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Fossiliferous sites of the southern coast of Rio Grande do Sul state, Brazil: geoheritage records of Quaternary sea-level, climate and environmental changes

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Abstract

The southern coastal plain of Rio Grande do Sul state hosts essential fossil records of both marine and terrestrial faunas that have provided invaluable information about the geological and environmental Quaternary history of southern Brazil. These fossils are found in surface and subsurface deposits on sites stretching from the continental shelf up to coastal lagoons inland. The sites on the shelf are time-averaged lag deposits formed of marine and terrestrial fossils exhumed and mixed together as a result of erosion of the original deposits by sea-level oscillations. Although lacking any precise stratigraphic context, the available numerical dates indicate Middle to late Pleistocene ages. Fossils removed from the shelf by waves today form large *Konzentratt-Lagerstätten* on the beach, called *concheiros*. The sites on continental areas occur in barrier-lagoon depositional systems, and include marine deposits formed under higher than present sea levels formed by Middle and late Pleistocene and Early-Middle Holocene marine transgressions. The fossiliferous sites with well-defined stratigraphic context encompass fluvial and aeolian (loess) deposits and paleosols associated with the Middle-late Pleistocene Santa Vitória Alloformation and Cordão Formation outcropping along Chuy Creek. Fossils of late Pleistocene terrestrial and Holocene marine organisms were collected from the bottom and marginal terraces of Mirim Lagoon. Although most sites are not directly under threat today, their wide distribution poses potential problems for protection. Current protection measures for the sites and associated fossils include requests by environmental agencies for preliminary surveys and fossil rescue programs prior to construction projects, and the proposal of a marine-coastal protected area is currently under consideration. Educational programs with schools and exhibits for the general public executed by the museums in the town of Santa Vitória do Palmar have contributed to public awareness about the importance of the regional paleontological heritage and have produced positive feedback and results that increased the number of known fossiliferous sites in the region thanks to communication by local people. These actions are essential to establish protection measures in case new developments emerge in the future that could threaten the sites and their fossils.

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1. Introduction

The coastal plain of Rio Grande do Sul state (CPRS) (Fig. 1), in southernmost Brazil, is a large geomorphological unit exhibiting a rich geodiversity of coastal features. The CPRS is the uppermost portion of the marginal Pelotas Basin, which encompasses sedimentary and fossil successions spanning from the Cretaceous to the Quaternary (Closs 1970; Barboza et al. 2021b). The sediments that form the Pelotas Basin were eroded from Precambrian rocks of the Sul-Rio-Grandense Shield and Paleozoic and Mesozoic sedimentary and volcanic rocks of the Paraná Basin (Villwock and Tomazelli 1995). Those sediments were accumulated on the continental margin after the opening of the Atlantic Ocean in the form of depositional systems, i.e., chronocorrelated facies associations that include an older Alluvial Fans System of Miocene-Pliocene? age, plus four Quaternary Barrier-Lagoon Systems and the adjacent continental shelf (Closs 1970; Villwock et al. 1986; Villwock and Tomazelli, 1995).

The Barrier-Lagoon Systems are the dominant geomorphological features of the CPRS, being the largest depositional systems of this type found along the Brazilian coast, and consist of long sandy barriers that isolate large coastal lagoons on the backbarrier lowlands (Villwock et al. 1986; Villwock and Tomazelli 1995). The older Barrier-Lagoon System II was established during the Middle Pleistocene,

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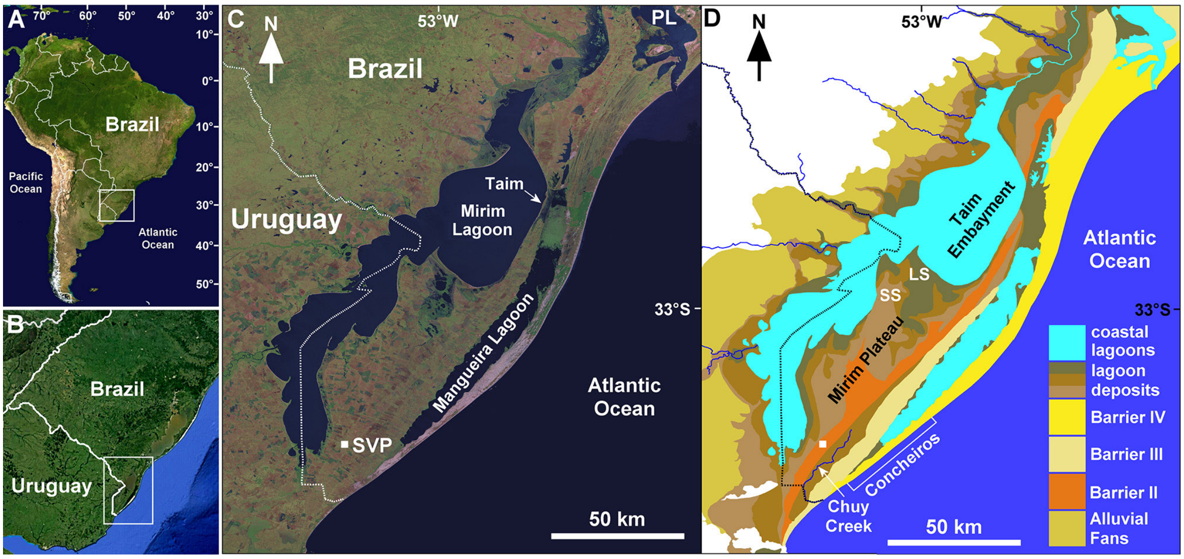

FIGURE 1 - A - Blue Marble image showing the location of Rio Grande do Sul. B - Location of the fossiliferous sites. LANDSAT image (C) and geological units (D) of the southern CPRS, with the fossiliferous sites indicated (not shown are the submerged deposits along the inner shelf and Mirim Lagoon) (PL: Patos Lagoon, LS: Latinos Spit, SS: Santiago Spit).

System III during the late Pleistocene, and System IV during the Holocene (Villwock and Tomazelli 1995; Lopes et al. 2014a). These systems are the result of glacioeustatic oscillations that produced high-frequency depositional sequences integrating a falling stage systems tract (Rosa et al. 2017). During glacial periods, sea level fell several tens of meters below the present, thus subaerially exposing most of the continental shelf. As a result of marine transgressions following the end of a glacial period, the advancing sea level reworked the upper 3-10 meters of the shelf sediments, thus building the coastal barriers that isolated large coastal lagoons on the back-barrier lowlands (Villwock and Tomazelli 1995; Dillenburg 1996).

The geological evolution of the CPRS favored the development of fossiliferous deposits that contribute to the rich geodiversity and geoheritage of the southern Brazilian coast. These deposits contain remains of different groups of organisms, including both marine and terrestrial species of invertebrates and vertebrates. Although such fossils are found along the entire CPRS, it is on the southern sector, between the estuary of Patos Lagoon and the mouth of Chuy Creek (Fig. 1), that such remains are more abundant. The fossils preserved along this area are important because they help to understand the geological evolution of the coastal plain, provide information on the marine and terrestrial faunas that inhabited the region in the past, and allow us to assess how climate changes throughout the Quaternary affected the environments and ecosystems in southern Brazil.

2. The fossiliferous sites of the southern CPRS

The oldest known published records of fossils from the southern CPRS date back to the late 19th century, when the naturalist Herrmann von Ihering described molluscan shells found near the town of Rio Grande and the locality of Santa Isabel on the eastern bank of São Gonçalo Channel that connects Mirim and Patos Lagoons (Fig. 1) (Ihering 1885, 1907). Later surveys and studies have shown that the fossils preserved in the southern CPRS occur essentially in two settings (Fig. 1D): 1) from the inner continental shelf to the beach, and 2) across terrestrial areas associated with the Barrier-Lagoon Systems II and III.

2.1. Submarine and coastal sites

The continental shelf stretching between southern Brazil and Uruguay is a low gradient (0.03º to 0.08º) prominent geomorphological feature measuring ~130 to 160 km in width, devoid of rocky features except for submerged linear rocky banks (Delaney 1965; Dillenburg and Barboza 2014; Caron 2014). Because the establishment of the barrier-lagoon systems since the Middle Pleistocene cut all fluvial discharges to the coastline, the shelf sediment cover is essentially relict terrigenous sand and contemporaneous hemipelagic mud (Martins et al. 1972; Kowsmann and Costa 1979; Kowsmann et al. 1977). Along the outer continental shelf off the northern-central CPRS, close to the shelf break, there is a strip of biogenic carbonate sediments formed mainly of broken and abraded shells (Kowsmann et al. 1977; Zembruscki 1979; Martins 1985). As the hydrodynamics of the outer shelf is not capable of producing such physical modifications, these are interpreted as relict material (*sensu* Emery 1968) originally accumulated and reworked in ancient shorelines under lower sea levels than the present.

