

The Santa Vitória Alloformation: an update on a Pleistocene fossil-rich unit in Southern Brazil

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Abstract

The Santa Vitória Formation is a lithostratigraphic unit known for its fossil assemblage of Pleistocene mammals, established in 1973 from sediments exposed along the banks of Chuí Creek, in the southern coastal plain of the state of Rio Grande do Sul (CPRS), Brazil. The original description was presented in a Masters' dissertation and never formally described in a peer-reviewed publication. Moreover, surveys and fossil collecting efforts developed in the last decade have led to a better understanding of its origin and nature. An updated description of this unit is presented here, which outcrops in areas occupied by barrier-lagoon depositional systems originated by eustatic oscillations. The formation encompasses Middle-Upper Pleistocene fluvial and eolian depositional systems and paleosols formed chiefly of fine to medium quartz sand, with subordinate clay, concentrations of iron and manganese oxides, and caliche nodules of pedogenic origin. It conformably overlies upper shoreface-foreshore marine deposits, and is overlain by loess deposited during the last glacial period. Here is proposed to re-define it as Santa Vitória Alloformation, considering that the use of an allostratigraphic framework to characterize this unit has the practical purpose of grouping depositional systems genetically unrelated to the barrier-lagoon systems.

KEYWORDS: Chuí Creek; coastal plain; Pleistocene; allostratigraphy; depositional systems.

INTRODUCTION

The coastal plain of the state of Rio Grande do Sul (CPRS), as defined by Delaney (1962), is a large geomorphological unit occupying the onshore portion of the Pelotas Basin, the marginal sedimentary basin developed along the southernmost sector of the trailing-edge (passive) Brazilian continental margin, which extends between the states of Santa Catarina and Rio Grande do Sul and reaches up to Cape Polonio in Uruguay. This basin was developed through deposition of sediments eroded from Precambrian and Mesozoic rocks after the opening of the Atlantic Ocean in the Cretaceous (Villwock and Tomazelli 1995, Barboza *et al.* 2008, Dillenburg and Barboza 2014, Rosa *et al.* 2017).

The sedimentary deposits that constitute the CPRS were formally described as lithostratigraphic units by Delaney (1962, 1965), who designed as Graxaim Formation the sediments regarded as of "Tertiary" age, and assigned the Pleistocene marine and Holocene aeolian sediments to the Chuí and Itapoã Formations, respectively. In the 1950s and 1960s, fossils of Pleistocene terrestrial mammals found along the coastline and in sediments exposed on the banks of the Chuí Creek

were described (Souza Cunha 1959, Paula Couto and Souza Cunha 1965). At first, the fossil-bearing sediments were interpreted as belonging to the Graxaim Formation, and regarded as of Pliocene-middle Pleistocene age (Delaney 1965), later regarded as of Pliocene age based on its position overlying Miocene marine deposits (Closs 1970). That formation, however, is not only lithologically distinct from the fossil-bearing units, but also unfossiliferous so far, except for giant vertebrate burrows (Buchmann *et al.* 2009b, Lopes *et al.* 2017). The absence of fossils in the Graxaim Formation led Paula Couto and Souza Cunha (1965) to recognize the fossil-bearing deposits as a distinct unit of Upper Pleistocene age, based on its mammal in fossil assemblage and biostratigraphic correlation with deposits in Argentina. Soliani Jr. (1973) established as "Santa Vitória Formation" the fossil-bearing deposits exposed along the banks of Chuí Creek and presumably overlying the Chuí Formation.

The "Santa Vitória Formation", as originally proposed, is not officially recognized as a formal stratigraphic unit (Figueiredo Filho and Bortoluzzi 1975, Baptista *et al.* 1984, Horbach *et al.* 1986), as it was described in the Masters' dissertation of Soliani Jr. (1973) rather than in peer-reviewed publications, which is a requirement to be accepted as a valid unit according to the Brazilian and International Stratigraphic Codes (Petri *et al.* 1986, Murphy and Salvador 1999). Later, the "Santa Vitória Formation" was regarded as a facies variation of the Chuí Formation, and informally referred to as "Santa Vitória Member" (Jost and Soliani Jr. 1976).

The geological surveys performed in the CPRS from the 1980s onward led to a re-interpretation of the Quaternary deposits, because of problems with the lithostratigraphic-based scheme.

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It became clear that the Pleistocene and Holocene deposits grouped as lithostratigraphic units were in fact chronostratigraphically distinct, rather than representing isochronous deposits. As a result, the lithostratigraphic scheme was mostly replaced by chronocorrelated facies associations grouped into barrier-lagoon depositional systems (Villwock 1984, Villwock *et al.* 1986, Tomazelli and Villwock 2005). This re-definition was based on the concept of depositional systems of Fisher and McGowen (1967), defined as large-scale natural, genetic units comparable to modern depositional systems and recognized by specific criteria (integration of facies) and designated by a genetic term (*e.g.*, lagoon system). In terms of sequence stratigraphy, the barrier-lagoon depositional systems encompass high-frequency (4th order) depositional sequences formed by successive sea-level highstands controlled by Pleistocene to Holocene glacioeustatic oscillations (Rosa *et al.* 2011, 2017).

Studies developed for the last ten years along Chuí Creek, employing stratigraphic surveys, descriptions of outcrops, sedimentology, fossil collecting, and numerical ages from fossils and sediments, resulted in a better understanding of the stratigraphic succession and provided a more precise chronostratigraphic setting for the depositional environments represented along the banks of the creek. These studies have led to the recognition of depositional systems that are not genetically related to the Late Pleistocene (~120 ka) Lagoon System III, and therefore cannot be regarded as facies of that system. This recognition provided the basis for re-establishing the “Santa Vitória Formation” as an allostratigraphic unit encompassing small scale depositional systems developed within the larger barrier-lagoon systems but without direct genetic relationship with the latter.

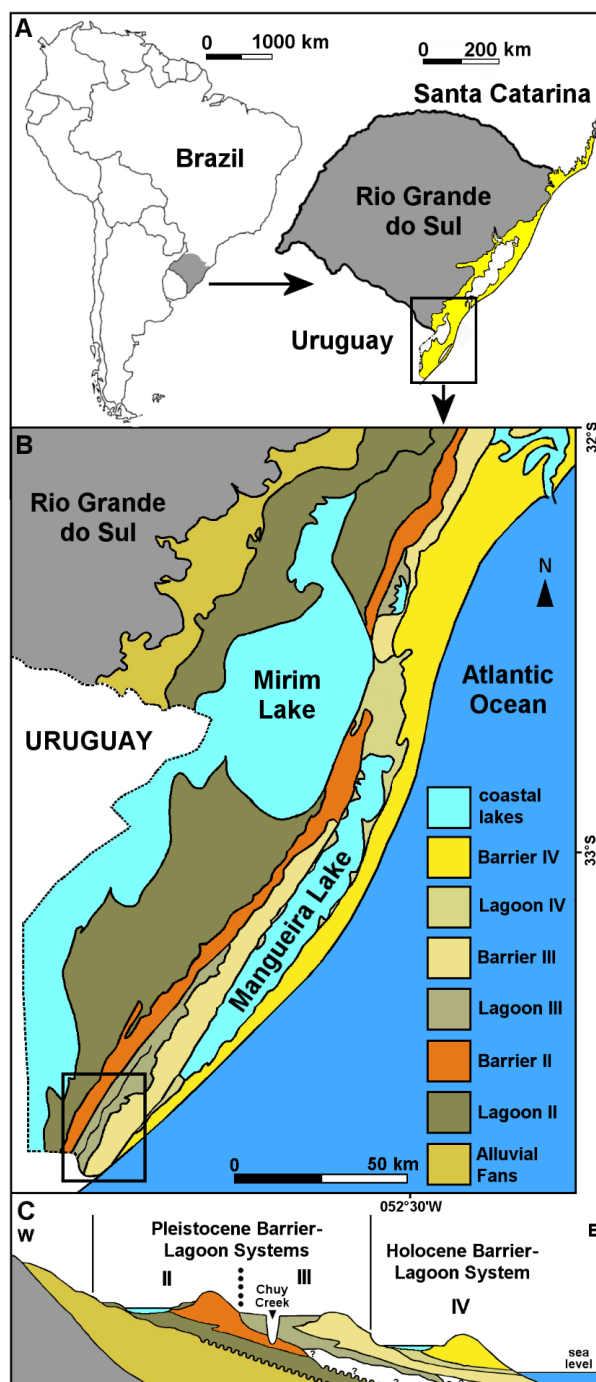
In order to provide an updated characterization of the “Santa Vitória Formation/Member” and to establish it as a formally acceptable stratigraphic unit at the hierarchical level of alloformation, here is presented a detailed description of the physical aspects of that unit, a re-interpretation of its depositional setting, and added new information regarding its origin and spatial relationships.

GEOLOGICAL SETTING

Following the concept of depositional systems, the CPRS, as recognized today, encompasses two large sets of depositional systems developed in the uppermost Pelotas Basin (Fig. 1): the Alluvial Fans System and four Barrier-Lagoon Systems (Villwock and Tomazelli 1995, Buchmann *et al.* 2009a). The Alluvial Fans correspond to the Graxaim Formation and encompass Miocene marine and Pliocene continental beds (Closs 1970), and each barrier-lagoon system consists of a long sandy barrier isolating lagoon, lacustrine or other freshwater environments in the backbarrier lowlands.

