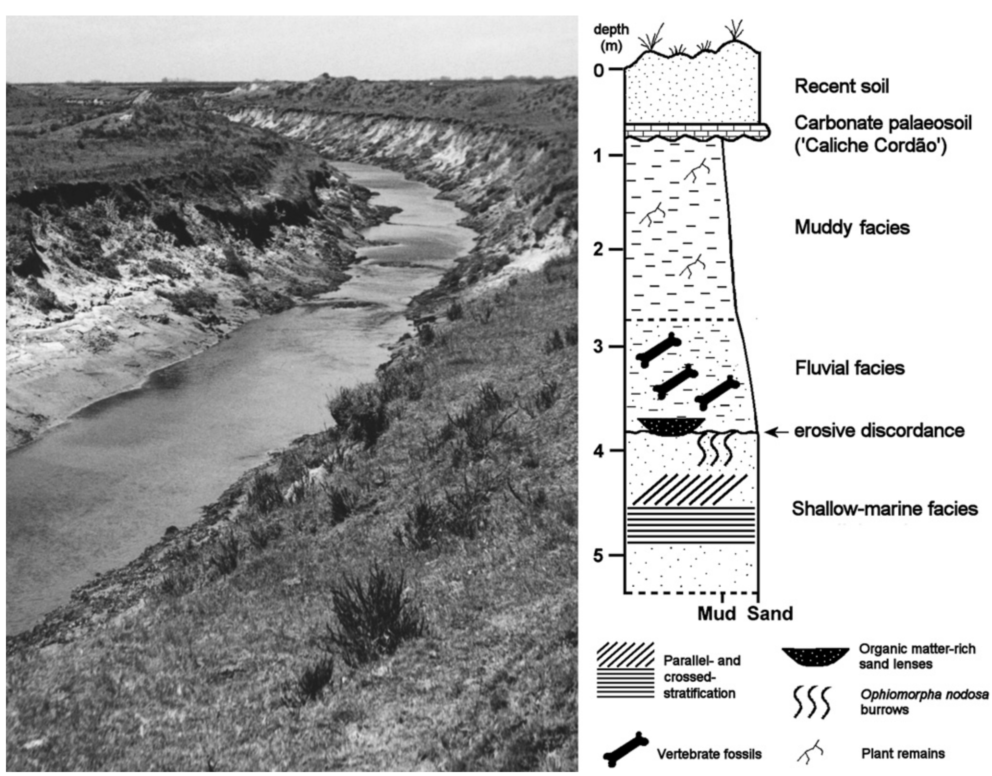

Fig. 4. On the left: panoramic view of Chuí Creek; on the right, the sedimentary sequences exposed along the banks.

Fig. 5. Fossil of terrestrial mammal found in the Concheiros, thrown onto the beach by storm waves.

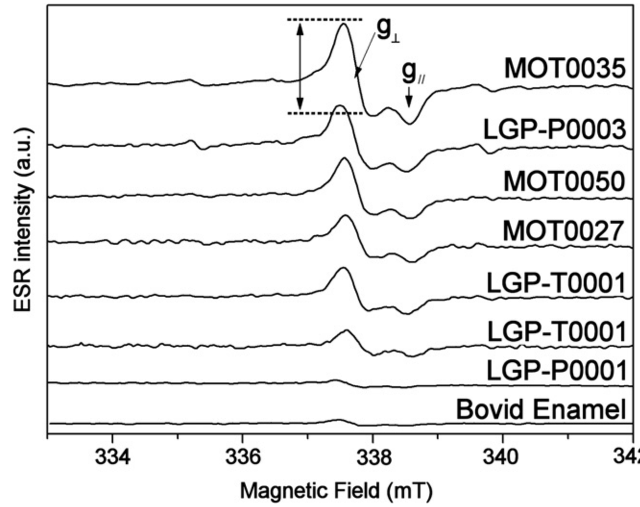

Fig. 6. ESR spectra of samples without additive dose. The bovid tooth enamel was exposed to 20 Gy of gamma rays to give an order of magnitude of the ESR signals. The peak to peak intensity measurement is indicated. Calibration curve (or dose response curve) was obtained for each sample separately to obtain the Archaeological Dose (AD).

Among the advantages of the ESR dating technique are the simplicity of sample preparation, the need for small quantities of material, the possibility of *in situ* measurements without destroying the sample (teeth, archeological objects) and the applicability to samples that do not have sufficient collagen for ^{14}C dating. ESR dating encompasses a wide range of ages, from hundreds to millions of years, including the interval between 40 ka and 200 ka, filling the gap between the ^{14}C maximum range and ^{40}Ar/^{39}Ar minimum range (Rink, 1997; Kinoshita and Baffa, 2005). The ESR method has been applied to dating of megafauna in northeastern and southeastern Brazil, with good results (Baffa et al., 2000; Kinoshita et al., 2005, 2008).