In certain areas along the southern CPRS, large concentrations of biodetrital material, mainly fossil mollusk shells and other invertebrates, but also including fossils of terrestrial and marine vertebrates and beachrock fragments, eroded from submerged lithified paleoshorelines called *parceis*, occur on the surface of the inner continental shelf at depths between 0 and 20 meters (Martins et al. 1972; Figueiredo Jr. 1975; Figueiredo et al. 1982; Corrêa and Ponzi 1978; Caron 2014). Although modern shells and remains of other organisms also occur on the concentrations, for simplicity we refer herein only to the fossil material. Those concentrations are regarded as lag deposits (Erthal and Ritter 2020), the fragmented and abraded state of the fossils indicate reworking and concentration on high-energy nearshore settings in the past (Figueiredo Jr. 1975; Lopes and Buchmann

2008), therefore their origin can be understood in terms of past sea-level oscillations. Following the marine high stands of the marine isotope stage (MIS) 5, the global mean sea level (msl) of the last glacial period reached some -80 meters below the present during the stadial MIS 4 (71-57 ka b2k, Grant et al. 2012), then rose again to about -38 m (Pico et al. 2016) during the interstadial MIS 3 (57-29 ka b2k), reaching up to about -23 to -5 meters off southern Brazil between 47.7 and 36.2 ka BP (Dillenburg et al. 2019). The lowest sea levels of the following stadial MIS 2 (29-11.7 ka b2k) reached a minimum of -120 m during the last glacial maximum (LGM) between 26.5 and 18 ka BP (Rohling et al. 1998). As a result of periodic sea level oscillations, the shelf surface was reworked and eroded repeatedly, and its fossils mixed with younger remains, producing fossil assemblages with large time-averaging. Although sea level oscillations as the ones described above may have occurred before the Middle Pleistocene, based on ages of fossil shells found on the southern CPRS (Lopes et al. 2020d), the original geological units these remains were associated with were eroded by later marine oscillations. The contemporaneous shelf deposits are the result of the most recent postglacial marine transgression (PMT) that occurred between the latest Pleistocene-Early Holocene transition.

The PMT started around 18 ka BP as the result of the most recent deglaciation (Termination I) (Denton et al. 2010; Hulton et al. 2002). The rising sea level reworked the uppermost 3-10 meters of the continental shelf off Rio Grande do Sul (Dillenburg 1996), and large quantities of sand eroded from the shoreface by the rising sea level were transferred landward thus building the coastal Barrier IV (Caron 2014). The winnowing of sand resulting from erosion and retreatment of the shoreface left transgressive lag deposits formed of coarser material exposed on the shelf surface as large biodetrital concentrations (Figueiredo Jr. 1975). Part of the winnowed sand was probably transported offshore by currents until being deposited at depths below the influence of waves, where mechanical remobilization is minimal or nonexistent (Swift 1974; 1975; Belknap and Kraft 1981; Roy et al. 1997), forming a sheet on top of the biodetrital concentrations. The contemporaneous shelf hydrodynamics affecting the shelf bottom at depths between 8 and 24 meters rework the sand cover in the form of 4-10 meter-high and >200 km-long linear sand ridges located several km apart from each other and oriented obliquely to the modern shoreline (Figueiredo 1980). The ridges exhibit graded layers of sand and shells and migrate in response to the action of waves and currents, leaving the biodetrital concentrations exposed on the troughs between them (Figueiredo et al. 1982).

As the coast of Rio Grande do Sul is subject to micro-tidal regime (0.47 m on average), waves are the main physical mechanisms responsible for transport and erosion of sediments on the inner shelf, including the fossils, which can be characterized as palimpsests (*sensu* Swift et al. 1971, Villwock and Tomazelli 1995). The wave-driven erosive processes affecting the southernmost coast and inner shelf of Rio Grande do Sul constantly remove the sand, thus exposing fossils and *parceis* on the shelf surface. The storm waves erode and carry the fossils and fragments of the *parceis* to the beach, forming shell-dominated *Konzentratt-Lagerstätten* deposits locally known as *concheiros* or *concheiros do Albardão*, named after the lighthouse located in the northern limit of the deposits. A short vide (in Portuguese) about the *concheiors* is available at: https://www.youtube.com/watch?v=_2zoexwk6Lc.

Although the presence of fossils of Pleistocene terrestrial mammals along the beach of the southern CPRS had been reported before (Souza-Cunha 1959; Paula-Couto and Souza-Cunha 1965), according to people from the region the *concheiros* did not exist until the late 1960s. In the first systematic study the *concheiros* were described as ~5 m-wide and 5 cm-thick patches of fossil shells stretching for a few kilometers (Figueiredo 1975). However, twenty years later the *concheiros* reached a thickness of >2 meters (Asp 1996). These changes point to long-term processes influencing the formation of these deposits. Although occurring for some 40 km along the coast, the distribution and presence of the *concheiros* are variable, seemingly resulting from medium- and short-term processes as well.

As the sources of the fossil material found along the beach are the concentrations on the inner shelf, the *concheiros* represent the subaerial extension of these concentrations, as indicated by the fossils and the sediments with similar composition and grain size (Caron 2014). The beach area where the *concheiros* occur is characterized as intermediate in terms of morphodynamics and is subject to high-energy waves (Calliari and Klein 1993), especially under storm conditions that remove and transport sediments and fossils to the shore. The action of waves on the fossils at the shore produces taphonomic modifications and influences their distribution across the beach. As a result of these processes, it is possible to recognize a zoning pattern of the *concheiros*:

Lower *concheiros*: Formed of fossils accumulated on the lower part of the beach within the swash zone (foreshore), and thus subject to constant reworking by waves under fair-weather conditions. The fossils are densely concentrated (Fig.2A) and consist of a mixture of more complete and less abraded fossils (Fig. 2B), recently removed from the shelf, and others that remain for long periods under the influence of waves on the swash zone, being reduced to highly broken and abraded, mostly unidentifiable shell hash (Fig. 2C), and vertebrate fossils (Lopes and Buchmann 2008; Lopes and Ferigolo 2015). The occasional erosion of the foreshore by storm waves exposes interspersed layers of fossils and sand (Fig. 2D) that can be related to variations in hydrodynamics (e.g., storm vs. fair-weather conditions).

Upper *concheiros*: These are located on the higher part of the beach (backshore), between the berm and the incipient or front dunes. The intercalated layers of sand and fossils are thicker than those of the lower *concheiros*. The fossils include complete shells, large vertebrate remains (Fig. 2E), and highly abraded small fragments. Once accumulated on the backshore the fossils of the upper *concheiros* remain stable, being only occasionally subject to remobilization by storm waves that manage to reach the upper beach. The more frequent modifications of these fossils are caused by sandblasting that polishes the shells, erosion by washouts (*sangradouros*) draining from wetlands behind the foredunes, and episodic covering by wind-blown sand from the beach.

Shells and vertebrate fossils are not usually found behind the incipient/front dunes, except in areas where these are absent and storm waves reach further landward. Nevertheless, the smaller shell hash, in the coarse sand size range (1-2 mm), is easily entrained and carried by onshore winds due to its platy shape, forming ripples on the surface of dunes (Fig. 2F) and other sedimentary structures (Fig. 2G), and is incorporated to the large mobile dune fields farther inland.

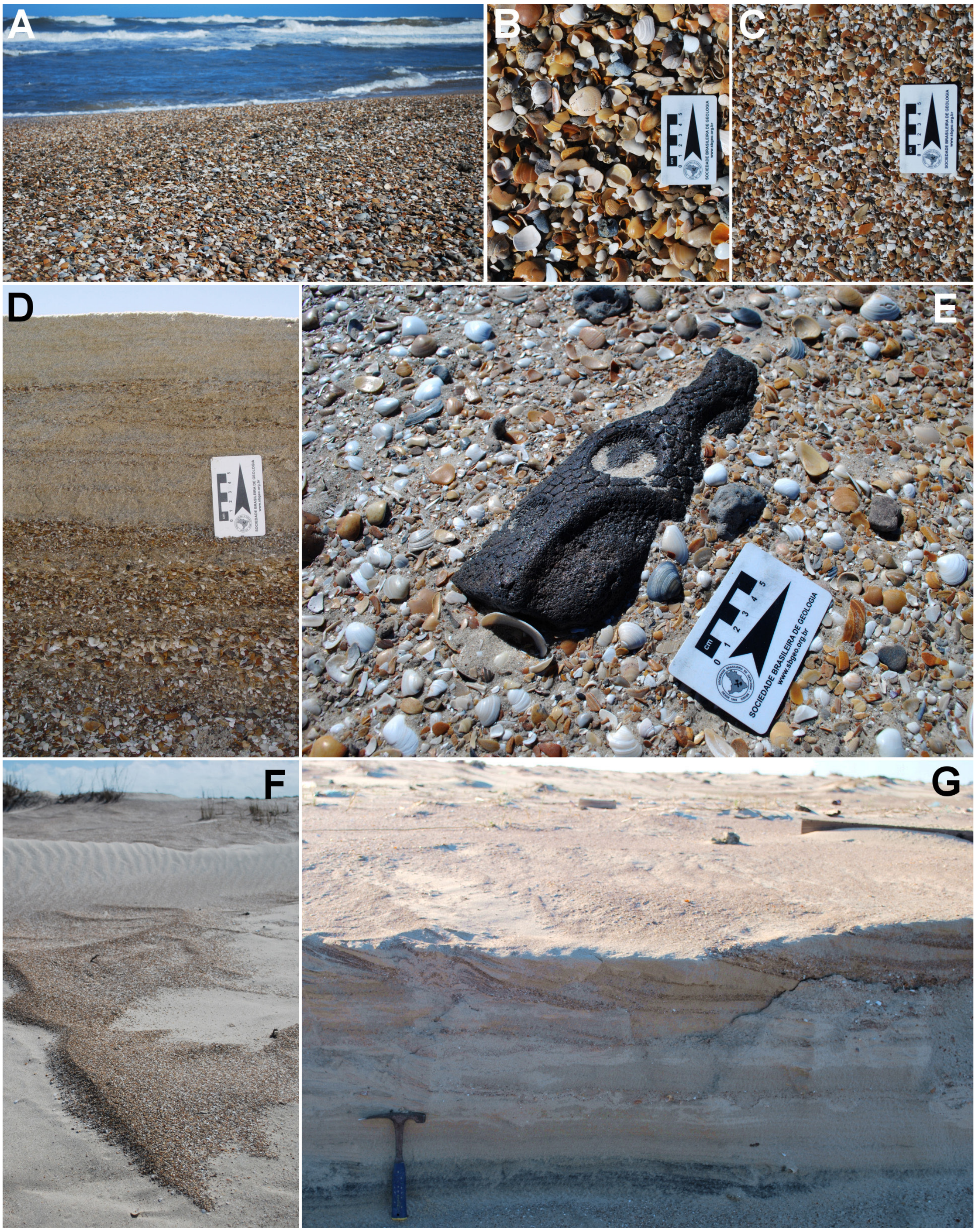

FIGURE 2 - A -A - Fossil concentration of the lower concheiros. B and C - Fossil shells photographed in the same scale showing the differences in size related to grades of abrasion and breakage. D – Interspersed layers of sand and shells exposed on the foreshore. E – Fossil of an extinct mammal (*Panocththus*) in the upper *concheiros*. F - Ripples formed of sand-sized shell hash accumulated on incipient dunes. G – Parallel- and trough cross-bedding formed of sand and shell hash layers in the upper *concheiros*.