Several numerical ages indicate that the Barrier-Lagoon Systems II and III are chronocorrelated to the Pleistocene interglacial marine isotope stages (MIS) 7 and 5, respectively (Buchmann and Tomazelli 2003, Lopes *et al.* 2014a, 2015, 2020c), and the system IV to the Holocene interglacial MIS 1 (Buchmann *et al.* 1998, Caron 2007, Lima *et al.* 2013, Dillenburg *et al.* 2017). The Chuí Formation originally

described by Delaney (1965) encompassed all Pleistocene marine deposits of the CPRS (*e.g.*, Soliani Jr. 1973, Poupeau *et al.* 1988), but now is recognized as the marine deposits of the Barrier System III (Lopes *et al.* 2015). The Barrier-Lagoon System I, found only in the northernmost CPRS, was correlated to the MIS 11 according to oxygen isotope curves (Villwock and Tomazelli 1995), but so far no absolute ages are available. The development of each barrier-lagoon system



mrsll: mean present-day relative sea-level.

Source: modified from Villwock and Tomazelli (1995), Tomazelli and Villwock (2005), and Rosa (2012).

Figure 1. (A) Location of the Pelotas Basin (in yellow) along the southern Brazilian coast. (B) Geomorphology of the southern CPRS, the rectangle indicates the type locality of the unit described here, detailed in Figure 3. (C) West-east transect of the southern coastal plain of Rio Grande do Sul state (CPRS) showing the three barrier-lagoon depositional systems and location of Chuí Creek.

was controlled by a marine transgression integrating cyclic 4th order (~100 kyrs) eustatic oscillations driven mainly by glacial-interglacial cycles (Rosa *et al.* 2017).

The Lagoon Systems II, III, and IV are mostly occupied today by large lagoons and lakes, but in the southern CPRS the Lagoon III occupies the basin developed between the Barriers II and III (Fig. 1). The surface of the Lagoon III is occupied by rice crops, pastures, and marshes, the only perennial fluvial system in this area is the Chuí Creek. Being the only lagoon system that is not covered by large water bodies, and whose stratigraphic succession is exposed along the banks of the creek, the Lagoon III in the southern coastal plain offered a unique opportunity for studying the facies and reconstructing the geological evolution and paleoenvironmental changes in the southern CPRS.

Chuí Creek flows along the flat terrain of the Lagoon System III in a NE-SW direction up to the town of Chuí, where it turns to SE until reaching the Atlantic Ocean. Being isolated from the hinterland after the Barrier II was formed around 220 ka ago, the Lagoon III does not receive fluvial input from rivers flowing from the west since then, and therefore local precipitation is the only source of water. The creek is fed mainly by marshes located some 30 km to the northeast of the town of Santa Vitória do Palmar, besides smaller marshes and ephemeral streams developed during the rainy seasons. The creek was originally a wide and shallow fluvial system draining the surrounding wetlands (Fig. 2A), but in the 1960s it was deepened for agriculture purposes, thus cutting through older deposits and exposing distinct sediment layers on its banks (Fig. 2B), remarkable for the presence of fossils of Pleistocene mammals (Paula Couto and Souza Cunha 1965, Lopes *et al.* 2009).

METHODS

The data presented here include results obtained through surveys in sediments exposed along the banks of the Chuí Creek

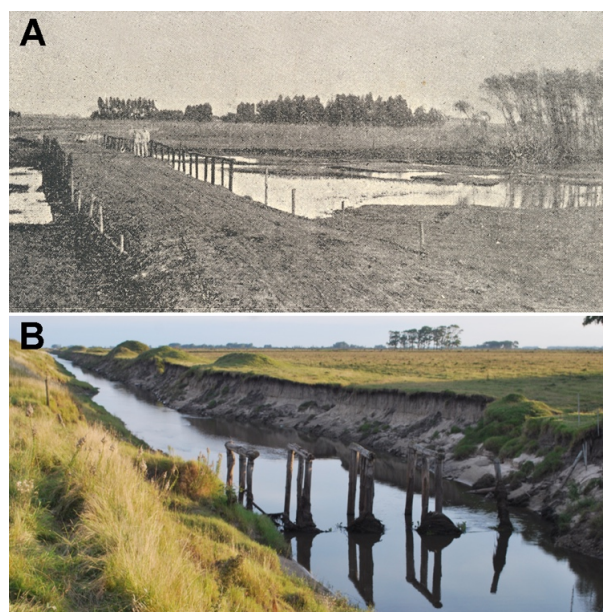


Figure 2. The Chuí Creek in the 1930s (A) before it was further excavated, and (B) today.

and described in the literature (Lopes *et al.* 2001, 2014a, Lopes 2013), complemented by new descriptions of other outcrops and data from boreholes made during the construction of wind farms. The interpretations are based on descriptions of the physical properties of the sediments exposed on the banks, including color, fabric, grain-size, contact relationships and dimensions and fossil content. The colors of the sediments are described according to the Munsell codes; the grain-size variations were determined through sieving and a Microtrac S3500 laser diffraction particle size analyzer at *Universidade Federal do Pampa* (UNIPAMPA). Sedimentological analyses followed the methodology of Folk (1980) and the sediments were classified according to Wentworth (1922) and Folk and Ward (1957). The facies were designed according to Farrell *et al.* (2012), and the architectural elements designations are given in double capital letters following Miall (1985, 2006).

The chronostratigraphic setting of the unit was determined through numerical ages obtained in mammalian fossils using the electron spin resonance (ESR) method, and from sediments using the thermoluminescence (TL) and optically-stimulated luminescence (OSL) methods. Besides those already published (Lopes *et al.* 2010, 2014a, 2014b, 2016c, 2019) two OSL ages were obtained from sediments collected at the outcrop chosen as the stratotype section, being one from a fluvial deposit and the other from a paleosol above. The samples were dated at the *Laboratório de Espectrometria Gama e Luminescência* of *Universidade de São Paulo* using the single aliquot regeneration (SAR) method. The ages are reported here as b2k (before year 2000 AD), according to the Greenland Ice Core Chronology 2005 (GICC, Andersen *et al.* 2006).

RESULTS

Stratotype and distribution

The type locality of the “Santa Vitória Formation” is the flat lowlands of the Lagoon System III between the Pleistocene Barriers II and III in the southern CPRS (Fig. 3A). The formation was described by Soliani Jr. (1973) from an outcrop close to the bridge on the road ERS-833, on the left bank of Chuí Creek, about 5 km south of the town of Santa Vitória do Palmar. The original stratotype is covered by vegetation today, therefore a new one was assigned for the Santa Vitória Alloformation (SVA), located across the creek right in front of the original stratotype (Fig. 3A), about 80 meters southwest of the bridge at the UTM coordinates 22H 0282777E by 6280614S (Fig. 3B). The SVA outcrops along the banks for some 20 km, usually exposed above the creek bed, but occasionally covered by water during floods. The sediment layers exposed along Chuí Creek gently dip toward the south, and close to the mouth of the creek the formation is covered by estuarine sediments deposited during the Holocene marine highstand of 5-6 ka b2k (Caron 2007). The outcrops along the banks of the creek and boreholes made in the Lagoon System III during the installation of wind farms show that the SVA is bounded below by marine deposits interpreted as marine facies of Barrier II (Rosa 2012).

The present distribution of the SVA is restricted to the Lagoon System III, but in an outcrop on the southeastern bank of Mirim Lake (ML-01, Fig. 3A) about 11 km to the west of Chuí Creek a fossil-bearing layer of muddy sand overlain by caliche nodules exposed along an irrigation channel was correlated to the SVA based on the presence of a similar paleomastofauna and comparable ESR and OSL ages

(Lopes *et al.* 2020a). Sedimentary successions obtained in boreholes made to the east of Chuí Creek during the installation of a wind farm show that recognition in subsurface of deposits correlatable to the SVA is difficult based on lithology alone. Nevertheless, these probably extended farther to the east but were reworked in the paleo-lagoon developed landward of the Barrier III in response to the sea-level highstand of