2. Geological setting

The origin of the RSCP dates back to the Late Cretaceous, when the final split between South America and Africa resulted in the formation of several marginal sedimentary basins along the Brazilian coast. In southern Brazil, the accumulation of sediments eroded from older rocks originating in the Pelotas Basin, separated from the northern Santos Basin by the Florianópolis Shelf and limited to the south by the Precambrian granitic rocks in the Uruguayan coast at La Coronilla (Closs, 1970). Drill holes by the Brazilian petroleum company on the continental shelf have reached the Mesozoic/Cenozoic boundary (Upper Maastrichtian/Lower Paleocene) at a depth of some 3200 m. On land, however, the oldest sediments are of Miocene age, and the crystalline bedrock is reached around 1570 m (Gomide, 1989).

Throughout the Neogene and Quaternary, sea-level oscillations resulting from glacial-interglacial cycles have reworked the upper portion of the Pelotas Basin, shaping the RSCP sediments in two major types of depositional systems: an Alluvial Fan System, located landwards, and four Barrier-Lagoon Systems seawards (Tomazelli et al., 2000). Due to the low slope (3° on average), fine sediment and micro-tidal regime of the coast, each Pleistocene transgressive event formed a barrier-lagoon system (Fig. 3). These systems developed parallel to the coastline and were correlated to MIS 11 (400 ka), 9c (325 ka), 5e (123 ka) and 1 (6 ka) (Villwock and Tomazelli, 1995). Today, the Alluvial Fan System and the Barrier-Lagoon Systems constitute the emergent portion of the RSCP, while the continental shelf constitutes the submerged portion.

The 123-ka Barrier-Lagoon System III is very well preserved along the RSCP. Barrier System III is constituted by a long sandy barrier 7 m above present sea-level on average (Tomazelli and Dillenburg, 2007), while in the northern-central portion of the RSCP, Lagoon System III is represented by the Patos Lagoon. In the southern portion, deposits corresponding to Lagoon System III, positioned between barriers II and III, are composed by wetlands and Chuí Creek. The type section of the outcrops along Chuí Creek (Fig. 4) is located at 33°35′26.39″S; 053°20′22.11″W. It is represented by a beach facies exposed at the base, overlain by a 1.5 m-thick sandy layer that contains fossils of Pleistocene mammals preserved *in situ* (Lopes et al., 2005). Above there is a muddy facies, in which no fossils have been found, with a carbonate layer on top (the "Caliche Cordão" of Delaney, 1965). The upper portion of the sequence is the present soil and vegetation. The palynomorph content found on dark-coloured sand lenses present on the fossiliferous layer indicate the presence of oxbow lakes, thus showing that this layer originated in a meandering stream (Lopes et al., 2005).

Fossils of the same mammals found in Chuí Creek occur along the coastline, removed from deposits in the continental shelf (at depths up to 10 m). These remains are subject to exhumation and re-working by present erosive processes affecting the southern portion of the RSCP (Dillenburg et al., 2004; Esteves et al., 2004). These deposits are regarded as continental environments that were covered by the Atlantic Ocean as a result of the Holocene sea-level transgressive event of 6 ka BP (Buchmann, 2002). The exhumation of the remains under a marine environment caused the fossils to become dark, extremely hard and heavy (Lopes et al., 2008). During autumn and winter, storm waves remove the fossils from the nearshore and transport them to the beach, where are collected (Fig. 5). Although found along the entire coastline, thee fossils are more conspicuous in the southernmost portion, between 150 and 190 km south of the Patos Lagoon Estuary (Buchmann, 1994). This sector (between 33°20′00.06″S and 33°39′57.7″S) is known as "Concheiros" due to the presence of thick deposits of marine shells and fossils of echinoderms, crustaceans, teleosts, elasmobranchs, cetaceans and pinnipeds, in addition to the terrestrial extinct mammals. Because these fossils are found scattered on the beach, disarticulated and removed from the submarine deposits, it is difficult to establish precise stratigraphic provenance. However, the presence of Lujanian (*sensu* Cione and Tonni, 1995, 1999) taxa does suggest a Late Pleistocene age (Fig. 5). The faunal and taphonomic