2.1.1. The spatiotemporal dynamics of the concheiros

The upper *concheiros* are accumulated on the backshore as the result of exceptionally intense storm waves that manage to reach this area, thus remain relatively stable due to the absence of mechanical processes capable of remobilizing the fossil material. The lower *concheiros*, on the other hand, are constantly subject to wave action and, thus, are not continuous in space and time. These deposits can stretch for several kilometers but be separated by stretches of sand mostly devoid of shells that can be equally as long. One possible reason for this pattern is that fossils can be accumulated or removed at certain beach parts by concentrated wave action or due to the longshore transport that proceeds predominantly northeastwards (Lima et al. 2001).

The *concheiros* are usually exposed on the beach surface but are occasionally buried by sand. The burial is generally cyclical, following changes in wave dynamics driven by the seasonal variations of the prevailing bidirectional winds (Tomazelli et al. 1998) that control the sediment balance on the foreshore (Fig. 3A, B). During autumn and winter, the strong waves constantly pushed ashore by southerly winds produce erosive scarps on the beach face (Fig. 3C), and the stronger storm waves can reach up to the backshore. During spring and summer the waves driven by the northeasterly winds blowing parallel to the shoreline accumulate sediments on the beach, creating a prominent berm that usually does not reach more than about 1.5 meters above the mean water line. This berm is constantly subject to overtopping by waves, producing washover deposits of sand and fossils (Fig. 3D) that bury the fossils previously accumulated on the beach. Seawater from storm waves and freshwater from the wetlands on the backshore accumulate between the berm and the incipient dunes, thus forming a type of creek or small lagoon parallel to the shore, locally called *albardão* (Fig. 3D), which gives the name to the lighthouse mentioned above. In some places, the *albardão* cuts across the berm as small *sangradouros* that can carry fossils from the upper *concheiros* back to the foreshore.

The accumulation of sand that buries the *concheiros*, however, also proceeds in longer timescales and may last for years (Fig. 4A, B). This occurs during certain periods when the beach receives more sediments than the waves can remove, resulting in the formation of a much larger berm that may reach more than two meters above the mean water line and attain widths of ~30 meters (Fig. 4C). The exact reason for this process is still unknown but may be related to the onshore migration of the linear sand banks submerged on the shelf (Figueiredo Jr. 1980; Figueiredo Jr. et al. 1982). When this high berm is present, the fossils are concentrated on the lower portion of the beach by fair-weather waves (Fig. 4C), as the only waves capable of transporting them across the berm through overwash are exceptionally high storm waves. That concentration increases the time the fossils are subject to swash and backwash action by fair-weather waves that produce mechanical abrasion and fragmentation.

The accumulation of the fossil material that forms the concheiros seems related to the sedimentary dynamics driven by wave regimes and thus varies seasonally, being more evident during autumn and winter due to the high-energy storm waves produced by southerly winds. The observation of physical processes and sedimentary features on the beach allows us to understand the formation of the concheiros as the result of cyclic events of erosion-deposition that follow a series of stages:

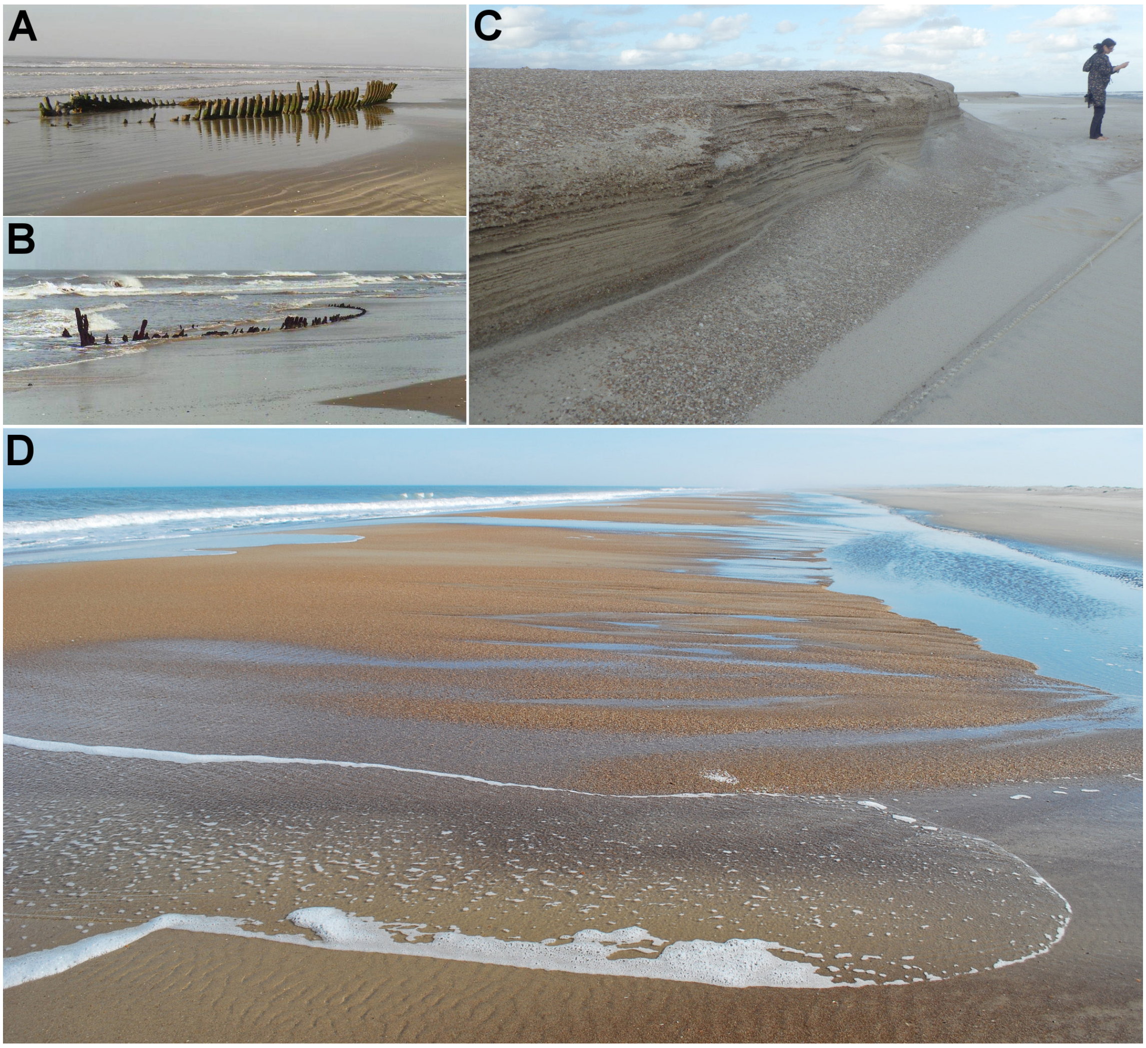

FIGURE 3 - The shipwreck 'Santa Maria' showing changes of beach sand volume between winter (A) and summer (B). C - Wave-cut erosive scarp on the foreshore. D - Berm with washover deposits of sand and shells on the foreshore, and an *albardão* formed of seawater on its rear.

FIGURE 4 - The shipwreck ‘Dona Iaiá’ showing increase of sand volume on the beach at the *concheiros* between 2010 (A) and 2015 (B). C - The *concheiros* in 2019 with a well-developed large berm stretching for tens of kilometers along the beach, with an *albardão* on its rear. Note the fossils concentrated on the lower foreshore (on the left) and their absence over the berm, differently from Figure 3D.

a) Under fair-weather conditions prevalent during spring and summer, sand and small fossils accumulated on the inner shoreface subject to wave action are carried to the beach. Although most fossils remain constantly moved and reworked within the swash zone, exceptionally strong waves or high tides can accumulate fossils above the mean water line, forming the lower *concheiros* on the foreshore. The sand deposited together with the fossils forms the berm (Fig. 3D), and is also carried landward by overwash or winds, thus covering the fossils on the highest part of the beach.

b) The storm events, more frequent and intense during autumn and winter, are driven by strong southerly winds that pile up water onto the shore, increase wave height and energy, and enlarge the breaker zone, thus causing waves to erode from the lower shoreface up to the foreshore. These waves rework sand and fossils that are carried to the shore, and remove sand from the foreshore. The extreme storm waves can overtop the berm and carry larger fossils up to the backshore.

c) The waves lose energy upon reaching the backshore, depositing the fossils at the foot of the foredunes or incipient dunes, and start to recede toward the sea. The returning backwash removes smaller sand grains, leaving behind lag deposits of densely concentrated fossils on the surface that form the upper *concheiros*. This is similar to one mechanism that can generate desert pavements through eolian deflation, leaving lag deposits of larger clasts (Knigh and Zerboni 2018).

b) The return to fair-weather conditions favors onshore eolian transport of sand that recomposes the berm and buries the fossils left on the foreshore by storm waves. The alternate episodes of erosion of sand/deposition of fossils and accumulation of sand across the beach are represented by the intercalated layers of fossils and sand observed on erosive beach scarps (Figs. 2D, 3C) or washout banks (Fig. 2G).