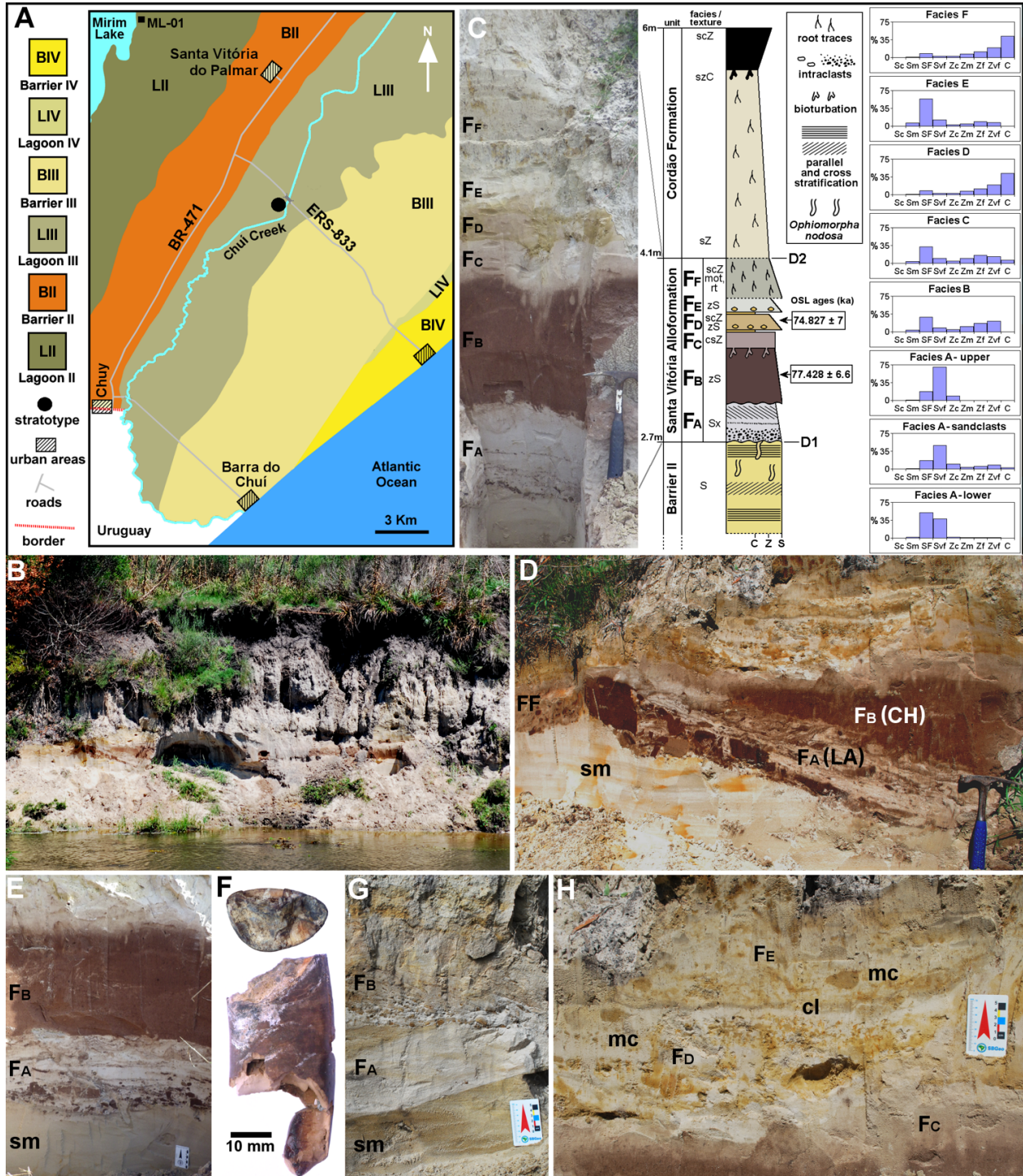


Figure 3. (A) Geomorphological map of the southernmost coastal plain of the state of Rio Grande do Sul (CPRS) showing the type locality of the Santa Vitória Alloformation (SVA); the outcrop ML-01 discussed in the text is also indicated. (B) The stratotype on the right bank as seen from the bridge over the creek. (C) Stratigraphic succession, interpretation, and grain-size variations observed at the stratotype (D1 and D2: bounding discontinuities). (D) Detail of the SVA on top of the shallow marine (sm) deposits, with the floodplain (FF) and lateral accretion (LA) elements of Facies A (F_A), and channel (CH) element of Facies B (F_B) indicated. (E) Sandclasts at the base of Facies A. (F) Fossil tooth of a mylodontid giant sloth from Facies B. (G) Detail of the opposite end (relative to the Figure D) of the base of the SVA, showing the FF element of Facies A directly on top of CH element of Facies B. (H) Cut-and-fill structure associated with Facies D and E, with mudclasts (mc) and a clay lamina (cl) between both (each division of the scale bar = 10 mm).

about 120 ka b2k (MIS 5e) (Bettinelli *et al.* 2018). Some of the ages obtained in mammalian fossils from deposits submerged on the continental shelf are similar to ages in fossils and sediments of the SVA (see below), indicating that fossil-bearing deposits correlatable to the SVA reached > 10 km farther to the east during the sea-level lowstand between the formation of the Barrier-Lagoon Systems II and III.

Hierarchy and name

According to the North American Stratigraphic Code (NACSN 1983, 2005) allostratigraphic units are defined by their bounding discontinuities (lithologic contrasts), which consist of any mappable lithologic contact representing time-significant surfaces. Although the discontinuities are generally indicated by time-significant hiatuses or erosive episodes (Salvador 1987), boundaries between allostratigraphic units can be of any type of stratigraphic contacts with or without hiatuses (unconformities, diastems or conformities) (Catuneanu 2006).

The SVA is herein defined by the sediment package bounded by two discontinuities: the lower one (D1) marking the transition from marine (shoreface-foreshore) to terrestrial (eolian, fluvial) depositional environments, corresponding to the sub-aerial unconformity developed during the eustatic fall following the sea-level highstand that formed Barrier II. The upper discontinuity (D2) is characterized by the change from the different facies of the SVA to the eolian (loess) deposits of the overlying Cordão Formation (Fig. 3C). Both discontinuities are conformable, *i.e.*, exhibit changes in sedimentation without major hiatuses or erosive surfaces, except in places where fluvial systems eroded the underlying marine deposits (see Description below), nevertheless they are continuously exposed along the banks of Chuí Creek for > 10 kilometers and mark important changes in sedimentation; therefore, they may be useful for regional-scale correlations across the coastal plain, and may even have chronostratigraphic utility, considering that the discontinuities can be time-significant (Salvador 1987).

Although the Brazilian stratigraphic code does not specifically address allostratigraphic units, the procedure is the same for the definition of lithostratigraphic units (NACSN 1983). The SVA meets the criteria established by the Brazilian and North American stratigraphic codes for description of lithostratigraphic units, including the traceable sedimentary discontinuities in relation to the adjacent units, lateral continuity, and mappability in the 1:25,000 scale (NACSN 1983, 2005, Petri *et al.* 1986, Murphy and Salvador 1999). The name Santa Vitória comes from the nearby town located about 5 km to the north of the neostatotype section. The different facies of this alloformation are composed essentially of very fine to medium siliciclastic sand with subordinate silt and clay, deposited and re-worked in fluvial and eolian depositional systems, and modified by weathering, thus forming incipient paleosols.

Description

At the neostatotype section, the bank reaches about 6 meters above the creek bed, and being on the outer side of a meander, it is subject today to erosive processes that expose the entire stratigraphic succession (Fig. 3C), as follows.

Marine deposits (Barrier II)

The lowermost ~2.7 meters of the succession rising above the creek bed consist of a layer of clean (up to ~3% mud), moderately well-sorted fine sand (S), interpreted as the uppermost shallow marine deposits (sm) related to the highstand systems tract (HST) of Barrier II (Rosa 2012). It was deposited in a shoreface-foreshore setting, as indicated by molluscan and microfossil assemblages, the presence of parallel and low-angle cross bedding, and by ichnofossils *Ophiomorpha nodosa* and *Rosselia* sp. (Lopes *et al.* 2014a). This sediment is essentially quartz sand with heavy minerals concentrated along bedding planes, and usually exhibits reddish color (10YR 5/4), indicating iron oxide precipitation under subaerial environment. The portions of this facies that remain at or below the modern water level exhibit greenish gray color (5GY 4/1). The discontinuity between marine and terrestrial facies is related to the regressive phase following the sea-level highstand (Rosa 2012).

Santa Vitória Alloformation

The boundary between the SVA and the underlying shallow marine deposits is conformable (with exceptions as described below) and characterized by the discontinuity between the latter and the continental deposits above. The sedimentary features of the SVA allowed the recognition of fluvial and eolian depositional systems and associated paleosols. At the outcrop where the stratotype section is exposed the SVA reaches some 1.4 meter in thickness and the physical features allowed distinguishing a succession of six distinct facies (Fig. 3B).

- *Facies A*: is a ~5 meter-across, 30 centimeter-thick, white (2.5Y 8/1) well-sorted fine to very fine sand (Sx). The lower contact is erosive, thus it unconformably overlies the shallow marine (sm) deposits below. This facies exhibits channel (CH) and lateral accretion (LA) architectural elements (Fig. 3D), the latter indicating lateral channel migration in a meandering fluvial system. The centimetric dark brown silty sandclasts (zS) with plant remains found at the base and middle of this facies (Fig. 3E) seem to be remnants of a pre-existing fluvial deposit that was eroded and reworked by the fluvial system that deposited Facies A. The primary sedimentary structures include sets of cross lamina that dip in opposite directions across the outcrop, besides sub-horizontal laminae. Thin (< 1 cm) concentrations of opaque dark heavy minerals along the bedding planes were also observed;
- *Facies B*: This is a ~5 meter-across and up to 40 centimeter-thick lens-shaped dark brown (10R 2.5/2), poorly sorted massive fine silty sand (zS), interpreted as a fluvial channel filled with organic matter-rich sediments (Fig. 3D) and containing fossils of mammals (Fig. 3F). This facies is bounded laterally by floodplain facies (FF, Fig. 3D) and paleosols. In the northern end of the outcrop the FF element directly overlies Facies A (Fig. 3G). Facies B seems to represent a change in fluvial dynamics relative to the underlying Facies A, *i.e.*, from fast-moving to slow-moving currents, which allowed for the accumulation of organic matter, thus it is probably a channel that became filled, or an oxbow lake formed by channel abandonment, also

suggested by its upper sharp boundary bioturbated by plants. The OSL obtained in this facies indicates deposition around 77.4 ± 6.6 ka b2k (Fig. 3C);

- Facies C: This is a ~15 centimeter-thick layer of pinkish light gray (2.SY 7/1) massive clayey sandy silt (csZ). Its lower contact is gradual but bioturbated, and its upper boundary is sharp and characterized by the presence of clay and iron oxide as the result of weathering. This facies is interpreted as fine sediments deposited during the final stages of infilling of the Facies B channel, and was partially eroded by a shallow stream developed above (Fig. 3H);
- Facies D: This is a massive, poorly sorted fine zS to sandy clayey silt (scZ) layer, yellow-colored (2.SY 6/6) due to the presence of iron oxide and with high clay content (Fig. 3C), thus interpreted as a paleosol. It measures up to ~15 cm in thickness, and exhibits a lateral variation in the form of a cut-and-fill structure with erosive base, iron oxide-rich mudclasts (mc) and a ~1 centimeter-thick clay lamina (cl) at the top (Fig. 3H), indicating a shallow ephemeral stream that reworked part of the underlying Facies C. The OSL age obtained in the paleosol indicates that it was deposited around 74.8 ± 7 ka b2k (Fig. 3C). Its upper contact is sharp and marked by the clay lamina (Fig. 3H);
- Facies E: Consists of a massive fine, pale brown (2.SY 8/2) moderately well sorted fine zS layer measuring up to 10 cm in thickness. Its sandier content and absence of clay (Fig. 3C) suggest deposition by eolian processes. It also exhibits a cut-and-fill structure with iron-rich mudclasts (Fig. 3H) as in the Facies D below, which indicate re-working and partial erosion of wind-blown sediments by an ephemeral stream. Its upper contact is gradual;
- Facies F: This is a ~35 centimeter-thick massive poorly sorted sandy clayey silt, mottled and with root traces (scZmot, rt). Its predominant color is light brownish gray (2.SY 6/2), and the mottling by concentrations of yellowish iron oxide (2.SY 6/6), subspherical iron-manganese masses, and plant roots, indicate a paleosol developed on eolian sediments deposited on top of Facies E. The contact of this facies with the overlying Cordão Formation is conformable and characterized by an increase in the proportion of silt related to the deposition of loess, therefore marking the upper bounding discontinuity of the SVA.