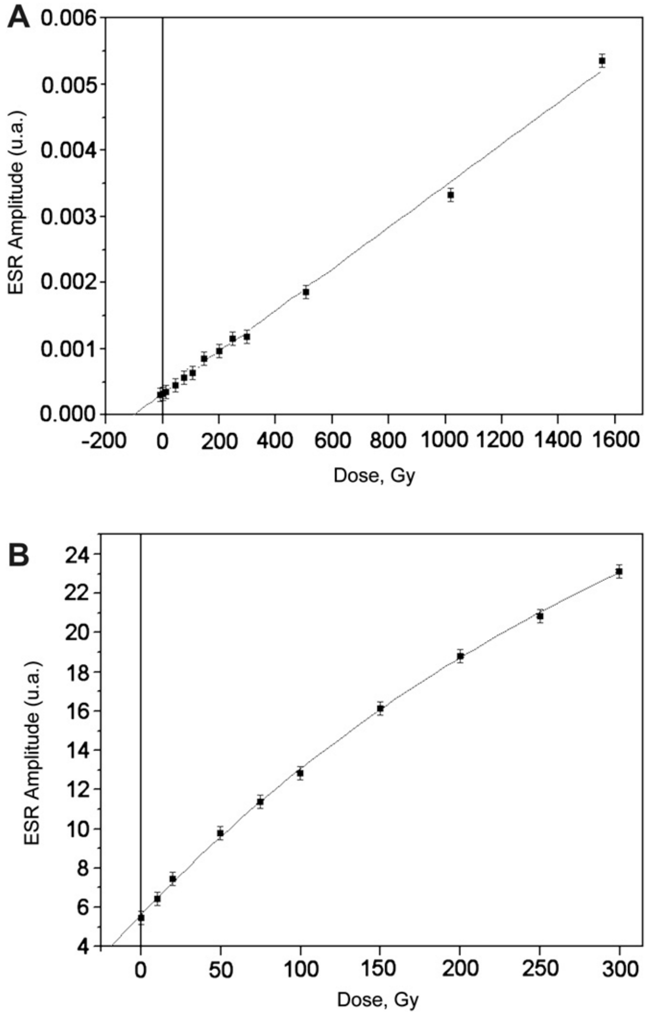

Fig. 7. Dose–response curves of the samples LGP-E0001 (A) and LGP-T0001 (B). Experimental data with linear and exponential adjustments, respectively.

similarity with the fossils from Chuí Creek suggests that both deposits originated as fluvial systems around 120 ka BP (Lopes et al., 2008). Fossils of terrestrial mammals have also been found on the continental shelf of Argentina (Cione et al., 2005) and Uruguay (Rinderknecht, 2006).

3. Materials and methods

Eleven teeth of three extinct mammalian taxa (*Stegomastodon waringi*, *Hippidion principale* and *Toxodon platensis*) from the paleontological collection of the Universidade Federal do Rio Grande (FURG) were selected for ESR dating. Seven of the specimens were from the nearshore continental shelf (from depths less than 10 meters) and four from Chuí Creek. These teeth are relatively conspicuous in the fossiliferous deposits, found either complete or as fragments. Special attention was paid to select from among the specimens from Chuí Creek only those that were collected *in situ*, directly from the layer where were embedded, although fossils removed from the layers can be found at the bottom of the creek. The dating experiments and analytical procedures were performed at the laboratory of Departamento de Física e Matemática of Universidade de São Paulo (FFCLRP-USP) and Instituto de Pesquisas Nucleares of Universidade de São Paulo (IPEN-SP). Along with the teeth, sediment samples were also collected for the analytical procedures. In the case of the teeth from Chuí Creek, two sediment samples were collected: one from the fossiliferous layer, from where the specimens LGP-E0001, LGP-P0004, and MOT0054 were excavated, and other from the layer below, where the specimen MOT0050 was collected. The sediments for dating the fossils from the submarine deposits were collected a few centimeters below the seafloor surface, at a depth around 1 m below the water surface. As the sediments that constitute the shoreline and continental shelf are essentially homogeneous medium- to fine-sized siliciclastic sands, mature and well-selected, (Villwock and Tomazelli, 1995; Tomazelli et al., 2000), and there are no fluvial discharges nearby that could bring allochthonous sediments, it is assumed that the sample is representative of the nearshore deposits in which the fossils are currently preserved, and thus would be suitable for radiation measurements.

An enamel sample was removed from each tooth and separated from dentine using the thermal expansion technique. The teeth were immersed in liquid nitrogen for few minutes and then heated at environmental temperature. Due to the differences in the thermal expansion coefficient between both tissues, after some repetitions of this process the enamel is detached from the dentine. The remaining dentine was mechanically removed with low-rotation diamond drills. The enamel was then subject to chemical etching in an acid solution (HCl 1:10) for about 2 minutes, to remove a fine (approximately100 μm) layer from both sides. The resulting material was then manually powdered to fine particles of about 500 μm in diameter. This powder was then fractioned in 200 mg samples, and each was irradiated with an additive dose to construct the dose–response curves. The irradiation of the samples was performed under environmental temperature, using a Gammacell source with dose rate of 2.47 kGy/h.