2.1.2. The fossil assemblages of the shelf and concheiros

Because the inner shelf deposits and *concheiros* result from periodic erosion of deposits and mixing of fossils of different ages, the fossiliferous assemblages exhibit large time-averaging. The fossil concentrations on the inner shelf and *concheiros* are dominated by shells of extant molluscan species, and the available radiocarbon ages range from ~200 to >30,000 years (Figueiredo Jr. 1975; Kowsmann et al. 1977; Lopes and Buchmann 2008; Ritter et al. 2017, 2023), although most of the shells display ages ranging up to 6,000 years (Ritter et al. 2017). In contrast, at water depths of 100 up to 242 meters on the outer shelf, the shelly concentrations are much older, with a median age of roughly 15,000 years (Ritter et al. 2023). The shells include from complete to fragmented and highly abraded specimens exhibiting varied colors ranging from white, yellow, reddish, and dark gray or black (Fig. 5A), and may show encrustation by barnacles, bryozoans and polychaetes, besides traces of bioerosion by invertebrate predators and parasites (Lopes and Buchmann 2008; Erthal 2012; Lopes 2012; Ritter et al. 2019). Other fossils of marine invertebrate species include echinoderms (Fig. 5B), corals (Fig. 5C); crustaceans represented mainly by lithified ichnofossils *Ophiomorpha nodosa* (Fig. 5D) and skeletal fragments (Fig. 5E) (Rocha et al. 1975; Buchmann 1994; Lopes 2011; Freitas et al. 2020). Marine vertebrates (Fig. 5F-K) are represented by fossils of sharks, rays, bony fishes, whales, pinnipeds and seabirds (Souza-Cunha and Nunan 1980; Souza-Cunha 1982; Richter 1987; Buchmann and Rincon 1997; Oliveira and Drehmer 1997; Drehmer and Ribeiro 1998; Lopes et al. 2006; Medeiros et al. 2023). The fossils of vertebrates are strongly mineralized, dark

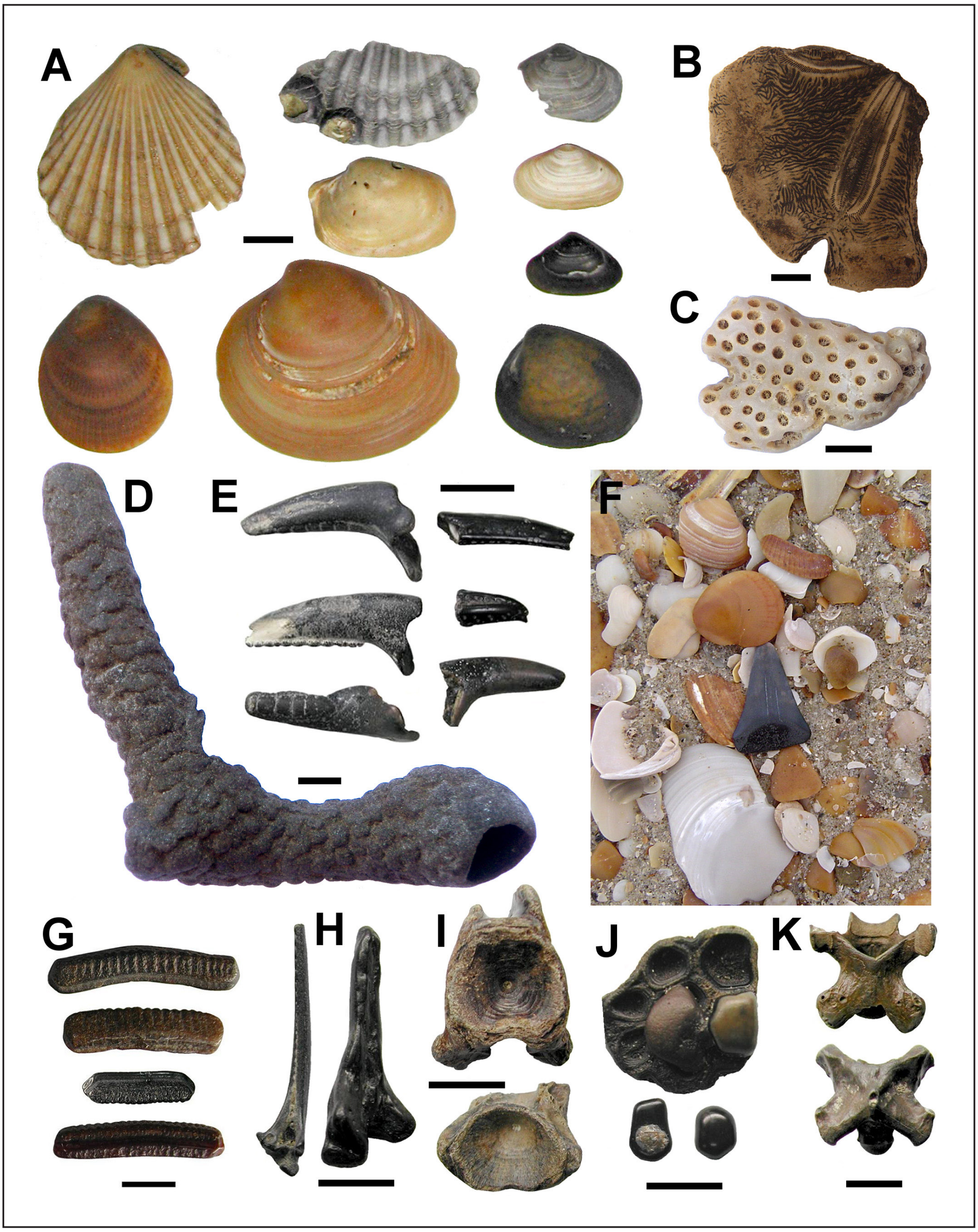

FIGURE 5 - Fossils from the concheiros: A - Mollusk shells. B - Echinoid *Encope emarginata* (sand dollar). C - Coral *Oculina patagonica*. D - Ichnofossil *Ophiomorpha nodosa*. E - Pincers of unidentified crustaceans. F - Fossil tooth of a white shark (*Carcharodon carcharias*) at the concheiros. G - Tooth plates of rays (Myliobatidae). H - Spines of unidentified teleost fishes, I - Vertebrae of cf. sciaenid fishes. J - Dental plate and two isolated teeth of *Pogonias cromis*. K - Vertebrae of seabirds cf. *Diomedea melanophrys* (scale bars = 10 mm).

reddish- to black-colored (Fig. 5F-K), probably due to the incorporation of exogenous elements as detected in fossils of terrestrial mammals from the shelf (Lopes and Ferigolo 2015). Virtually all fossils of marine vertebrates belong to species that inhabit the waters off southern Brazil, but the presence of white sharks (*Carcharodon carcharias*) and bull sharks (*Carcharhinus leucas*), characteristic of cold and tropical waters, respectively, not found in southern Brazil today, indicate variations in oceanographic conditions in the past related to glacial-interglacial cycles.

The most remarkable fossils found on the continental shelf and *concheiros* belong to terrestrial Pleistocene mammals (Fig. 6), especially large species of the megafauna (Souza-Cunha 1959; Buchmann 1994; 2002; Aires and Lopes 2012). The presence of terrestrial fossils today at water depths of up to at least 40 meters indicates that during glacial periods most of the continental shelf was subaerially exposed and occupied by terrestrial environments (Villwock 1984, Lopes and Buchmann 2010). The fossils are strongly mineralized; those found on the beach are mostly abraded and broken due to reworking by waves. In contrast, some complete specimens found on the beach were probably transported recently from the shelf deposits (Lopes and Ferigolo 2015). Their color varies between reddish, brown or black due to the incorporation of exogenous elements such as iron and magnesium. The few specimens collected directly from the shelf exhibit encrustation by marine epibionts such as corals, barnacles or bryozoans (Fig. 6A,G), whereas some specimens exhibit beachrock-like crusts (Fig. 6M) of sand and shells cemented by calcium carbonate (Lopes and Buchmann 2010; Lopes 2012; Lopes and Ferigolo 2015; Lopes and Pereira 2019).

The electron spin resonance (ESR) datings of some mammal teeth indicate Middle to late Pleistocene ages ranging from ~18 to ≥650 ka that coincide with periods of sea level lowstands (Lopes et al. 2010, 2014b). This considerable temporal mixing results from the erosion of terrestrial deposits by successive marine transgressions, which reworked and mixed fossils of different ages in the lag deposits. Because of this, the fossil mammals from the continental shelf and *concheiros* do not have stratigraphic context and cannot be correlated to any specific stratigraphic unit, although some dated remains (see Figure 8F) are chronocorrelated with fossils from terrestrial deposits (Lopes 2013; Lopes et al. 2021a). Nevertheless, the fossils from the shelf encompass a diverse fauna consisting mainly of extinct mammals such as giant sloths, glyptodonts, meridiungulates, mastodons, rodents, cervids, camelids, horses and carnivorans, and extant forms such as capybaras, jaguars, cougars and tapirs (Rodrigues and Ferigolo 2004; Rodrigues et al. 2004; Scherer 2005; Scherer et al. 2007; 2009; Pitana and Ribeiro 2007; Ribeiro et al. 2008; Lopes and Pereira 2010; 2018; Ferreira et al. 2015; Lopes et al. 2015; 2020a). Besides mammals, one fossil of a caiman (Hsiou and Fortier 2007) was also found at the *concheiros*. This diverse assemblage of terrestrial vertebrates represents different types of ecosystems and thus provides a record of environmental changes in southern Brazil during the Quaternary.