Loess deposits (Cordão Formation)

The Cordão Formation consists of loess deposited during the most recent stadial (MIS 2), between ~30 and 10 ka b2k (Lopes *et al.* 2016c). It was originally regarded as a pedostratigraphic unit named “Caliche Cordão” by Delaney (1965) due to the presence of abundant caliche nodules in some areas of the southern CPRS, later designed as Cordão Soil Unit (Jost and Soliani Jr. 1976). The loess is mostly massive, and at the

neostatotype section exhibits plant root traces and iron-manganese masses and nodules indicating oscillations of the water table. It grades from sZ at the base to a organic matter-rich dark brown sandy silty clay (szC) and sandy clayey silt (scZ) deposited at its uppermost ~0.4 meter in wetland environments, as indicated by freshwater mussels and diatoms (Lopes *et al.* 2016b).

Age

Following the interpretation of Paula Couto and Souza Cunha (1965), Soliani Jr. (1973) attributed an Upper Pleistocene age to the Santa Vitória Formation based on the biostratigraphic correlation of the mammalian fossil assemblage with the Lujanian Land-mammal Age of the Buenos Aires Province of Argentina (*sensu* Pascual *et al.* 1966). That author also suggested an age of about 80 ka, putting the formation in chronostratigraphic correlation with the Piso Pampeano Superior (*sensu* Ameghino 1889). Later interpretations have placed the onset of the deposition of the unit around 120 ka ago (*e.g.* Lopes *et al.* 2009), based on the estimated age of the Barrier-Lagoon System III from correlation with oxygen isotope curves (Villwock and Tomazelli 1995). The absolute ages obtained in later years, however, have shown that the deposition of the SVA in fact began just after the sea-level highstand that originated Barrier II, thus predating the Barrier-Lagoon System III by about 100 ka, and led to a re-interpretation of the bio- and chronostratigraphic settings of the SVA.

Direct numerical ages were obtained from sediments of the SVA using TL and OSL techniques. One eolian deposit at the base of the formation was dated as of 214 ± 21 ka, whereas marine sediments collected 1 meter below yielded an age of ~235 ka. One fluvial deposit at the base of the unit, in erosive contact with the marine deposits provided an age of 173 ± 21 ka, whereas a sediment sample obtained in a paleosol developed on eolian sediments conformably overlying the marine deposits was dated as of 132 ± 18 ka (Lopes *et al.* 2014a). Another OSL age of 37.9 ± 5.08 ka was obtained in a fossil-bearing channel deposit located about 1 km to the north of the neostatotype (Lopes *et al.* 2019). The two sediment samples obtained at the stratotype provided ages of 77.4 ± 6.6 ka from the fluvial Facies B and 74.8 ± 7 ka from Facies D (Tab. 1, Fig. 3B).

The ESR ages from fossil teeth obtained so far are coherent with the luminescence results, and range from ~226 to 33 ka (Lopes *et al.* 2010, 2014b). These ages put the mammalian assemblage in chronocorrelation with deposits containing fossils of the Bonaeran and Lujanian faunas (*sensu* Cione and Tonni 1995, 1999) of the Buenos Aires Province (Fig. 4). In biostratigraphic terms, those faunas correspond to the biozones of *Megatherium americanum* and *Equus (Amerhippus) neogeus*, respectively (Cione and Tonni 1999). One fossil tooth of *Toxodon* found *in situ* at the base of an outcrop (ML-01 in Figure 3A) along an irrigation channel excavated on the southeastern shore of

Table 1. OSL ages according to the central age model (CAM) obtained in sediments from the stratotype section of the Santa Vitória Alloformation.

Sample	Dose rate (Gy/ka)	Dose (Gy)	O.D. (%)	Age (years)
Facies B	0.73 ± 0.06	56.9 ± 2.0	15.3	$77,428 \pm 6,600$
Facies C	0.82 ± 0.07	61.1 ± 2.8	21.8	$74,878 \pm 7,024$

Mirim Lake was dated as of 68 ± 13 ka, and the quartz grains in one caliche nodule above this fossil were dated by OSL as 32 ± 5.1 ka (Lopes *et al.* 2020a), thus chronocorrelating this deposit to the SVA. Three fossil teeth from deposits of the continental shelf provided ESR ages of ~ 146 , ~ 165 and ~ 207 ka (Lopes *et al.* 2010). These ages correspond to the late interglacial stage MIS 7 and the glacial MIS 6, when large areas of the continental shelf were exposed due to lower sea-level and occupied by terrestrial environments and a diverse mammalian fauna (Lopes and Buchmann 2011). The similar fossils and ages indicate that deposits chronocorrelated to the SVA extended to the east up to the subaerially-exposed shelf.

Two sediment samples from the overlying Cordão Formation provided OSL ages of 27.1 and 26 ka (Lopes *et al.* 2016c). These results bracket the deposition of the SVA to the Middle (Chibanian Stage/Age) and Upper Pleistocene, between ~ 220 and ~ 30 ka b2k, from the interglacial stage MIS 7 and the interstadial MIS 3, encompassing the glacial period MIS 6, the interglacial MIS 5 and the stadial MIS 4 (Fig. 4). The ages and mammalian fossil assemblage allow correlating the SVA

with the Touro Passo Formation of western Rio Grande do Sul (Kerber *et al.* 2011, Lopes 2013, Lopes *et al.* 2020b) and to several fossil-bearing units of Uruguay and Argentina (Tonni *et al.* 2003, Ferrero and Noriega 2009, Toledo 2011, Zurita *et al.* 2014, Ubilla and Martinez 2016, Ferrero *et al.* 2017). Such correlations allow comparing faunas and depositional environments and may be helpful to assess the effects of Pleistocene climate changes on the biota and physical environment across the region.

Physical features of the SVA

The stratigraphic succession exposed along the banks of Chuí Creek shows that the deposition of the SVA began during the sea-level fall after the highstand that deposited the marine sediments below. The SVA is formed essentially of very fine to medium sand, but mostly fine, eroded and transported from the subaerial portion of Barrier II as well as from Barrier III after it was formed around 125 ka ago. The facies variations indicate deposition in fluvial and eolian depositional systems, and postdepositional modification as paleosols.

Washout deposits

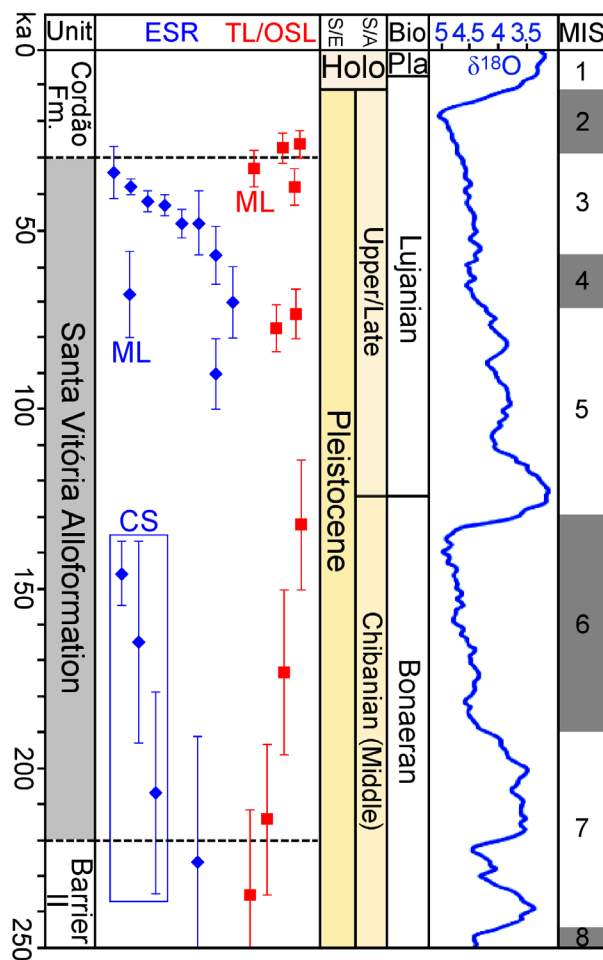
Washouts are shallow ephemeral streams formed on the shoreline during rainy seasons by water accumulated behind the frontal dunes, that discharge onto the foreshore usually through narrow channels, but wider channels measuring several meters across have been observed. These streams transfer considerable amounts of sediment from the dunes to the foreshore (Silva *et al.* 2003, Figueiredo and Calliari 2004). The deposits interpreted as washouts consist of layers of massive or laminated sand, without ichnofossils, pedogenic or erosive features, accumulated at the interface between the marine deposits and the overlying SVA. They are formed of the same fine sand as the foreshore-foredune deposits, therefore difficult to recognize, but the presence of rounded mudclasts (Fig. 5A) and lamination point to deposition by flowing water. The absence of major breaks in sedimentation or hiatuses indicates continuous deposition, marking a gradual transition from shallow marine (upper shoreface-foreshore), to beach and finally continental facies, related to coastal progradation (Rosa 2012).