The ESR spectra were registered in a modified Varian E-4 spectrometer, set with following parameters: central field 338 mT; modulation amplitude 2 mT and microwave power 50 mW (below signal saturation in this system). Experimental data of ESR signal intensity were fitted by linear (equation (1)) or exponential (equation (2)) function to find the best adjustment. Through the dose–response curve, the AD values for each fossil sample were obtained. The concentration of ^{238}U, ^{232}Th and ^{40}K radioisotopes on enamel, dentin for each sample and for the soil were obtained through Neutron activation (NAA) technique. The conversion of the

Table 1
Radioisotope concentrations present in the samples.

Sample	Dentine			Enamel		
	U (ppm)	Th (ppm)	K (%)	U (ppm)	Th (ppm)	K (%)
LPG-P001	1.2 ± 0.4	<0.02	<15	5.1 ± 0.5	<0.02	<15
LGP-P004	205 ± 18	<0.02	<15	23 ± 2	<0.02	<15
MOT0050	212 ± 17	<0.02	<15	<0.1	<0.02	<15
MOT0054	129 ± 15	<0.02	<15	7.3 ± 0.7	<0.02	<15
MOT0056	121 ± 15	<0.02	<15	1.8 ± 0.2	<0.02	<15
LGP-P003	33 ± 3	<0.02	<15	<0.1	<0.02	<15
LGP-P002	79 ± 7	<0.02	<15	<0.1	<0.02	<15
LGP-T001	36 ± 3	<0.02	<15	<0.1	<0.02	<15
MOT0035	14 ± 1	<0.02	<15	<0.1	<0.02	<15
MOT0027	20 ± 2	<0.02	<15	<0.1	<0.02	<15
LGP-E001	114 ± 11	<0.02	<15	8.4 ± 0.3	<0.02	<15

Table 2
Radioisotope concentrations present in the sediments.

Sample	U (ppm)	Th (ppm)	K (%)
Chuí Creek sediment – LGP-P004	16.6 ± 0.5	2.5 ± 0.1	0.9 ± 0.1
Chuí Creek sediment	1.50 ± 0.05	6.3 ± 0.2	1.0 ± 0.1
Continental shelf sediment	<0.05	3.8 ± 0.1	0.4 ± 0.1

Table 3
Archaeological Dose (AD) and ages obtained by ESR dating on fossil mammal teeth from the Pleistocene fossiliferous deposits of the RSCP, according to the radioisotope uptake model.

Origin	Sample	Taxonomy	AD (Gy)	Age EU (ka)	Age LU (ka)	Age CU (ka)
Chuí Creek	LGP-E0001	*Hippidion principale*	103 ± 8	33 ± 7	50 ± 8	34 ± 7
Chuí Creek	LGP-P0004	*Stegomastodon waringi*	228 ± 1	38 ± 2	68 ± 4	38 ± 2
Chuí Creek	MOT0050	*Toxodon platensis*	104 ± 17	184 ± 9	240 ± 38	226 ± 35
Chuí Creek	MOT0054	*Toxodon platensis*	90 ± 1	41 ± 3	71 ± 4	42 ± 3
Continental Shelf	MOT0056	*Hippidion principale*	153 ± 1	140 ± 8	228 ± 12	146 ± 9
Continental Shelf	LGP-P0003	*Stegomastodon waringi*	153 ± 1	438 ± 8	511 ± 40	464 ± 65
Continental Shelf	LGP-P0002	*Stegomastodon waringi*	56 ± 1	147 ± 14	178 ± 10	165 ± 28
Continental Shelf	LGP-T0001	*Toxodon platensis*	61 ± 3	196 ± 26	217 ± 18	207 ± 28
Continental Shelf	MOT0035	*Toxodon platensis*	189 ± 1	630 ± 100	686 ± 60	650 ± 100
Continental Shelf	MOT0027	*Toxodon platensis*	126 ± 1	412 ± 30	451 ± 32	428 ± 30
Continental Shelf	LGP-P0001	*Stegomastodon waringi*	22 ± 4	18 ± 3	29 ± 5	18 ± 3

ADs in ages was made by the ROSY software (Brennan et al., 1999), which calculates the ages through the internal and external dose rates given by the radioisotope concentrations and cosmic rays.