2.2. Terrestrial sites

The fossiliferous sites in onshore areas on the southern CPRS are located south of the estuary of Patos Lagoon, between Taim and the Brazil-Uruguay border (Fig. 1). The fossils include essentially the same marine and terrestrial organisms found on the shelf and *concheiros* but preserved in the Middle Pleistocene to Late Holocene shallow marine, lagoon and fluvial deposits, mainly in the subsurface, but also occur at or close to the surface in some areas. In geological terms the fossiliferous sites are part of the Barrier-Lagoon Systems II and III (Fig. 7A). The fossils have been recovered so far from three main sites: the Barrier III, Chuy Creek (Barrier II and Lagoon III) and Mirim Lagoon (Lagoon II).

2.2.1. Barrier III

The fossils preserved in deposits of the Barrier III belong to extant (and a few locally extinct) species of invertebrates that inhabit marine or lagoon environments (Bettinelli et al. 2018). These fossils are preserved in sediments accumulated

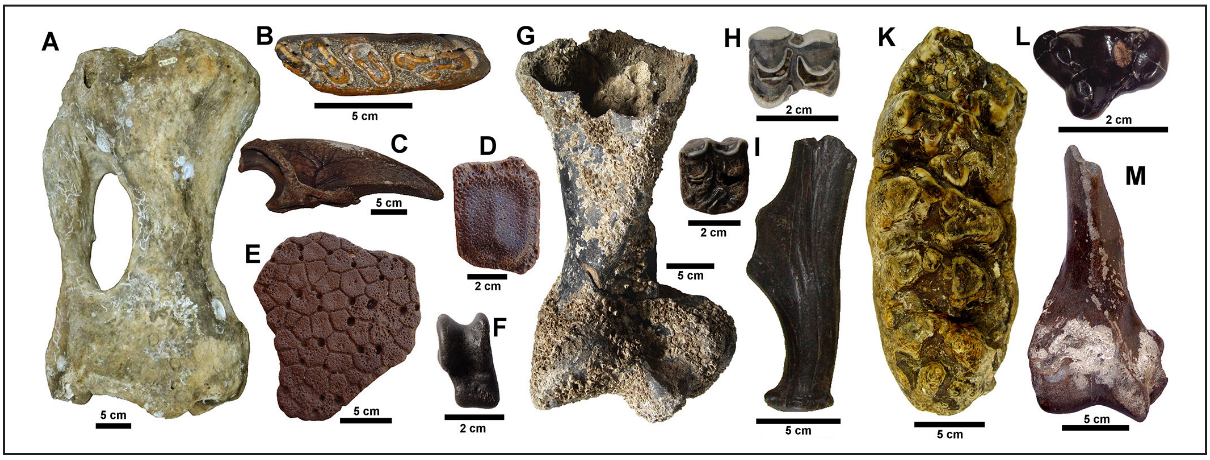

FIGURE 6 - Fossils of terrestrial mammals from the continental shelf/*concheiros*: A - Tibia and fibula of *Megatherium*. B - Partial jaw of a giant sloth (cf. *Catonyx*). C - Phalange of unidentified sloth. D - Osteoderm of a giant armadillo (cf. *Holmesina*). E - Fragment of the carapace of a glyptodont (*Glyptodon*). F - Astragalus of a proterotheriid (*Neolicaphrium*). G - Humerus of *Toxodon*. H - Tooth of a camelid. I - Tooth of a horse (*Equus*). J - Antler of a cervid (*Antifer*). K - Tooth of a mastodon (*Notiomastodon*). L - Tooth of a wild dog (*Theriodictis*). M - Humerus of a sabertooth cat (*Smilodon*), the light areas on the bone are crusts of cemented sand and shells.

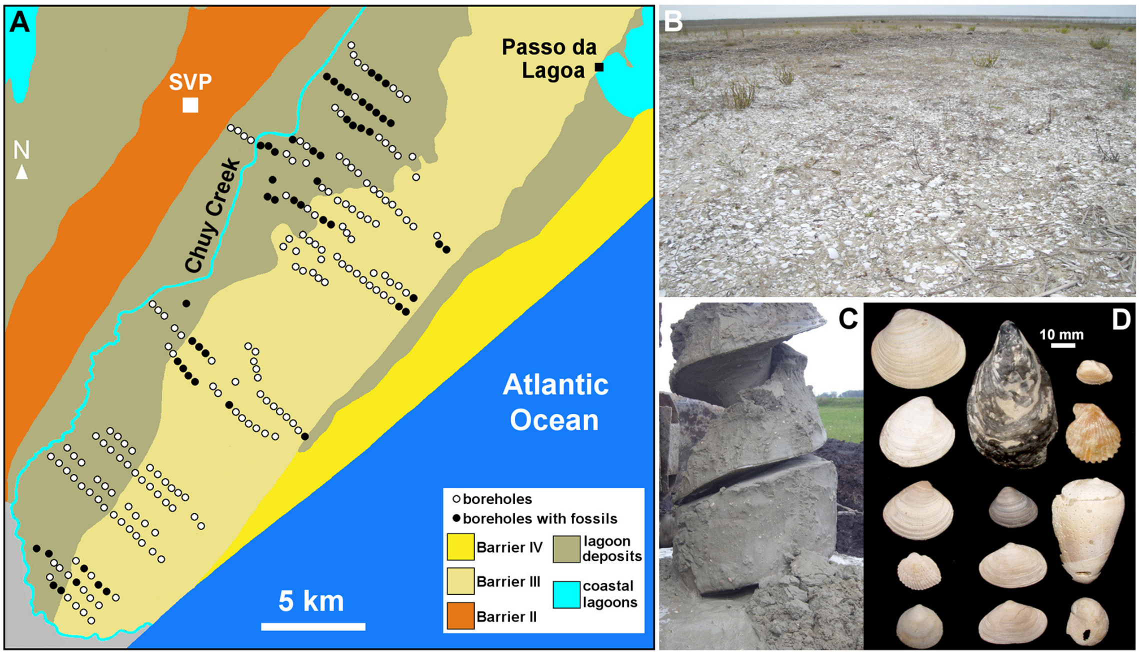

FIGURE 7 -A - Geological map of the southernmost CPRS showing the location of the onshore fossiliferous sites (excluding Mirim Lagoon). B - Fossil shells removed from the Barrier III scattered on the margin of the irrigation channel at Passo da Lagoa. C - Drilling equipment used to make the boreholes for the wind farm (shown in 7A). D - Fossil shells extracted from the boreholes.

on shallow marine (foreshore-shoreface) and lagoon margin deposits found in the subsurface on the seaward and back barrier portions of the barrier (Fig. 7A). The fossils from the seaward portion were obtained at depths of ~7 to 17 meters below the terrain surface (corresponding to altitudes of +3 to -7 meters relative to the present sea level), from sediments removed during the excavation of a channel at the locality of Passo da Lagoa (Fig. 1; Fig. 7B), and extracted by rotating drills during the installation of a wind farm (Fig. 7C) (Lopes and Buchmann 2008; Lopes et al. 2020d).

Fossiliferous deposits are widely distributed across the Lagoon System III on the back barrier (Fig. 7A), where the fossils were also extracted by rotating drills, embedded in sediments accumulated on lagoon margin environment on the back barrier, but also include material eroded from deposits of the Barrier II (Bettinelli et al. 2018; Lopes et al. 2024a). The fossils occur at depths of ~8 to +19 meters (altitudes of -6 to +5 meters), and besides mollusk shells and foraminifers they also include echinoderms and crustaceans (Bettinelli et al. 2018). The fossils are primarily unidentified fragments, but several well-preserved shells were also recovered (Fig. 7D). Most shells are white-colored due to partial dissolution by acidic water of the phreatic. However, some exhibit traces of the original color pattern and a few have preserved parts of the periostracum. The altitudes at which the shells are preserved show that the fossiliferous deposits were formed by a marine transgression that reached altitude of up to about +6 to + 7 meters relative to the current mean sea-level, consistent with the estimate of +5.1 to +7.7 meters from shoreface-foreshore deposits of the Barrier III in the northern CPRS (Tomazelli and Dillenburg 2007). The ESR ages of shells from the seaward barrier range from ~87 to 240 ka, whereas those from the back barrier are older, ranging from ~178 to 359 ka (Lopes et al. 2020d). The youngest ages are consistent with the estimated late Pleistocene (MIS 5) age of the Barrier III (Villwock and Tomazelli 1995). However, the older figures indicate the mixing with shells eroded by the MIS 5 marine transgression from the Barrier II or even older deposits.

2.2.2. Chuy Creek

This fluvial system flows along the Lagoon System III (Fig. 7A), which in geomorphological terms is a small basin bounded west and east by the Barriers II and III, respectively (Fig. 1). The creek drains from the surrounding rain-fed wetlands and was a shallow stream until being further excavated during the 1960s for irrigation purposes, thus exposing sediment layers within the Lagoon System III (Paula-Couto and Souza-Cunha 1965). The outcrops along the banks of the creek exhibit the best Middle Pleistocene to Holocene stratigraphic successions known so far in the southern CPRS. The succession exposed above the creek bed (Fig. 8A) comprises a marine deposit at the base (Fig. 8B), interpreted as deposited in shallow marine (shoreface-foreshore) environments associated with the Barrier II (Rosa 2012; Lopes et al. 2014a). This deposit contains a rich fossil assemblage dominated by mollusk shells, foraminifers, ostracods, and cirripeds, besides ichnofossils *O. nodosa*, *Rosselia* isp. and *Conichnus* isp. (Closs and Forti-Esteves 1971; Forti-Esteves 1974; Lopes and Bonetti 2012; Lopes et al. 2013b; 2020b). The shells are mostly fragmented and white-colored, and several are corroded by acidic water in the form of pitted rough surfaces (Lopes et al. 2013b). Some luminescence and ESR ages obtained in sediments and shells, respectively, point to an age of ~220 ka for the top of the marine deposit, corresponding to the interglacial MIS 7 (Lopes et al. 2014a, 2014b; 2020a), when the relative sea level reached a measured altitude of ~10 meters above the present (Rosa 2012).