Eolian systems

The eolian depositional systems include small dunes and sand sheets, massive or with low-angle parallel stratification, that conformably overlie marine and fluvial deposits (Fig. 5B). The postdepositional weathering and pedogenesis masked most of the sedimentary structures, but in some cases these are highlighted due to the concentration of iron oxides along the bedding planes. Several highly poorly-preserved fossils with extensive surface flaking and cracking (Lopes and Ferigolo 2015) preserved in sediments with root traces and iron-manganese masses indicate exposure to subaerial weathering followed by burial by wind-blown sand.

Paleosols

These are not well-developed soils, *i.e.*, with distinct horizons, but the term is employed here to describe sandy



S/E: Series/Epoch; S/A: Stage/Age; Bio: biostratigraphic unit (Pla = Platan). **Figure 4.** Temporal range of the Santa Vitória Alloformation (SVA) based on ESR and luminescence datings, including the chronocorrelated fossils from the continental shelf (CS) and from the outcrop on the shore of Mirim Lake (ML). Glacial/stadial (shaded) and interglacial/interstadial periods represented by marine isotope stages (MIS) and $\delta^{18}O$ curve from Lisiecki and Raymo (2005).

deposits that had its physical aspects modified by weathering and plant growth. The development of paleosols apparently began as the sea-level receded following the sea-level highstand, thus exposing the uppermost marine sediments to subaerial weathering. The most conspicuous result is the concentration of iron oxides along the bedding planes and around ichnofossils. Other paleosols

developed on eolian sediments (Fig. 5B), on top of buried fluvial channels (see Figure 3B), and on interfluvies. The features resulting of weathering and incipient pedogenesis include the presence of plant root traces and accumulations of secondary minerals (clay, iron and manganese oxides), usually concentrated in discrete horizons but also dispersed within the layers.

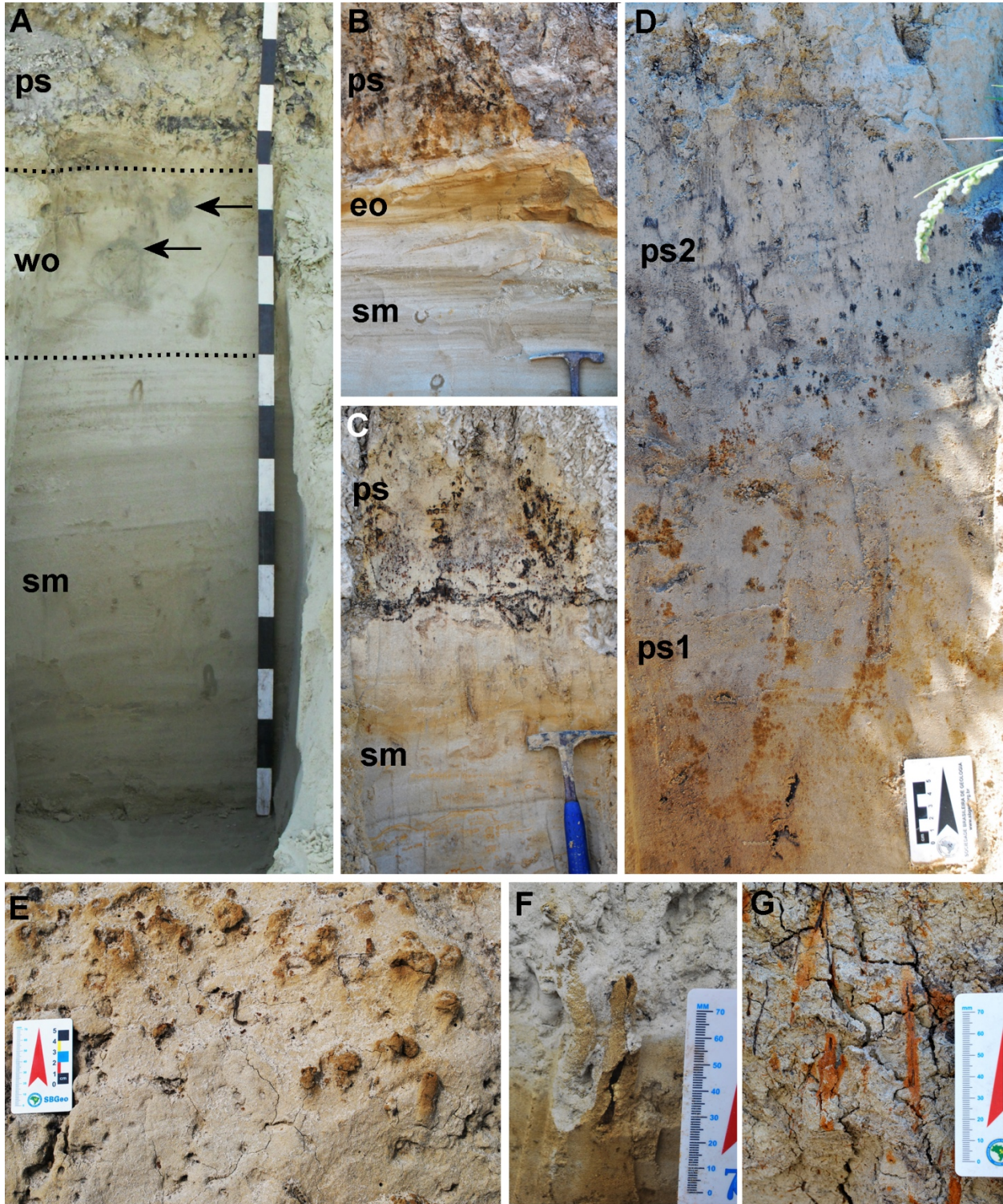


Figure 5. (A) Washout (wo) deposit interbedded between the shallow marine deposits (sm) and a paleosol (ps) of the Santa Vitória Alloformation (SVA), with mudclasts indicated by arrows (each division of the scale = 10 cm). (B) Eolian deposit (eo) stained by iron oxide, between the marine deposits and paleosols. (C) Iron oxide concentrated in the upper marine deposits (BII) and dark Fe/Mn masses in a paleosol at the base of the SVA. (D) Gradual transition from an orange paleosol with FeO masses (ps1) to a grayish one (ps2) with Fe/Mn masses. (E) Iron oxide nodules in a paleosol. (F) Root moulds formed by clay. (G) Root traces surrounded by halos of iron oxide (each division of the scale bar = 10 mm, except in A).

The clay was probably formed as the result of weathering of feldspar and mica grains in the sand, as observed in the subaerial portion of the Pleistocene barriers (Birkeland 1992, Villwock and Tomazelli 1995). The amount of clay forming the sedimentary matrix infilling spaces between sand grains in the SVA reaches up to about 20%. In addition to being dispersed between sand grains, clay is also found concentrated in discrete centimeter-thick laminae (see Figure 3H) and as rounded mudclasts re-worked in fluvial environment.

Some weathered horizons usually contain iron-manganese (Fe/Mn) masses, redoximorphic features developed in A and B horizons of waterlogged (poorly drained) soils subject to oscillations of the water table (Birkeland 1974, Winters 1938, Drosdoff and Nikiforoff 1940, Evans 1992, D'Amore *et al.* 2004, Vepraskas 2015). The masses consist of grains coated with black-reddish Fe/Mn oxides, forming subspherical aggregates dispersed within the matrix but also forming discrete sub-horizontal concentrations (Fig. 5C). Crusts of sand grains cemented by Fe/Mn oxides were found in some mammalian fossils. The palaeosols exhibit yellow-orange hue, thus indicating concentration of iron oxides in well-drained sediments. The color suggests the presence of goethite, which is formed in general by weathering under cool and humid climate (Davey *et al.* 1975, Kämpf and Schwertmann 1983, Schwertmann 1988, 1993). The vertical transition from orange to gray color observed in some paleosols (Fig. 5D) indicate change from good to poor drainage conditions. Iron oxide concentrations occur mostly as coatings on sand grains, but well-developed nodules also occur (Fig. 5E). These can evolve from Fe/Mn masses after 3 to 4 thousand years of continuous pedogenesis (Golden *et al.* 1988, Stiles *et al.* 2001). In mammalian fossils, FeO is also precipitated as surface crusts or incorporated during diagenesis, staining the bones in pinkish hues (Lopes and Ferigolo 2015). Although organic-rich A horizons have not been observed, plant remains occur as moulds formed by precipitation of clay (Fig. 5F) or iron oxide (Fig. 5G) around the roots.

Along some portions of the banks of Chuí Creek, paleosols exhibit carbonate accumulations named "Caliche Cordão" by Delaney (1965), forming two petrocalcic horizons (Fig. 6A). The lower one (c1), within the SVA, consists of vertical rhizocretions (*sensu* Klappa 1980) formed by carbonate precipitated around plant roots, whereas the upper (c2) occurs between the upper SVA and the lower half of the Cordão Formation, and includes rhizocretions but also irregular nodules and subspherical concretions (Lopes *et al.* 2016a).