4. Results

Fig. 6 shows the initial ESR spectra, without additive doses, from each fossil and a bovid enamel sample irradiated with 20 Gy for comparison. Fig. 7 shows the dose–response curve from LGP-E0001 and LGP-T0001 samples, which experimental data of amplitude at $g_{\perp}$ as function of dose were fitted by linear (A) and exponential (B) functions according to equations (1) and (2). The same procedures were adopted for the other samples. Samples LGP-P004, MOT0050, MOT0056, LGP-P003, LGP-P002, LGP-T001, MOT0035, MOT0027 and LPG-P001 were fitted by equation (1), and samples LGP-E0001, MOT 0054 by equation (2).

The concentration of ^{238}U and ^{232}Th obtained by Neutron Activation Analysis are shown in Table 1 for enamel and dentine of each tooth sample and Table 2 for the soil. The ^{40}K concentrations were determined by Absorption Atomic Spectroscopy (AAS) and are listed together. The results of AD as well as the ages for Early, Linear and Combination models for radioisotopes uptake provided by ROSY software are shown in Table 3. The internal and external dose rates are listed in Table 4, according to the radioisotope uptake model. The combination uptake model was obtained considering the Early uptake model for enamel and Linear uptake for dentine. The value of 0.15 was used for the k-value, the ratio of defects creation efficiency for α particles to internal dose rate calculation. The energy released by α particles by the soil was not considered because the maximum penetration depths of these particles are 40 to 60 μm, shorter than the layer extracted in the sample preparation. Initial ^{234}U/^{238}U ratio of 1.4 was assumed for age calculations, and the value of 250 μGy/year was used as the annual dose rate from cosmic rays.

Enamel samples from the specimens LGP-P0003, LGP-P0004 and MOT0050 were also sent to the Beta Analytics laboratory (Florida, U.S) in an attempt to apply the ^{14}C dating technique and compare ages from both methods. However, these samples were not suitable, due to the low collagen content (less than 1%). This problem was also reported in fossil bones from the La Chumbiada Member of the Luján Formation, Argentina (Tonni et al., 2003), and was attributed to diagenetic alteration of the collagen. The fossils from the RSCP that did not contain enough collagen were dated by ESR as being older than 30 ka, and in the Guerrero Member of the Luján Formation, fossils 11 ka or less were suitable for ^{14}C dating. Thus, it is possible that younger fossils from the RSCP may be dated also by ^{14}C, which would allow a comparison between the results of both methods, thus obtaining well-calibrated ages.

The fossils from Chuí Creek show little chronological variation, between 33 and 42 ka. The exception is the specimen MOT0050, an upper incisor of a *Toxodon platensis* dated as older than 200 ka. This fossil was embedded in a sand bank below the fossiliferous layer, at the level of the beach facies. Its position and age suggest that it came from older deposits that were re-worked during the last Pleistocene transgressive event of 123 ka and was re-deposited in younger sediments.

The teeth from the continental shelf show a wide age range, spanning some 6×10^4 years, thus indicating the mixing of fossils from Medium to Late Pleistocene-age deposits. The mixing of fossils of different ages is probably a result of the reworking of several fossiliferous deposits by the successive sea-level transgressive events during the Quaternary, contrary to former estimates that attributed ages ca. 120 ka or less, coincident with the last regressive event alone (Lopes et al., 2005).

Table 4
Internal and External dose rates used for age calculations, according to the radioisotope uptake model.

Sample	Early Uptake (μGy/y)				Linear Uptake (μGy/y)			Combination Uptake (μGy/y)		
	Dext.sed	Dext.dent	Dint.ena	Dtotal	Dext.dent	Dint.ena	Dtotal	Dext.dent	Dint.ena	Dtotal
LGP-E001	7.7	97.9	2749.0	3104.6	48.9	1770.9	2077.5	47.7	2757.7	3063.1
LGP-P004	78.1	177.9	5556.0	6062.6	90.2	2946.7	3365.1	86.4	5578.8	5993.4
MOT0050	7.7	208.3	100.5	566.5	101.4	76.3	435.4	100.7	103.6	461.9
MOT 0054	7.7	112.8	1820.6	2191.0	57.0	952.3	1267.0	54.7	1834.1	2146.5
MOT0056	2.9	100.2	735.6	1088.9	50.3	370.4	673.5	47.6	746.9	1047.3
LGP-P003	2.6	37.6	58.7	349.0	18.2	25.8	299.6	18.1	59.2	329.9
LGP-P002	2.6	84.5	334.3	381.5	40.9	21.6	315.2	40.6	46.2	339.4
LGP-T001	2.6	33.0	25.9	311.6	15.9	13.0	281.5	15.9	26.4	294.8
MOT0035	2.6	16.2	30.4	299.3	7.9	15.1	275.6	7.87	30.4	291.0
MOT0027	2.9	22.7	30.6	306.3	10.9	15.5	279.3	10.9	30.8	294.5
LPG-P001	3.3	1.3	988.7	1242.8	0.6	505.3	759.3	0.6	988.8	1242.8

Dext.sed: external dose rate from sediment; Dext.dent: external dose rate from dentine; Dint.ena: internal dose rate in enamel; Dtotal: total dose rate including dose from cosmic rays.