The marine deposits are overlain by the Santa Vitória Alloformation (SVA), that encompasses paleosols and fluvial deposits (Lopes et al. 2021a). The fossil-bearing deposits were initially interpreted as deposited in lagoon environments and classified as a lithostratigraphic unit named `Santa Vitória Formation` (Soliani 1973; Soliani and Jost 1975). More recent studies have shown that these deposits consist of small lakes and channels of meandering-braided fluvial systems, characterized by tabular and lens-shaped, massive to laminated muddy sand facies, several exhibiting high organic content (Fig. 8C) and rounded millimetric mudclasts (Lopes et al. 2021a). The paleosols consist of massive sand with iron oxide as coatings on the grains or forming hard centimetric nodules; iron-manganese oxides occur in the form of irregular masses (Fig. 8D) or hard subspherical nodules. Pedogenic carbonates (calcretes, Fig. 8E) originally designated as 'Caliche Cordão' (Delaney 1962) occur as subspherical to irregular nodules and rhizocretions (Lopes et al. 2024b). The SVA also includes eolian (loess) deposits apparently accumulated during the stadial MIS 4 according to luminescence ages in some calcrete nodules. The calcretes associated with loess indicate a dry and probably cold climate during MIS 4, followed by warmer and wetter conditions during the following interstadial MIS 3.

The fossils found within the SVA (Fig. 8G-Q) include essentially the same Pleistocene mammals found on the continental shelf-*concheiros*, although some species from the latter have not been found so far in the SVA, and vice-versa. The species known only from the SVA include the peccary *Brasilochoerus stenocephalus* (Copetti et al. 2021), the canids *Protocyon troglodytes* (Oliveira et al. 2005), *Dusicyon avus* (Pereira et al. 2011) and *Cerdocyon* or *Lycalopex* (Lopes et al.

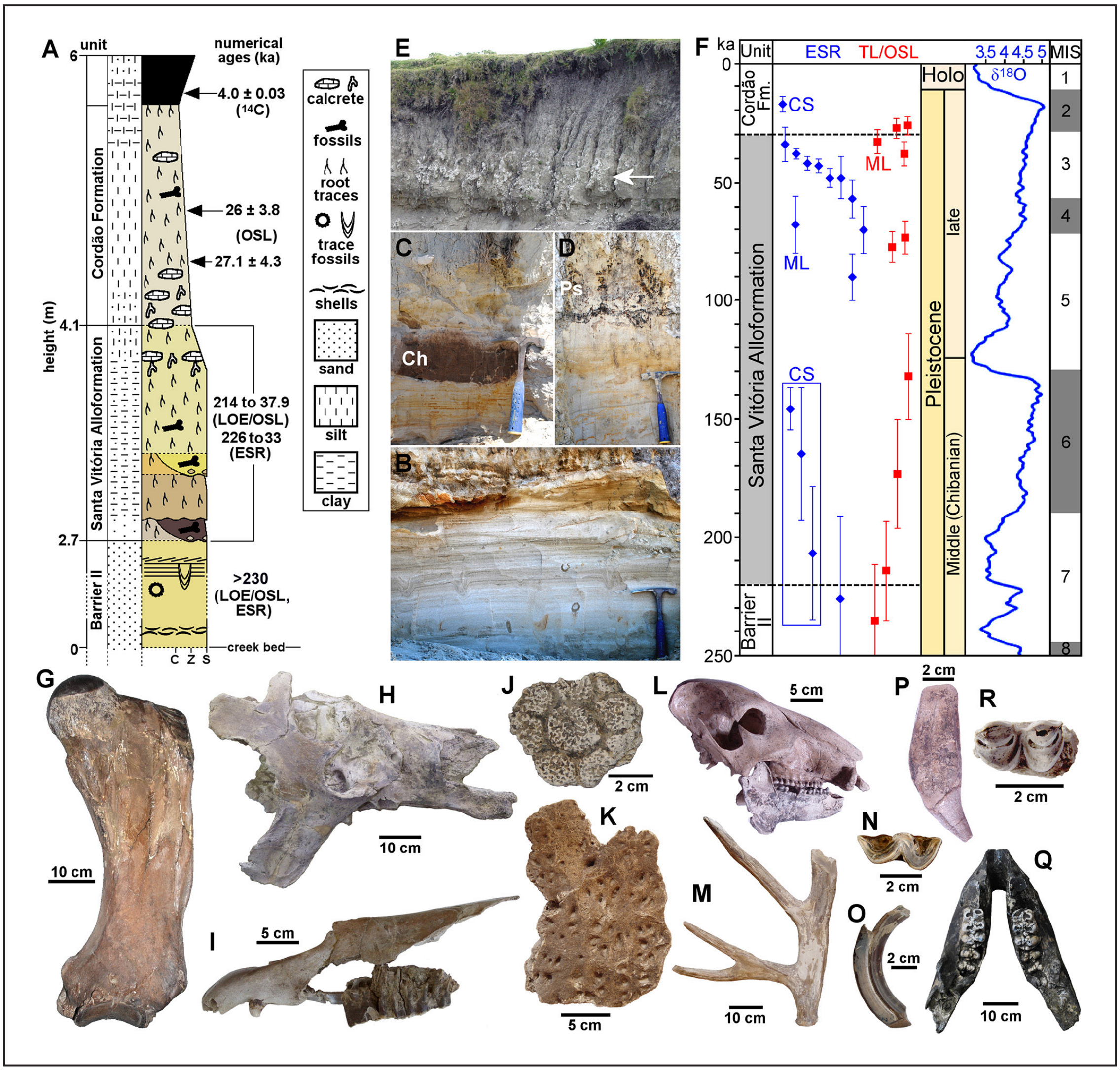

FIGURE 8 - A - Stratigraphic succession at the type section of the Santa Vitória Alloformation (modified from Lopes et al. 2021a). B - Marine trace fossils at the base of the succession. C - Fluvial channel deposit (Ch) and C - paleosol (Ps) of the Santa Vitória Alloformation. E - The Cordão Formation with calcrete horizon (indicated by the arrow) at its base. F - Chronostratigraphy of the deposits exposed along Chuy Creek based on ESR ages of fossils and TL/OSL ages of sediments from Chuy Creek, ages from Mirim Lagoon, (ML) and continental shelf (CS) are shown for comparison ($\delta^{18}O$ curve and MIS boundaries from Lisiecki and Raymo 2005). Fossils of mammals from Chuy Creek: G - Femur of *Lestodon*. H - Skull of *Megatherium*. I - Skull of *Equus*. J - Osteoderm of *Glyptodon*. K - Osteoderms of *Doedicurus*. L - Skull and jaw of *Brasilochoerus*. M - Antler of *Antifer*. N - Tooth of Macrauchenia. O - Tooth of *Toxodon*. P - Tooth of *Arctotherium*. Q - Jaw of *Notiomastodon*. R - Tooth of *Hemiauchenia*.

2015), the rodent *Holochilus brasiliensis* (Kerber et al. 2012), the ursid *Arctotherium* cf. *wingei* (Pereira et al. 2012), the giant sloth *Eremotherium laurillardi* (Lopes and Pereira 2019) and the giant armadillo *Pampatherium humboldti* (Ferreira et al. 2018), besides a stork *Ciconia* sp. (Lopes et al. 2019).

Most fossils from the SVA are either incomplete bones or unidentifiable fragments due to reworking by fluvial dynamics (Lopes and Ferigolo 2015), although complete remains can also be found (see one example in the video at https://www.youtube.com/watch?v=8ahSK3KIhyY). The fossils are generally pinkish-colored due to the incorporation of iron oxide from the surrounding sediments (Lopes and Ferigolo 2015). The weathered fossils exposed on the banks are white, whereas fossils eroded from the banks and found at the creek bottom are black. Some are encrusted by calcrete, and others exhibit crusts of muddy sand cemented by iron or iron-manganese oxides. Stable isotopes of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) in teeth of mastodons and toxodonts indicate open grassland environments (Lopes et al. 2013a). The available ESR ages of the fossils range from ~226 to 33 ka (Lopes et al. 2010; 2014b), coherent with luminescence ages that indicate deposition of the SVA between ~220 to 30 ka b2k, thus encompassing from MIS 7 to MIS 3 (Fig. 8F) (Lopes et al. 2019; 2021a). The youngest ages from the SVA and the luminescence ages from the overlying unit allow to put the disappearance of virtually all mammalian fossils (with a few exceptions, see below) from the stratigraphic succession at an interval estimated as ~30 ka b2k that coincides with the transition from the relatively warm and humid interstadial MIS 3 to the cold and dry stadial MIS 2.

The SVA is overlain by loess deposits of the Cordão Formation (CF), formed of wind-blown silt-sized dust transported from periglacial deposits in Argentina during MIS 2 as indicated by luminescence ages of ~27 and 26 ka (Fig. 8F) obtained at its type section (Lopes et al. 2016). The loess was originally described as a pedostratigraphic unit named 'Cordão Soil Unit' (Jost 1975). The lower half of this unit exhibits a calcrete horizon thicker than the calcretes found within the SVA, which suggests a longer and drier period compared to MIS 4. The only fossils discovered so far within the CF are a few fragmented teeth of rodents, and one jaw fragment of a camelid *Hemiauchenia* (Fig. 8R) bearing one molar tooth, found at a stratigraphic level slightly above the level dated as of ~26 ka. The $\delta^{13}C$ and $\delta^{18}O$ obtained in the tooth indicate a diet of desert-adapted plants (xerophytes), comparable to modern camelids that inhabit dry steppes of Argentina (Lopes et al. 2023). The disappearance of the megafauna from the stratigraphic succession along the banks, coinciding with the accumulation of loess and aridification, as inferred from the fossil of *Hemiauchenia*, suggests that the expansion of dry environments up to southern Brazil during MIS 2 may have influenced the local extinction of the Pleistocene megafauna (Lopes et al. 2020c).