Fluvial systems

The fluvial systems of the SVA, including small ephemeral streams, are recognized mostly by fossil-bearing channel elements (CH) and cut-and-fill structures, although floodplain and lateral accretion elements (see Figure 3D) also occur. CH elements are lens-shaped or tabular deposits exhibiting erosive base, usually with paleosols developed on top of them, although stacked channels have been observed (see below). The flat, subhorizontal terrain, the unconsolidated sediments along which the channels flowed, and the low thickness of the deposits (< 50 cm) imply that the streams were shallow, probably

meandering-braided and unconfined, subject to variable discharge that promoted deposition of high amounts of mixed bed- (vertebrate fossils) and suspended loads (fine sand and mud) (Schumm 1981, Behrensmeier and Hook 1992, Miall 2006, Alekseevskiy *et al.* 2008). Most channel deposits are massive, but others exhibit horizontal parallel stratification, indicating deposition by low-velocity currents (Picard and High Jr. 1973). On the other hand, the presence of re-worked fossils and rounded centimetric mudclasts preserved in floodplain and CH elements indicates conditions of strong flow, possibly related to periodical floods (Karcz 1969, Picard and High Jr. 1973). The absence of deeper channels in the studied outcrops suggests that incisions (degradation) related to regional base level change driven by sea-level lowstands were compensated by lateral migration of the channels (meandering) and the low gradient of the coastal plain (Schumm 1993).

Since these deposits are exposed along the banks and only visible in 2-D, it is difficult to assess features such as channel width and sinuosity, but the physical features allow making some inferences and identifying at least two types of channels so far:

- Type 1: Tabular to lens-shaped channels measuring 3 to 5 meters in length and up to 0.4 meter in thickness, filled with massive or stratified muddy sand and often exhibiting clay lamina or rounded mudclasts. The reworked fossils and sand infilling suggest episodic deposition under relatively high discharge, similar to the observed today in shallow ephemeral streams formed on the beaches of the CPRS during rainy seasons. Due to postdepositional weathering, these deposits may be difficult to distinguish from the surrounding paleosols, being more evident by the erosive lower contact and presence of rounded mudclasts and fossils (Fig. 6B). They usually exhibit redoximorphic features (iron-manganese masses) indicating poor drainage conditions, but also exhibit concentrations of yellow-orange iron oxides precipitated under drier conditions, thus pointing to alternating wet-dry conditions. As in the stratotype of the SVA (Facies A and B, Fig. 3), superimposed fluvial deposits with different physical aspects are observed in other outcrops. In the example shown in Figure 6C, the lower deposit (CH1) is characterized by grey muddy sand with spherical Fe/Mn masses and FeO-rich levels that suggest seasonal variations of discharge, the layer of sand cemented by FeO at its top that indicates weathering and incipient soil formation related to cessation of water flow. The upper deposit (CH2) is separated from CH1 by an erosive surface, and is filled with laminated white sand with mud concentrated along the bedding planes and also as centimetric mudclasts at the base, reworked from the top of CH1;
- Type 2: Consist of 3- to 5-meter-long and 0.3-0.4-meter-thick deposits, filled with organic rich, dark brown and massive fine and very fine silty sand with small amounts of clay. This type of channel, well-represented in the stratotype section (see Figure 3), contains disarticulated, fragmented and isolated mammalian fossils, and mudclasts (Fig. 6D), which indicate transportation and deposition by flowing water. The organic matter, on the other hand, indicates

accumulation in low-energy setting. This combination of features is similar to oxbow lakes, formed by cutoff due to channel meandering (Miall 2006). The channels exhibit erosive base, cutting directly into the marine sediments below (Fig. 6E) or in preexisting fluvial deposits (as shown in the Figures 3B and 6C). Some channels grade laterally to ~10-20-centimeter-thick deposits characterized by weathered, massive or laminated sandy deposits with reworked

mudclasts and organic-rich sand (Fig. 6F), interpreted as FF elements. A similar organic-rich deposit (Fig. 6G) consists of fossil-bearing tabular-shaped, ≥ 10 meters wide and up to 0.3-0.4-meter-thick channels separated by a sand bar (SB), suggesting deposition in a fluvial system with multiple channels and high sediment load (Leopold and Wolman 1957, Miall 2006). Possible modern analogs are the wide, shallow meandering streams with several channels that cut

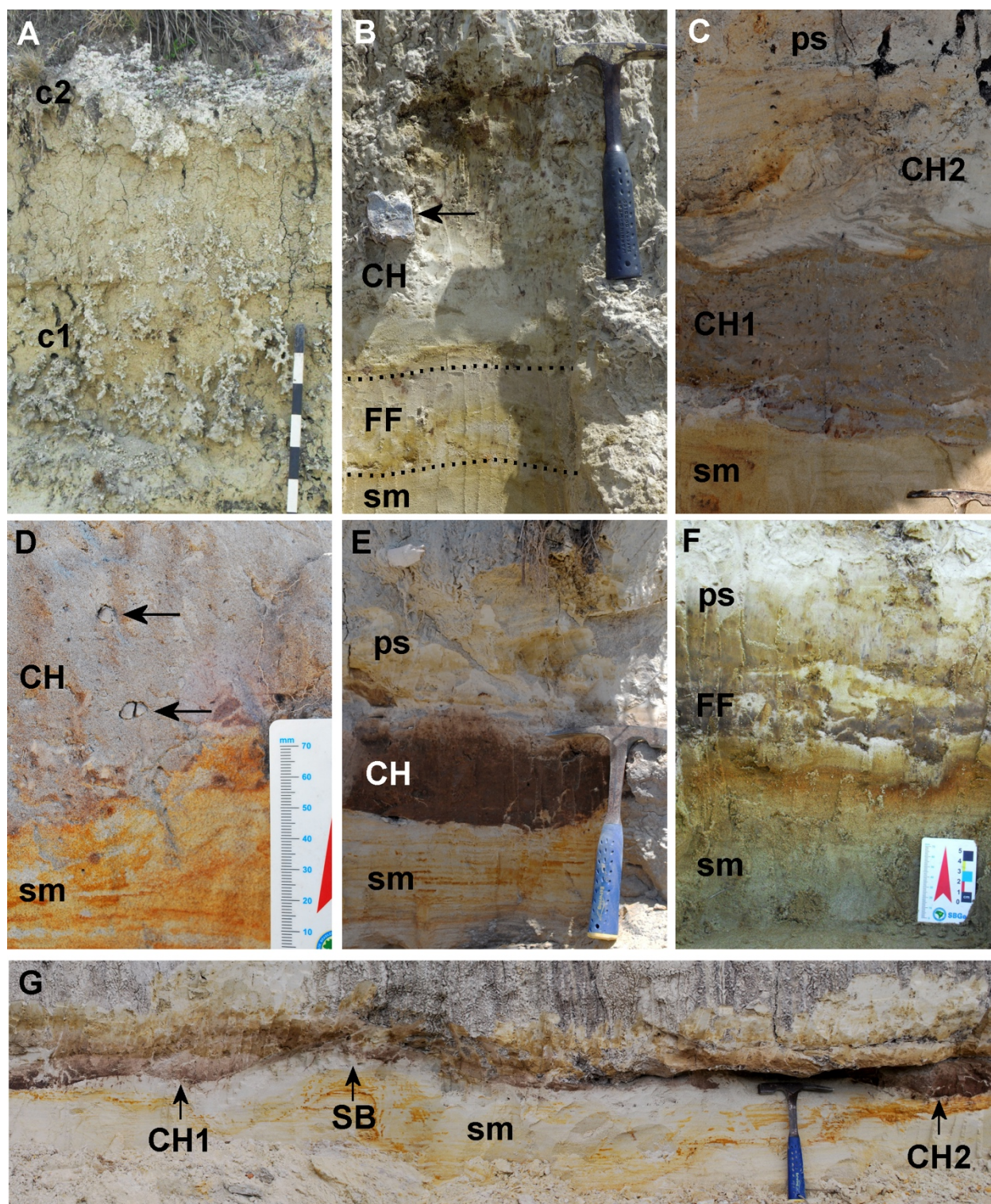


Figure 6. (A) Petrocalcic horizons (c1 and c2) developed in the Santa Vitória Alloformation (SVA) (each division of the scale = 10 cm). (B) Fluvial deposit (CH) overlying a floodplain (FF) facies, with one vertebrate fossil indicated by the arrow. (C) Two superimposed fluvial deposits (CH1 and CH2). (D) Channel element with mudclasts indicated by arrows. (E) Channel element cutting into the marine sediments and overlain by a paleosol. (F) Floodplain element (FF) interbedded between the marine deposits and a paleosol. (G) Two channel elements (CH1 and CH2) divided by a sand bar (SB) (each division of the scale bar = 10 mm, except in A).

across the front dunes up to the shoreline (Fig. 7A) along the beaches of the CPRS during rainy seasons. On the other hand, the organic matter indicates that the Type 2 channels became filled with organic-rich sediments due to reduced flow conditions and development of marshlands in its surroundings. One fossil of a semi-aquatic rodent, *Holochilus brasiliensis* (Brazilian marsh rat) found in one of these deposits (CH2 in Figure 6D), indicates perennial water bodies with abundant vegetation (Kerber *et al.* 2012), similar to the marshes found in lowland areas of the CPRS today (*banhados*, *sensu* Saint-Hilaire 2002). The yellow muddy

layer on top of these channels, also observed in other outcrops, suggests that they became inactive and were subject to subaerial weathering and pedogenesis.