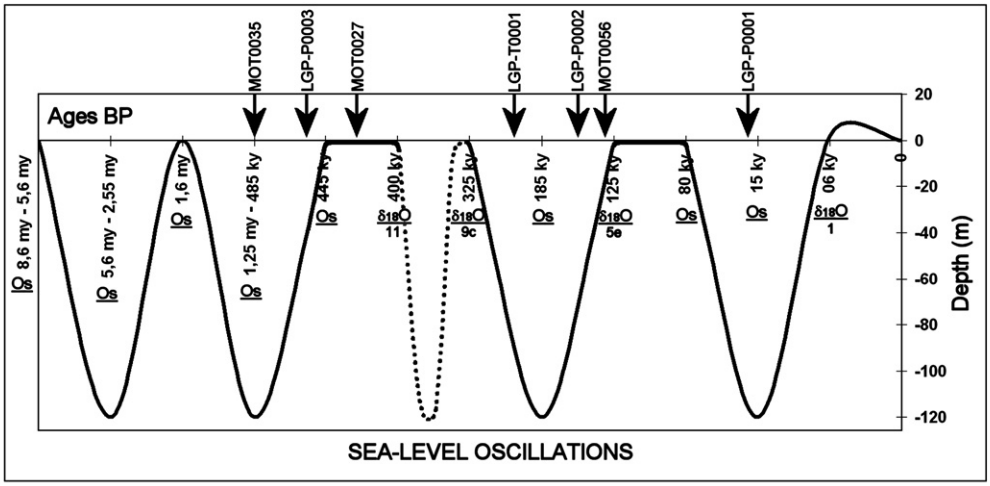

Fig. 8. Reconstruction of the sea-level oscillations recorded in the RSCP, based on ostracod assemblages (Os, according to Carreño et al., 1999) and correlation with oxygen isotope curves ($\delta^{18}O$; Villwock and Tomazelli, 1995). Indicated by arrows are the ages obtained by ESR on the mammalian teeth from the continental shelf, showing its correlation with regressive events. The dotted line indicates a regressive event that was not recorded by microfossils.

5. Discussion

The ages calculated by combination model of radioisotope uptake were obtained considering early radioisotope uptake by enamel and linear uptake by dentine. This is a plausible model for radioisotope accumulation in the sample and thus is usually considered the most adequate value for the sample age.

5.1. Chuí Creek

The ages of the fossils do have implications for the evolution models of Chuí Creek. The plain where the creek flows through is associated with Lagoon System III, positioned between the 325-ka Barrier System II (landwards) and the 123-ka Barrier System III (seawards) (Villwock and Tomazelli, 1995). According to the geological evolution model proposed by Villwock et al. (1986), the fossiliferous deposits of Chuí Creek would have originated around 120 ka. The presence of disarticulated but associated, as well as articulated mammalian remains along the banks of the creek (Lopes et al., 2005), indicates that these were deposited directly into the fluvial system, not the result of the reworking of older fossiliferous deposits.

On the other hand, the much older age obtained for the specimen MOT0050, and its presence in the beach sediments underlying the fossiliferous fluvial sediments, suggests that this tooth and the other remains found associated were originally deposited on continental sediments that were re-worked by the sea-level transgression around 123 ka. Thus there is a considerably large time hiatus between the beach facies at the base of the banks and the overlying fossiliferous layer, due to erosion of the beach facies, as indicated by the erosive discordance.