The uppermost ~1-meter-thick portion of the stratigraphic succession along the banks consists of dark brown clayey to sandy silt with bivalve mollusk shells, diatomites, phytoliths and sponge spicules that indicate expansion of wetland environments under wet and warm climate during the Holocene (Lopes et al. 2021b).

2.2.3. Mirim Lagoon

This large coastal lagoon and the terraces along its margins form the Lagoon System II, developed landward of the Barrier II (Fig. 1D). The origin of the Barrier-Lagoon System II was not precisely determined yet, having been correlated to the sea level highstand of MIS 11 (424-374 ka b2k) through correlation with marine $\delta^{18}O$ curves (Villwock and Tomazelli 1995), whereas the numerical ages from the marine deposits along Chuy Creek correlated to that system indicate it could have been formed by the MIS 7 (243-191 ka b2k) marine transgression. Being an old and large water body (>170 km-long and up to ~80 km-wide), Mirim Lagoon is also a large fossiliferous site, as shown by several fossils found at its bottom and margins that record significant environmental changes in the southern CPRS between the Pleistocene and Holocene.

In recent years, several fossils have been retrieved from the bottom of Mirim Lagoon by fishermen from the town of Santa Vitória do Palmar. These fossils include extinct terrestrial mammals such as mastodons, giant sloths, glyptodonts, toxodonts, rodents, horses and cervids (Fig. 9A-I), found at water depths between 2 and 4 meters and hundreds of meters from the lagoon margin (Lopes et al. 2020b). The presence of large (and heavy) bones of giant mammals far from the margin implies that the lagoon was much smaller in the past (Fig. 9O), considering the absence of large rivers that could have transported those remains, and the low-energy hydrodynamics today. The area occupied by the lagoon was likely reduced during past glacial periods due to a combination drier climate and relative sea levels that reached up to >100 meters below the present, thus lowering the regional base level of coastal water bodies. This interpretation is consistent with seismic data showing incised fluvial channels across the area occupied today by the lagoon (Barboza et al. 2021a).

Some fossils of terrestrial mammals have been found scattered on the lagoon shore, probably eroded from Pleistocene deposits along its margins. Other fossils were found *in situ* on an irrigation channel some 1,700 meters inland from the southeastern lagoon shore. The fossils consist of isolated elements of different species, and fragmented bones of one *Toxodon* that include a tooth dated by ESR which provided ages of ~68 ka (according to the early uptake model, EU) and ~127 ka (linear uptake model, LU) (Lopes et al. 2020b). These fossils were embedded in a muddy sand overlain by a clayey to silty sand layer exhibiting a calcrete horizon. Luminescence ages in quartz grains from one calcrete nodule show that the carbonate precipitated after ~33 ka b2k (Lopes et al. 2020b), consistent with drier conditions between MIS 3 and MIS 2 inferred from the geological records found along Chuy Creek.

The other known fossils discovered in Mirim Lagoon are marine organisms. These include a diverse assemblage of molluscan shells found along the western lagoon shore in Uruguay (Martínez 1989), whereas on the Brazilian side one oyster was retrieved from the bottom by fishermen close to the port of Santa Vitória do Palmar (Lopes et al. 2021c). Other fossils found on the shore of Santiago Spit (Fig. 1D), include teeth of bull sharks (Fig. 9J,K), a species that today occurs only in warmer areas north of Rio Grande do Sul, plus a dental plate (Fig. 9L) and one dermal buckle of rays (Lopes et al. 2020b). The vertebrate fossils also include bones of one adult (Fig. 9M) and one juvenile (Fig. 9N) of southern right whales, probably a mother and the calf that entered the lagoon during the Holocene marine incusion and became stranded at the shore.

FIGURE 9 - Fossils of vertebrates from Mirim Lagoon: A - Femur of a megatheriid sloth. B - Osteoderm of *Glyptodon*. Part of the skull (C), tooth (D), and phalange (E) of a *Toxodon*. F - Tooth of *Equus*. G - Antler of *Morenelaphus*. H - Tooth of *Notiomastodon*. I - Tooth of a rodent. J - Upper (J) and lower (K) teeth of bull sharks (*Carcharhinus*). L - Dental plate of a myliobatid ray. Humerus of an adult (M) and vertebra of a juvenile (N) southern right whales (*Eubalaena*). O - Hypothetical configuration of Mirim Lagoon during the last glacial stage (modified from Lopes et al 2020). P - Shell mining at Latinos Spit. Q - Fossil mollusk shells from Latnos Spit. R - Simulated flooding of Mirim Lagoon by the Holocene sea level high-stand, the white lines show the modern coastal configuration (PL: Patos Lagoon, SGC: São Gonçalo Channel).

The fossils of marine organisms are more abundant in the Latinos Spit (Fig. 1D). This spit consists of a series of linear sand ridges developed on the northern end of Mirim Plateau, along the southern margin of the Taim Embayment (Abreu et al. 1985; Lopes et al. 2021c). These ridges contain a ~1-meter-thick deposit close to the terrain surface, formed of densely-packed mollusk shells mined for years to obtain calcium (Fig. 9P). The shells (Fig. 9Q) are mainly of two species (the bivalve *Erodona mactroides* and the gastropod *Heleobia australis*) that today are abundant in brackish conditions in the estuary of Patos Lagoon. The fossils of marine species include the sciaenid fish *Micropogonia furnieri* (black drum or *corvina*) and several mollusks that inhabit the coast of Rio Grande do Sul today, but also include the bivalves *Anomalocardia flexuosa* and *Cyrtopleura costata*, which currently inhabit only warmer areas to the north (Lopes et al. 2021c).

The sedimentary succession described from cores (Abreu et al. 1985) and hand auger samples (Lopes et al. 2021c) at Latinos Spit and the fossils of estuarine and marine species indicate a marine incursion during the Middle Holocene, between ~8 and 3 ka ago based on radiocarbon and luminescence ages (Martínez and Rojas 2013; Lopes et al. 2021c). This incursion resulted from the marine transgression that reached ~2.5 meters above the present level between 6 and 5 ka, thus flooding large areas of the southern CPRS. Seawater entered Mirim Lagoon through the incised valley at Taim (Barboza et al. 2021a) and through the São Gonçalo Channel that connects it to the Patos Lagoon (Fig. 9R). Marine and estuarine fossils have also been discovered along the São Gonçalo Channel (Ihering 1885, 1907; Godolphim et al. 1989). The presence of extralimital species found today only to the north, and the $\delta^{18}O$ in shells from Latinos Spit indicate warmer coastal waters during the marine incursion, which favored the southward dispersion of those species, possibly taking advantage of the coastal lagoons as corridors (Lopes et al. 2021c; 2022). On the other hand, the radiocarbon ages obtained in two shells of the estuarine species indicate that the lagoon became fully fresh by ~3 ka ago because of sea level fall and the establishment of the Barrier IV that cut the connection with the ocean through Taim (Lopes et al. 2021c).

3. Potential threats and protection measures

The Quaternary fossiliferous sites of the southern CPRS represent considerable periods of time and contain fossils that show significant climate-driven changes in environments and fauna, including shifts in the distribution of marine animals in response to changes in oceanographic conditions (Lopes et al. 2013b; 2021c; 2022). The terrestrial fossil assemblages are composed of a mixture of species of tropical (Brazilian) and subtropical-temperate (Pampean) origin that can be explained by repeated latitudinal shifts of climatic zones, vegetation types and mammalian faunas (Oliveira et al. 2005; Lopes 2013; Lopes et al. 2021; 2023). The changes in terrestrial plant communities, inferred from dietary patterns of herbivore mammals, may bear relationship with the local extinction of the Pleistocene megafauna (Lopes et al. 2013a; 2020c; 2023). As the plant communities of the coastal plain belong to the Pampa biome, the understanding of the vegetation dynamics in the CPRS between the Pleistocene and Holocene based on fossil records can help to assess how the contemporaneous Pampa was established and how it responds to environmental and anthropogenic pressures, thus may contribute for its conservation and management, under the concept of conservation paleobiology (Louys 2012).

The marine and terrestrial fossils provide invaluable contributions to the knowledge of the effects of climate changes and sea level oscillations on the coastal ecosystems of southern Brazil. Obtaining information about those processes, however, requires some protection measures to either prevent or mitigate possible impacts on the fossiliferous sites derived from anthropogenic activities, thus preventing the loss of important scientific information. Under the Brazilian law, fossils and paleontological sites are considered natural geoheritage and thus are legally protected, although economic activities or constructions in fossiliferous areas can result in legal and protection issues. The large area encompassed by the fossiliferous sites implies potentially multiple threats and poses significant challenges for conservation. Nevertheless, the current land use and activities in the southern CPRS apparently have low impact potential on the deposits and associated fossils.

In the case of the fossil concentrations submerged on the shelf, there are no direct sources of impact other than the natural erosive processes acting on the shoreface-foreshore. Although some fossils have been retrieved from the shelf by fishing vessels using bottom trawls (Lopes and Buchmann 2010), the use of this fishing technique is not widespread, especially in the southernmost CPRS where the submerged *parceis* and sand banks (Delaney 1965; Figueiredo Jr. et al. 1982; Caron 2014) are obstacles for the trawls. Possible future impacts on the shelf concentration include the projected installation of offshore wind farms along the inner and middle shelf of Rio Grande do Sul at depths of up to 50 meters (https://www.sindienergiars.com.br/offshore-a-nova-fronteira-da-energia-eolica).

