



Geomorphological Heritage on the North Coast of the State of São Paulo: A Perspective About Current and Past Climate Changes

Eliana Mazzucato¹ · Denise de La Corte Bacci² · Celia Regina de Gouveia Souza³

Received: 31 December 2020 / Accepted: 31 October 2022 / Published online: 14 November 2022
© The Author(s), under exclusive licence to International Association for the Conservation of Geological Heritage 2022

Abstract

Palaeoenvironmental records contribute to understanding different climatic contexts of the past and allow to construct future scenario models, including human actions. Furthermore, the inclusion of representative sites of climate change in geoconservation strategies is an important step to inform the public about the climate system, its changes from a geological perspective and the impact of current global warming on nature and society. Thus, this study aims to present geomorphosites representatives of the past and current climate changes on coastal features on the north coast of the State of São Paulo, Brazil, and discuss their conservation implications. The methodological proceedings consisted of the inventory of geomorphosites, followed by the selection of eight climate change representative geomorphosites, as well as their analysis. The geomorphosites testify processes from the Pleistocene to the recent days associated with the coastal dynamic, influenced by sea level fluctuations. The features included cliffs on marine terraces, beachrocks, ancient channels, rocky shores, beach ridges, erosive features such as the destruction of vegetation, and anthropic constructions. The identification of geomorphosites was relevant to enable the development of geoconservation strategies facing their natural dynamic and the interactions of human processes, urban growth, and mass tourism. Also, it allowed the integration into management plans, aiming the conservation and use in teaching programs. This selection could improve the widespread knowledge about climate change and how this could affect nature and society.

Keywords Geoconservation · Palaeoenvironmental records · Climate change · Coastal geomorphology · North Coast of the State of São Paulo

Introduction

The consolidation of geoconservation as a new scientific domain in Geosciences (Henriques et al. 2011) has contributed to the development of new approaches and concerns.

This article is part of the Topical Collection on The Oxford Geoheritage Virtual Conference: Reshaping discourse in a time of social distancing.

✉ Eliana Mazzucato
mazzucato@usp.br

¹ Department of Mineralogy and Geotectonics, Institute of Geosciences, University of São Paulo, São Paulo, Brazil

² Department of Sedimentary and Environmental Geology, Institute of Geosciences, University of São Paulo, São Paulo, Brazil

³ Institute of Environmental Researches, Secretariat for Infrastructure and Environment of the State of São Paulo, São Paulo, Brazil

That includes the development of geological heritage inventories in different parts of the world, contributing to the knowledge of the Earth's geological history and promoting their conservation. Besides, geoconservation has affected nature conservation guidelines (IUCN 2008; Crofts et al. 2015, 2020), sustainable development in geoparks areas, and the popularisation of geosciences and geological heritage.

In Brazil, the first initiative on geoconservation was the creation of the Brazilian Commission of Geological and Palaeobiological Sites (SIGEP) in 1997. The Geological Survey of Brazil (CPRM) played an essential role in this process and has improved the geoparks programs and the mapping of geodiversity at state and national levels. Moreover, the increase in scientific publications in the last 20 years discussing the inventory of geological heritage, geoconservation, geotourism (Romão and Garcia 2017; Ruchkys et al. 2017), and geomorphological heritage (Mazzucato et al. 2021) also contributed to the scientific evolution of the area.

Regarding the importance of Geoconservation, the history of Earth's climate change is one of the keys elements that the geoheritage inventories can provide (Reynard et al. 2007), promoting the recognition and preservation of the palaeorecords and a better understanding of the function of the climate system and the current global warming. In this context, improving the knowledge about climate change and their future scenarios considering the anthropogenic factors is an emergent demand claimed on the thirteenth sustainable development goal (climate action) to mitigation, adaptation, impact reduction, and early warning about climate change (UN 2022).