Despite the progressively drier climate during the last glacial event, the ages between 42 and 33 ka for the fossils suggest that this period was marked by a wetter climate regime, leading to base-

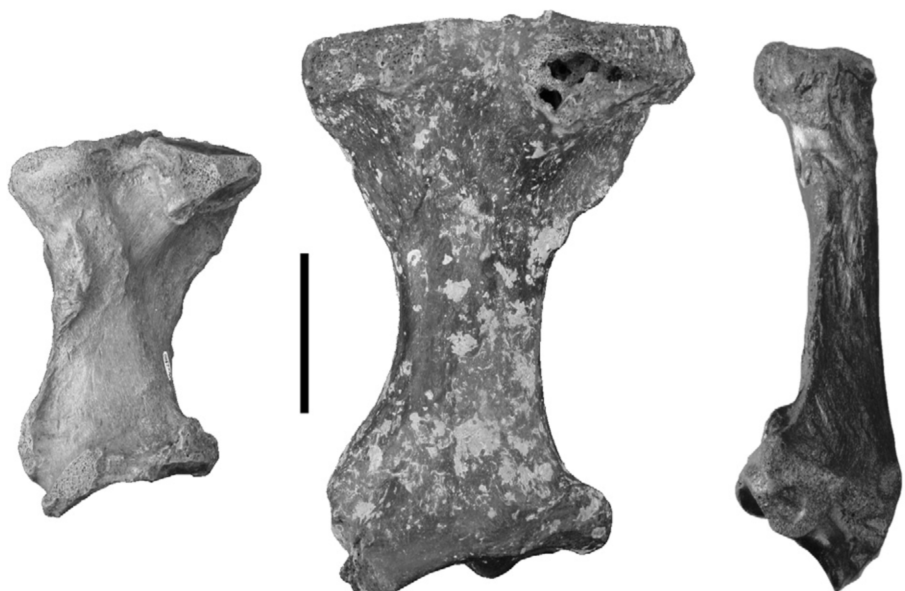

Fig. 9. Several fossils from the backshore, such as these two tibiae of ground sloths (MCN-PV-2388 and -1112 from the paleontological collection of the Fundação Zoobotânica do RS) and this left radius of a *Toxodon platensis* (LGP-H0103), exhibit good preservation, indicating that suffered little or no transport (scale bar = 10 cm).

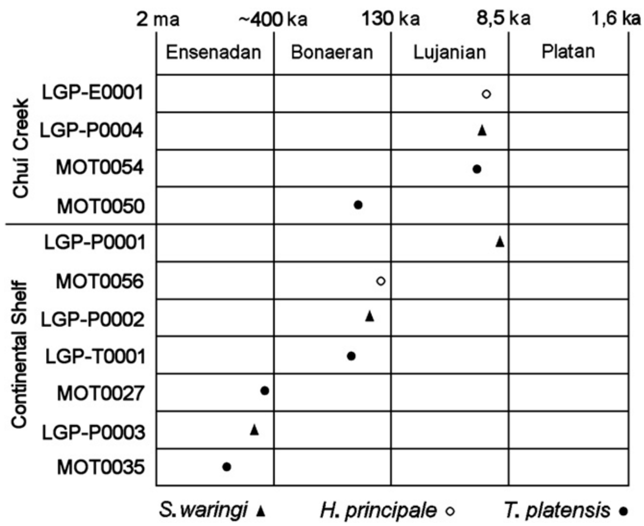

Fig. 10. Distribution of the fossil ages superimposed to the biostratigraphic scale of Cione and Tonni (1995, 1999).

level rise. The ages also indicate that the carbonate layer on top of the muddy facies might be related to the dry climate of the last glacial maximum around 17 ka, thus being directly correlated to the carbonate layers found in the Touro Passo Creek, in the western portion of the Rio Grande do Sul State, which have been formed around 17 ka (Da Rosa, 2003), although originally considered Holocene (3.5–2.5 ka) by Bombin and Klamt (1975).

5.2. Continental shelf

Except for the specimen MOT0027, all ages obtained on the fossils are correlated to periods of sea-level lowstands (Fig. 8). This suggests a correlation between these regressive periods and the origin of the fossiliferous deposits on the continental shelf. These regressions are related to glacial epochs and are documented by several features found on the continental shelf (Corrêa et al., 1996; Martins et al., 1996). In the RSCP, at least four major sea-level transgressive-regressive events are registered, in the form of the barrier-lagoon systems. Ostracod assemblages obtained from drill holes made by Petrobras in the continental shelf indicate the presence of sea-level regressive events at 2.6 Ma, 1.25 Ma–485 ka, 185 ka, and 15 ka, intercalated with transgressions (Carreño et al., 1999).

The continental shelf of Rio Grande do Sul shows a very low slope (1:1.000 ratio). This implies that during the regressive maxima, when the sea-level was some 100 m below the present level (Corrêa et al., 1996), the coastline was located around 100 km to the east. Thus, the emergent portion of the RSCP would be twice its present area. The presence of terrigenous clastic sediments (Kowsmann and Costa, 1974), submerged paleo-coastlines (Asp, 1999), heavy mineral concentrations (Corrêa and Ade, 1987) and geomorphological features in the form of incised valleys (Abreu and Calliari, 2005) along the continental shelf, indicate that during the last regressive maximum this large plain was cut by rivers. Probably this large area was also a habitat for terrestrial mammals, that died and had remains preserved in these fluvial systems.