The presence of sediments deposited in fluvial settings at different times (173, 77.4, and 37.9 ka), exhibiting physical and textural differences, stacked fluvial deposits, with paleosols or eolian sediments on top, indicates periods of increased fluvial activity intercalated with periods of decreased flow. Considering that the formation of Barrier II cut all fluvial discharge to areas seaward of it, the fluvial systems of the

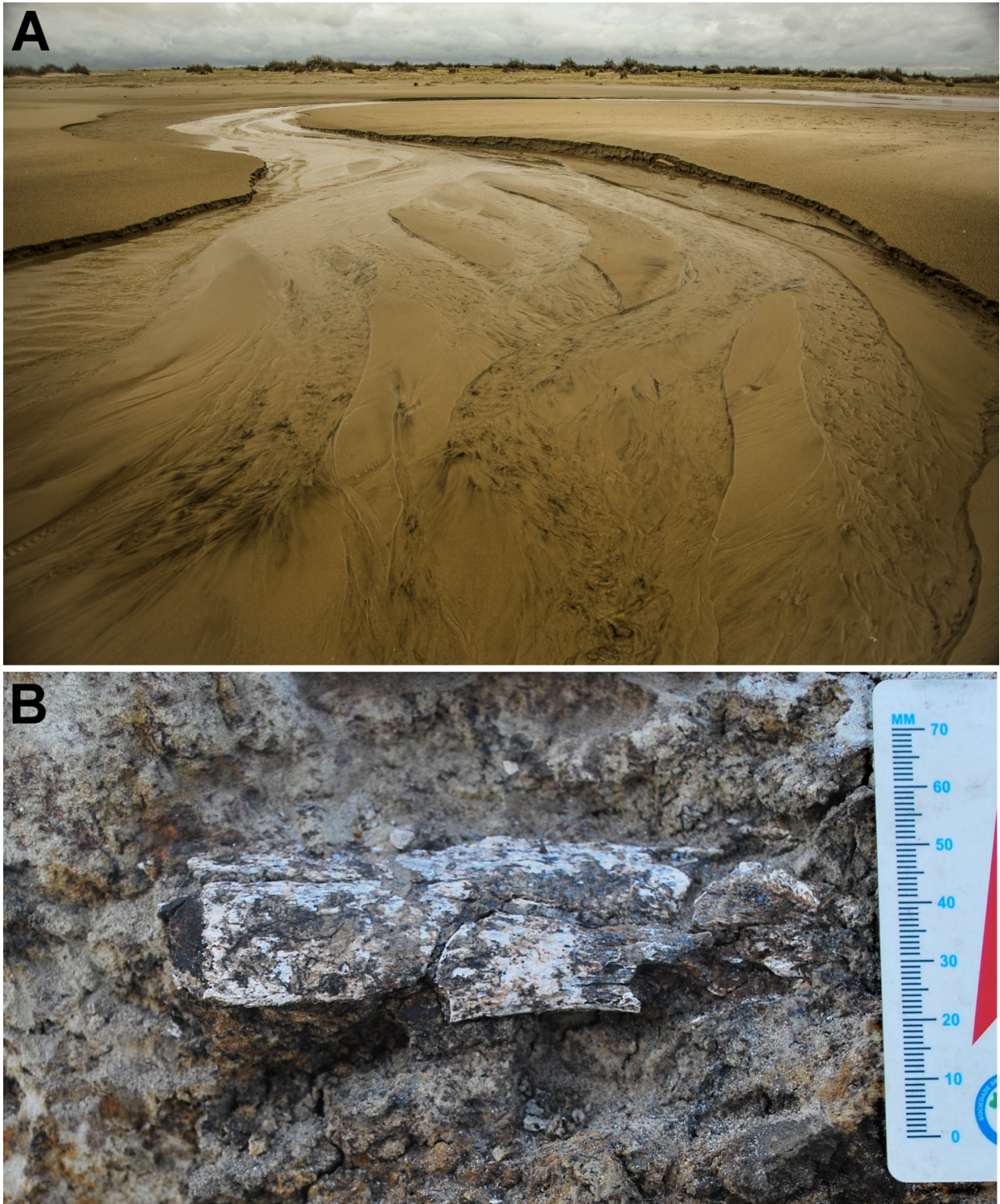


Figure 7. (A) Ephemeral stream crossing the modern shoreline. (B) Highly weathered vertebrate fossil in a paleosol of the SVF.

SVA can be regarded as ephemeral streams fed by rainfall; therefore, the variations of fluvial discharge represented by the sedimentary records were controlled by climate-driven alternating wet and dry phases.

Fossil content

Although fossils are not a criterion for the definition of litho- and allostratigraphic units (Salvador 1987), the SVA is remarkable from the paleontological standpoint due to the presence of a diverse fossil assemblage, the Chuí Creek Local Fauna

(Lopes *et al.* 2020a), consisted mostly of mammals (Tab. 2). Except for a few remains found in the overlying the Cordão Formation (CF) (Lopes *et al.* 2016c), all fossils found *in situ* along the banks of Chuí Creek come from the SVA (Soliani Jr. and Jost 1975, Oliveira 1992, Lopes 2013, Lopes *et al.* 2020b), and a few species were identified from fossils re-worked by erosion, therefore lack precise stratigraphic context (Tab. 2). The assemblage consists largely of extinct species, but fossils of some species that are still living today have also been found (Pereira *et al.* 2012, Kerber *et al.* 2012). The mammalian fauna of the SVA is

Table 2. Vertebrate taxa of the Chuí Creek Local Fauna (Oliveira 1992, Lopes 2013, Lopes *et al.* 2020b). Most specimens were excavated from the Santa Vitória Alloformation, other fossils found without precise stratigraphic provenance (re-worked material) are marked with the (?).

Group		Taxon			
Actinopterygii	Siluriformes	Pimelodidae	cf. <i>Pimelodus</i> / <i>Parapimelodus</i>		
Aves	Ciconiiformes	Ciconiidae	<i>Ciconia</i> sp.		
Mammalia	Cetartiodactyla	Cervidae	<i>Antifer ensenadensis</i>		
			<i>Morenelaphus brachyceros</i>		
		Camelidae	<i>Hemiauchenia paradoxa</i> (?)		
			<i>Brasilchoerus stenocephalus</i>		
		Perissodactyla	Equidae	<i>Equus neogeus</i>	
				<i>Hippidion principale</i>	
			Litopterna	Macraucheniidae	<i>Macrauchenia patachonica</i>
			Notoungulata	Toxodontidae	<i>Toxodon platensis</i>
		Carnivora		Felidae	<i>Smilodon populator</i>
			Canidae		<i>Dusicyon</i> cf. <i>D. avus</i>
				<i>Lycalopex</i> / <i>Cerdocyon</i>	
			<i>Protocyon troglodites</i>		
	Rodentia	Ursidae		<i>Arctotherium</i> cf. <i>A. wingei</i>	
			Cricetidae	<i>Holochilus brasiliensis</i>	
			Echimyidae	<i>Myocastor coypus</i>	
			Chinchillidae	<i>Lagostomus</i> sp. (?)	
			Caviidae	<i>Microcavia</i> sp. (?)	
				<i>Dolichotis</i> cf. <i>D. patagonum</i> (?)	
	Proboscidea	Gomphotheriidae		<i>Notiomastodon platensis</i>	
	Xenarthra	Megatheriidae		<i>Megatherium americanum</i>	
			<i>Eremotherium laurillardii</i>		
Mylodontidae			<i>Myodon darwini</i>		
			<i>Lestodon armatus</i>		
			<i>Glossotherium robustum</i>		
			<i>Catonyx cuvieri</i>		
Glyptodontidae			<i>Glyptodon reticulatus</i>		
			<i>Doedicurus clavicaudatus</i>		
			<i>Panochthus</i> sp.		
			<i>Neuryurus rudis</i>		
		<i>Neosclerocalyptus</i> sp. (?)			
Pampatheriidae		<i>Pampatherium humboldtii</i>			
		<i>Pampatherium typum</i>			
		<i>Holmesina paulacoutoi</i>			
Dasypodidae		<i>Dasypus</i> sp.			
		<i>Propaopus sulcatus</i>			
		<i>Propaopus grandis</i>			

dominated by species of megamammals (body mass > 1,000 kg), including mastodons, toxodonts, glyptodonts, and giant sloths, but several large taxa (body mass between 44 and 1,000 kg) and a few fossils of small species (mostly rodents) are also present. Fossils of siluriform fishes (catfishes) and one aquatic bird (*Ciconia* sp.) were also found in the fluvial deposits (Lopes and Pereira 2011, Lopes *et al.* 2019).

The fossils are in general disarticulated and fragmented, but several complete and even articulated specimens have been discovered (Pereira *et al.* 2012, Lopes and Ferigolo 2015, Copetti *et al.* 2020). The fragmented state of most fossils found in channel facies indicate burial and re-working by fluvial processes. Other fossils have been found in eolian deposits and paleosols, but these are poorly preserved (Fig. 7B), usually cracked due to subaerial weathering prior to burial and exhibiting crusts of sand grains cemented by iron and manganese oxides (Lopes and Ferigolo 2015).

Most of the fossils dated by ESR have ages correlated to the MIS 3 (Fig. 4), an interstadial that in southern South America was characterized by warmer and more humid climate (Gasparini *et al.* 2016) compared to the preceding MIS 4 and subsequent MIS 2 stadials. The diets of the extinct *Notiomastodon* and *Toxodon* herbivores that lived at that time, inferred from $\delta^{13}\text{C}$ in fossil teeth from the SVA, indicate that both fed on a mixture of C3 (herbs, shrubs and/or trees) and C4 (grasses) plants, thus indicating a landscape of open grasslands with sparse trees and shrubs, similar to the modern vegetation of wooded savannas, developed under seasonal climate (Oliveira 1999, Lopes *et al.* 2013).

DISCUSSION

The studies performed during the last decade have provided more details about the stratigraphic succession exposed along the banks of Chuí Creek, resulting in a better picture of the origin and evolution of the SVA. Through these studies, a more precise chronostratigraphic setting and better understanding of the depositional environments of the formation were obtained. As a result, the newly acquired data led to a better understanding of the fossiliferous deposits along Chuí Creek.