However, the fossil concentrations along the *concheiros* are the most impacted fossiliferous site of the southern CPRS, because cars and motorcycles are allowed to travel along the beach. Although the access to certain parts of the beach, especially along the *concheiros*, is limited to four-wheel drive vehicles, unregulated rallies and motorized tourist groups cause significant impacts on the beach, by reworking sand (Fig. 10A) that can increase beach erosion, and also by destroying fossils deposited on the beach (Fig. 10B). One proposal for the establishment of a protection area in the southern CPRS is currently under scrutiny by the federal environment protection agencies. This area encompasses not only the beach as a whole (including the *concheiros*), but also the adjacent marine environment up to the isobath of ~50 meters (Fig. 10C). Although the goal is the protection of endangered species of turtles, porpoises, sharks and rays against illegal fishing, that proposal would also ensure the protection of the fossiliferous concentrations on the shelf.

The marine fossils from the Barrier III had been known only from the irrigation channel at Passo da Lagoa (Fig. 7B) (Lopes and Buchmann 2008), but the real subsurface extent of the fossiliferous deposits became known during the installation of the wind farm on the southern CPRS (Fig. 7A). Because of the known presence of fossils in the area established for the wind farm, and the large number of wind turbines to be installed, the environmental agencies requested a preliminar paleontological survey and a rescue plan to ensure the preservation of the fossils found in the area of the wind farms. As the rescue of fossils prior to the installation of the wind turbines was not possible because of the depths (up to about 20 meters) to be reached by the foundations, an alternative approach was adopted that consisted of a monitoring program to rescue any fossils extracted by the drillings for the foundations. Although the rotating drills stirred the upper meters of the sediments, upon reaching the predetermined depth they were stopped and were retrieved, bringing to the surface undisturbed sediments containing the fossils (Fig. 7C). The environmental protection agencies were mainly concerned with the possible destruction of mammalian fossils by the rotating drills, but only two small bone fragments were recovered by the drillings. On the other hand, the drillings reached fossil-rich marine and lagoon deposits of the Systems II and III, whose extent and structure

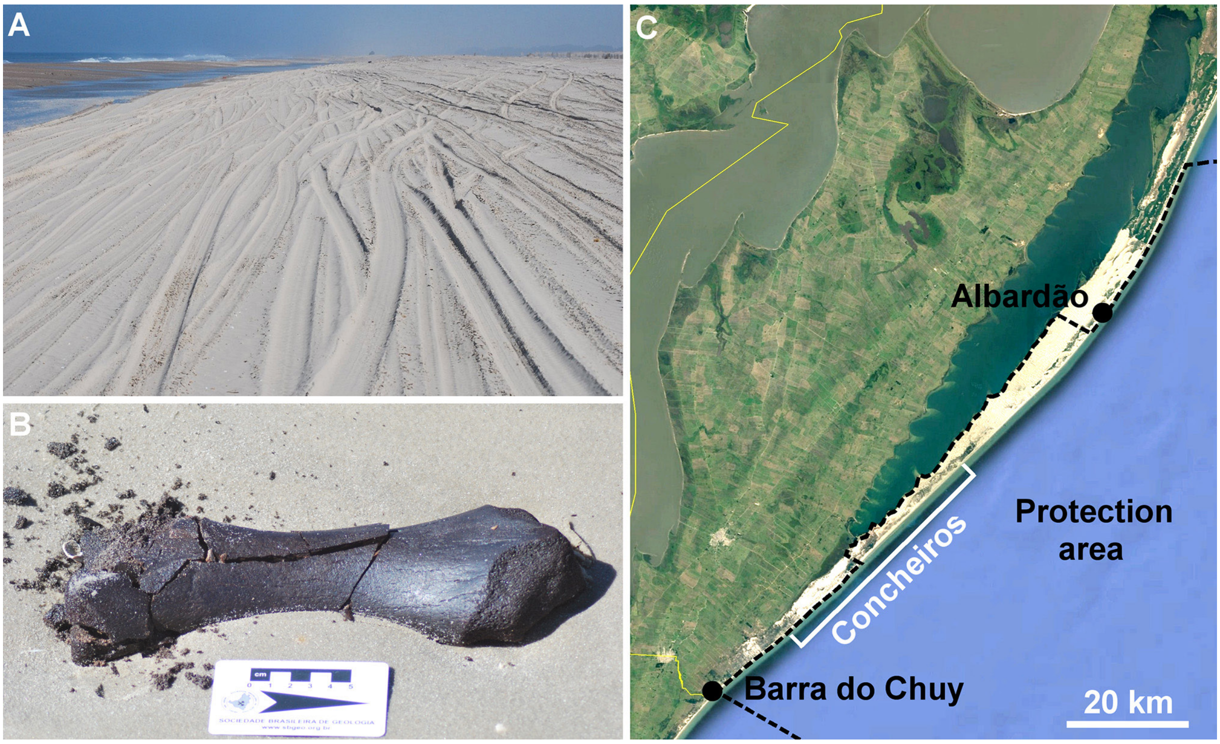

FIGURE 10 - Beach surface after the passage of a group of vehicles. B - Fossil of a giant mammal on the beach, ran over by a car. C - Google Earth image showing the proposed area (black dashed line) for a coastal and marine protection in the southern CPRS.

were unknown at the time. Together with the geological samples obtained from the boreholes, thousands of molluscan shells and other marine invertebrates were recovered across a large area (Fig. 7A). These fossils increased the knowledge of the subsurface structure and extent of the depositional Systems II and III, resulting in different scientific publications (Bettinelli et al. 2018; Lopes et al. 2020d; 2024a). The fossils were incorporated to the paleontological collection of the Museu Coronel Tancredo Fernandes de Mello, in the town of Santa Vitória do Palmar, and put on public display (Fig. 11A) as part of the scientific divulgation activities that integrated the monitoring program.

The fossil deposits along Chuy Creek are not currently under direct threat, as the creek cuts across private farmlands that use only the uppermost centimeters of the terrain for crops or pastures. In the last decade there was an increase of colluvial and alluvial sediments accumulated along most of the banks, forming deposits that are now largely covered by vegetation, which decreased erosion of the banks, thus protecting the fossils from erosion. The fossiliferous sites of Mirim Lagoon are not currently threatened, but future projects related to the Mercosul Waterway may require dredging of parts of the lagoon, which potentially can affect the fossils at its bottom. Under the Brazilian environmental laws, the water courses, lagoons, and the surrounding shores, including potentially associated fossiliferous sites, are under permanent protection. This demands that any activities to be developed around these water bodies must respect the buffer areas along the margins and may require previous environmental studies to assess the potential presence of fossils, and monitoring programs to rescue any fossil remains that might be affected.

Although the paleontological sites of the southern CPRS are not under formal protection, the *concheiros* and Chuy Creek (Lopes et al. 2009a, 2009b) are recognized as geoheritage sites of scientific and cultural importance by the Brazilian Commission of Geological and Paleobiological Sites (https://sigep.eco.br) that integrate the UNESCO World Heritage Committee. Despite the lack of formal protection for the sites, their fossils are protected in paleontological collections of universities and museums, especially the Coronel Tancredo Fernandes de Mello Museum in the town of Santa Vitória do Palmar. This museum has a collection of thousands of fossils and archaeological materials found in this area, several of which are part of a permanent exhibit that receives thousands of visitors yearly, including Brazilian and foreign tourists, schools, and universities.

Besides the public exhibition, the museum staff has been developing an educational program for more than twenty years to ensure the local people value the rich paleontological geoheritage of the region. The program includes activities with schoolchildren such as lectures and exhibitions of fossils and replicas in schools (Fig. 11B), guided tours of the museum exhibit (Fig. 11C) and simulated digging and identification of fossil replicas (Fig. 11D), besides radio interviews that reach a wide public. As a result of that program, the prehistory of the region is now included in the elementary and high school curricula; the fishermen who accidentally catch fossils from the bottom of Mirim Lagoon have donated the specimens, which are now on public display at the Mário Costa Barberena Museum, in the port of Santa Vitória do Palmar. Other people had informed the museum staff about the presence of fossils in some areas,

FIGURE 11 - A - Exhibition of fossils from the wind farms. Educational activities with schoolchildren: B - Lecture, C - Guided tour through the museum exhibit, D - Digging of fossil replicas

thus revealing new paleontological sites. Presentations for the staff working in the border post at the Brazil-Uruguay border are sometimes requested, to train the police agents to recognize fossils that may be smuggled across the border, although this had not been recorded so far. The educational program has raised the interest of the local people in the prehistory and increased the public awareness about the importance of preserving the fossils for the knowledge they provide about the geological formation and environmental changes of the coastal plain.

4. Conclusion

The southern coastal plain of Rio Grande do Sul harbors rich fossil assemblages that record important environmental changes throughout the late Quaternary. The fossils are preserved on sites distributed across a large area on both marine and terrestrial settings. Although most the fossiliferous sites are not currently under serious threat at, future developments and constructions in the area may pose risks that must be considered to establish the best measures for their protection. The protection of the sites and associated fossils is essential for their scientific relevance, but also have cultural importance as part of the geodiversity of this area and may contribute for social development through the educational value and as potential tourist attractions. Thanks to the exhibitions in local museums and associated educational activities, the local people have learned to value this geoheritage, and in turn contributed to its appreciation and preservation through identification of new fossiliferous sites and donation of fossils found accidentally.

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