By extrapolating the processes that occurred during the last transgressive event to the older three ones, it can be concluded that each transgression reworked fossiliferous deposits that were formed during the previous regressive event, resulting in the mixing of fossils of different ages in the same coastal environment. Taking in account the geomorphology of the continental shelf, models have showed that a sea-level transgression would erode a 10-m thick portion of the sediment record (Dillenburg, 1996). The presence of fossils that are well-preserved (Fig. 9) indicates *in situ* preservation of these remains in the continental shelf area, instead of being brought to the coast by fluvial transport from areas located landwards. In addition, from around 325 ka BP onwards, when Mirim Lake was formed, all continental fluvial drainage that would reach the southern portion of the coastal plain was retained by this large water body, and thus does not reach the coast. In the northwestern coast of the United States and in the North Sea, fossils of terrestrial mammals have also been found in marine environment, and their presence is attributed to sea-level transgression over continental fossiliferous deposits (Whitmore et al., 1967; Cutler, 1998; Van Kolfschoten and Laban, 1995; Mol et al., 2006).

6. Conclusions

The ages between 42 and 38 ka obtained for the fossils from Chuí Creek indicate that this is the period in which this deposit have originated, much younger than previously estimated (Lopes et al., 2001, 2005). These ages also confirm a Lujanian (*sensu* Cione and Tonni, 1995) age for these fossils, except for the specimen MOT0050, whose presence in this outcrop is probably due to the erosion of older deposits, re-worked by the transgression of 123 ka BP. These ages also reinforce the time correlation with the fossiliferous deposits of the Touro Passo Formation, in the Campanha Region, which have been dated between 42 ka and 16 ka (Da Rosa, 2003), and suggest that the carbonate layer on top of the muddy sand facies may be correlated to the last glacial maximum around 17 ka BP. More detailed surveys and fossil collecting in both deposits should allow better evaluation of the paleobiogeography of the extinct fauna, as well as correlation with climate and environmental changes during the Quaternary.

Because the paramagnetic defects on enamel are a product of ionizing radiation from the surrounding sediment, the ages obtained for the fossils from the continental shelf should be considered minimum age estimates of how many years these fossils have been covered by sediments. The wide age range found among these fossils indicates that they come from deposits of different ages that were successively reworked and re-deposited in younger sediments by sea-level oscillations. This process would be analogous to what occurs today on the RSCP, with Pleistocene fossils being exhumed from submarine deposits and concentrated on the coastline together with recent sediments. The ages obtained indicate that the fossiliferous deposits on the continental shelf include fossils of Ensenadan, Bonaeran and Lujanian ages (Fig. 10). As well, the coincidence of the ages with periods of sea-level regression, and the good preservation of many fossils, indicates that the source of these remains are fossiliferous deposits that originated in the emergent portion of the continental shelf during the sea-level lowstands. This is also reinforced by the presence of fossils of terrestrial mammals in deeper areas of the shelf, several kilometers far from the coast (Lopes and Buchmann, 2009), although some fossils (such as the specimen MOT0027) might have been transported by paleo-fluvial systems to the shelf. The presence among the fossils from the continental shelf of the glyptodont Neuryurus rudis and the canid Theriodictis sp. (Rodrigues et al., 2004), which have a biostratigraphic distribution restricted to Ensenadan in the Pampean Reion of Argentina (Cione et al., 1999) might be related to the old ages of the deposits, instead of indicating that these taxa were late survivors in southern Brazil after their disappearance from the Argentinean Pampas. However, the presence of *Lestodon armatus* and *Antifer* sp. among the fossils from Chuí Creek does indicate that these taxa persisted in Brazil much later after their disappearance in the Pampean Region.

The ages obtained by ESR spectroscopy in the mammal teeth from the RSCP contribute to the understanding of the origin of the fossiliferous deposits. While the stratigraphic context of the fossils from the submarine deposits is as yet unknown, these remains now can be put in a chronologic context, thus opening new perspectives for more accurate biostratigraphic and paleoecologic correlations with deposits from Argentina and Uruguay. Moreover, the ages obtained on these teeth can be used to refine the models for the geologic evolution of the RSCP, by providing new information regarding the timing and duration of the sea-level regressive events. It also allows development of studies on the paleoclimatic and paleoenvironmental changes in the area, putting these changes in a timeframe and evaluating its influence on the origin and geologic evolution of the Rio Grande do Sul coastal area.

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