In his description of the outcrops along the Chuí Creek, Soliani Jr. (1973) did not follow the interpretation of Delaney (1965), who considered the fossil-bearing deposits of the CPRS as belonging to the Graxaim Formation. Instead, he designated as Santa Vitória Formation the layer of fossiliferous fine to medium quartz sand with silt and clay positioned below the Cordão paleosol (Fig. 8). Although stating that the lower boundary of the Santa Vitória Formation was not reached by a 3 meter-deep drilling with hand auger made close to the bridge, the unit was nevertheless positioned above the Chuí Formation. That statement suggests that the underlying marine sediments were misidentified as the Santa Vitória Formation, as the base of the latter is clearly visible at about 2.5–2.7 meters above the creek bed. Besides, no deposits of the SVA with thicknesses exceeding about 1.5 meter were observed so far, and the marine sediments below reach a thickness of at least 11 meters, based on direct observation of drillings made

for the foundations of a bridge across the creek. That misinterpretation seems to be confirmed by the statement that primary sedimentary structures were abundant (Soliani Jr. 1973), since these are conspicuous in the marine sediments, but scarce in the SVA.

Jost and Soliani Jr. (1976) proposed that the fossil-bearing and marine deposits found in the southern CPRS were facies variations within the Chuí Formation, thus subdividing the latter into two members (Fig. 6). As a result, the fossiliferous deposits described by Soliani Jr. (1973) were re-designated as Santa Vitória Member, and the marine sediments as Taim Member. Today, it is recognized that the Chuí Formation of Delaney belongs to the Upper Pleistocene Barrier System III, whereas the marine deposits found along Chuí Creek are correlated to the Middle (Chibanian) Pleistocene Barrier II (Rosa 2012).

The fossil-bearing sediments of the SVA were interpreted as deposited in shallow lagoon or lacustrine environments formed during a transgression around 80 ka ago, correlated with the Sangamon Interglacial of North America (Soliani Jr. 1973, Soliani Jr. and Jost 1975), but the absolute ages (described in the Results section above) show that the deposition of the SVA began much earlier and spanned an interval of about 190 thousand years (Fig. 4). Moreover, the lateral facies variations and taphonomy of the fossils indicate different depositional environments within the SVA as described above. The presence of sediments apparently deposited in lagoon environments during the last interglacial highstand (MIS 5e) were identified to the east of the creek in subsurface (Bettinelli *et al.* 2018), thus suggesting that the paleo-lagoon proposed by Soliani Jr. (1973) existed, though apparently of smaller extension.

Considering the descriptions presented above, the SVA seems to have been formed by aggradation of sediments eroded from the surrounding barriers and deposited by eolian and fluvial processes on top of the marine facies of Barrier II. These sediments were reworked and eroded by fluvial systems and modified by weathering and incipient pedogenesis under different climatic conditions.

The use of allostratigraphic units in the CPRS

Depositional systems, as described by Fisher and McGowen (1967), consist of tridimensional facies associations that characterize distinct depositional environments, exemplified by those

Delaney, 1965	Soliani, 1973	Jost and Soliani, 1976	This paper
Cordão paleosol	Cordão paleosol	Cordão Soil Unit	Cordão Formation
Graxaim Formation	"Santa Vitória Formation"	"Santa Vitória Member"	Santa Vitória Allofm.
Chuy Formation	"Chuy Formation"	"Taim Member"	Barrier II

Figure 8. Different subdivisions proposed for the Pleistocene lithological units of the southern coastal plain of Rio Grande do Sul state (CPRS).

authors by deltas. Since the facies are related to specific environments within a system, such as the distributary channels, interdistributary basins or prodelta of a deltaic system, they imply a genetic link to that system. Although the concept of barrier-lagoon depositional systems developed under eustatic-driven depositional sequences explains well the origin, evolution, and large-scale structure of the CPRS (Villwock 1984, Villwock *et al.* 1986, Villwock and Tomazelli 1995), the recognition of sedimentary environments and facies whose origins are independent of sea-level oscillations that originated the barrier-lagoon systems results in nomenclature and conceptual problems.

Under the concept of depositional systems, the fossil-bearing deposits of the SVA and the overlying loessic Cordão Formation (Lopes *et al.* 2016c) that outcrop along Chuí Creek are located in the Lagoon System III (Villwock and Tomazelli 1995), even though facies characteristic of lagoon/lake environments were not identified along the banks of the creek so far. Nevertheless, lagoon facies within System III apparently exist only to the east of the creek in areas now covered by thick eolian sediments of Barrier III (Bettinelli *et al.* 2018). The absence of genetic link of the SVA (and also the Cordão Formation) to lagoon environments indicate that these units cannot be regarded as part of the facies association that constitute the Lagoon System III, therefore should be regarded as distinct units. Because the Cordão Formation was defined on the basis of its silty (loess) sediments (Lopes *et al.* 2016c), and the lithologic content is not a criteria for establishing allostratigraphic units (NACSN 2005), it seems appropriate to keep it as a lithostratigraphic unit.

Under the concept of sequence stratigraphy, the position of the SVA on top of marine deposits indicates that it was developed on the subaerial unconformity marking the boundary between two depositional sequences driven by successive marine transgressions (Catuneanu 2006, Rosa *et al.* 2017). Sequence stratigraphy, however, emphasizes the hiatal/erosional character of the subaerial unconformity rather than the subaerially-developed depositional environments, being considered a boundary instead of being part of a sequence (Salvador 1987, Embry and Johannessen 1992). The boundary between the marine deposits and the SVA is gradual, without an apparent erosive subaerial unconformity on top of the former, which according to Walker (1992), emphasizes the utility of allostratigraphic units that allow different types of discontinuous bounding surfaces when unconformities are absent or difficult to identify. Moreover, the allostratigraphic units are descriptive rather than genetic, *i.e.*, their definition and characteristics do not depend on the processes that led to its deposition (tectonics, eustasy), differently from the sequence stratigraphy (Salvador 1987, Miall 2010).

The lithostratigraphic scheme adopted by Soliani Jr. (1973) was based on the sedimentary aspects of the fossil-bearing layer exposed at the stratotype. This approach recognizes units based on their lithological content alone, which requires the designation of a new lithostratigraphic unit when facies change laterally within a bed of similar age (Miall 2010). Considering the lateral facies variations observed along the banks, which reveal different depositional environments of similar lithology (primarily

siliciclastic sand), the lithostatigraphic approach does not recognize facies that would provide details about the depositional history of the unit. The allostratigraphic units are bounded by discontinuities, and therefore allow for internal heterogeneities that represent distinct depositional environments (Walker 1992). According to the North American Stratigraphic Code (article 58), allostratigraphic units can encompass lithologically heterogeneous deposits, as well as distinguish between deposits of similar lithologies separated by discontinuities (NACSN 1983, 2005).

In this sense, the adoption of a descriptive, discontinuity-based allostratigraphic framework allows characterizing depositional systems that were not deposited under eustatic-driven sequences, were formed in depositional environments not associated genetically with the barrier-lagoon systems, and exhibit different facies composed of similar lithologies. The allostratigraphic framework is non-genetic and scale-independent, and has been useful for characterizing quaternary deposits with low thickness, consist of individual bodies of small extension distributed for large areas, were not generated by eustasy, and exhibit lithological similarity (Etchebehere 2002). This framework has been used for defining stratigraphic units in fluvio-lacustrine, fluvio-marine, deltaic, shallow marine, and alluvial settings, usually in conjunction with sequence stratigraphic approach (Bhattacharya and Walker 1991, Autin 1992, Oviatt *et al.* 1994, Plint 1996, 2000, Holbrook 2001, Gibling *et al.* 2005, Sallun *et al.* 2007, Beilinson *et al.* 2013).

The allostratigraphic approach proposed here has the purpose of describing and defining smaller-scale depositional systems formed within the confines of the barrier-lagoon systems but under distinct paleo-environmental settings, and may be helpful for delimiting depositional sequences developed in time scales different from the 4th order eustatic oscillations. The recognition of such units within a chronostratigraphic framework may help assessing the role of processes other than sea-level oscillations that shaped the depositional systems, such as climate and environmental changes, therefore contributing to a better understanding of the evolution of the CPRS.

CONCLUSIONS

The fossil-bearing sedimentary layers exposed along the banks of Chuí Creek, interbedded between marine deposits below and eolian (loess) deposits above exhibit features that indicate deposition in fluvial and eolian depositional environments, and posterior modification by weathering and incipient pedogenesis. Originally described as late Pleistocene lagoon deposits and named as Santa Vitória Formation, based on its lithology, more recent studies have shown that this unit consists of distinct depositional systems developed between the middle and late Pleistocene. Its distribution today seems restricted to the flat lowlands of the Lagoon System III, bounded to the west by the eolian deposits of Barrier II and to the east by Barrier III, but deposits of similar age and fossiliferous content are found on the margin of Mirim Lake, about 11 km to the west of the creek. Other correlated deposits probably existed also to the east, but were eroded by sea-level oscillations, as indicated by ages of fossils from the continental shelf.

This unit is important from a paleontological standpoint, being the only unit known so far in the CPRS with Pleistocene mammalian fossils preserved within a precise stratigraphic setting. The facies variations observed within that unit indicate changing climate conditions throughout its deposition. The facies variations related to distinct depositional environments, the absence of facies genetically related to the barrier-lagoon systems of the CPRS, and the fact that the paleosols and fluvial and eolian deposits represent the subaerial unconformity between eustatic-driven depositional sequences, justify its description as distinct unit, at the hierarchic level of alloformation. Following this rationale, the unit is re-designed as Santa Vitória Alloformation, bounded by the discontinuities

in relation to the marine sediments below, and above with the loess layer of Cordão Formation.

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R.P.L. collected field data, wrote the first draft of the manuscript and prepared the figures, J.P.C. collected field data and provided paleontological information, J.F.S. provided the luminescence dating and made suggestions and corrections to the manuscript, and S.R.D. was the advisor of the postdoctoral research, and also provided suggestions and corrections to the manuscript.

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