According to Prosser et al. (2011), climate changes present opportunities and challenges for geoconservation. The opportunities concerned the preservation of palaeoclimate records that indicates how these features reacted to past climate changes. On the other hand, the main challenges are associated with the conservation and management of sites threatened by recent global warming. Therefore, some studies have dealt with the global climate change on the geoconservation framework, highlighting the past climate change records and the impacts of current climate change on geoheritage, tourism, conservation, and management (e.g. Prosser et al. 2010, 2011; Brazier et al 2012; Brown et al 2012; Ravelle et al 2014; Lozar et al. (2015); Wignall et al 2018; Āekada et al 2020; Berred and Berred 2021; Gordon et al 2022; Selmi et al 2022).

Coratza and Hobléa (2018) pointed out that climate change is one of the key issues in geomorphological heritage. Because of the dynamic dimension and the imbrications of scales, the study of geomorphosites is a relevant topic to discuss climate issues. The dynamic dimension concerns a set of processes that have created and modified the landforms over time, allowing the best observation of past and ongoing Earth processes (Pelfini and Bollati 2014). Similarly, the imbrications of scales represent variations on temporal and spatial scales, so a range of past and current conditions influenced features in varying dimensions (Reynard 2009; Coratza and Hobléa 2018). According to Pelfini and Bollati (2014), the specificities of geomorphosites cover the evaluation, valorisation, protection, and impact and risk analysis of geomorphosites.

The classification of geomorphosites is based on the dynamic processes to form the landscapes. According to Reynard (2004) and Pelfini and Bollati (2014), geomorphosites are classified into three categories: (i) active geomorphosites, (ii) passive geomorphosites, and (iii) evolving passive geomorphosites. Active geomorphosites allow the visualisation of processes in action (Reynard 2004), and they can be relevant records to understand the effects of climate change through time (Pelfini and Bollati 2014). Passive geomorphosites are records of the past environments (Reynard 2005), and “they have a particular heritage value as Earth

memory” (Reynard 2009, p. 9). On the other hand, the term evolving passive geomorphosites (Pelfini and Bollati 2014, p. 139) was created to refer to a passive geomorphosite “that are rapidly changing under the current dynamic conditions”; it differs from active ones due to the distinction concerning both genetic and current processes. Then, climate change is considered a factor in promoting the self-destruction of active and passive landforms (Pelfini and Bollati 2014), which is a fundamental criterion for promoting the site's management.

Coastal zones are especially vulnerable to the effects of climate change, such as variations in relative sea level (RSL), ocean warming, ocean acidification and deoxygenation, rain patterns, and frequency and magnitude of storms (e.g., Cooley et al. 2022). Besides, the effects of global warming increase in coastal zones because they are densely settled (e.g., Bardach 1989). In Brazil, more than 26% of the population lives in coastal areas, equivalent to 50,7 million inhabitants (IBGE 2011). The selection of geomorphosites in coastal zones is an important step in contributing to the knowledge of long-term and current climate changes. The inventory data allows the incorporation of geological heritage into coastal planning.

Considering the significance of the identification of geomorphosites that represent past and current climate changes and discussing their management implications on coastal zones, the objective of this work was to (i) present the geomorphosites related to past and current climate changes of the inventory carried out on the North Coast of the State of São Paulo, Brazil; (ii) discuss the conservation implications of this type of geomorphosites.

Study Area

General Settings

The study area is located on the North Coast of the State of São Paulo, in Brazil (Fig. 1). This region covers an area of 1,927,88 km² (Souza and Luna 2008) and is formed by the municipalities of Ubatuba, Caraguatatuba, São Sebastião, and Ilhabela. Recognised as a touristic destination, the North Coast of the State of São Paulo has an estimated 2020 population of 341,123 inhabitants (IBGE 2020), and its value can triplicate during the summer holiday. The touristic attractiveness is related to the natural landscape and beaches, showing a diversity of coastal and mountain components, preserved biodiversity, and traditional cultures.

The city of Caraguatatuba has the biggest population in the region, with a total of 123,389 estimated inhabitants (IBGE 2020). Thereby, the city developed on the largest coastal plain on the north coast of the State of São Paulo. Its extension is almost 12 km (Suguió and Martin 1978). In

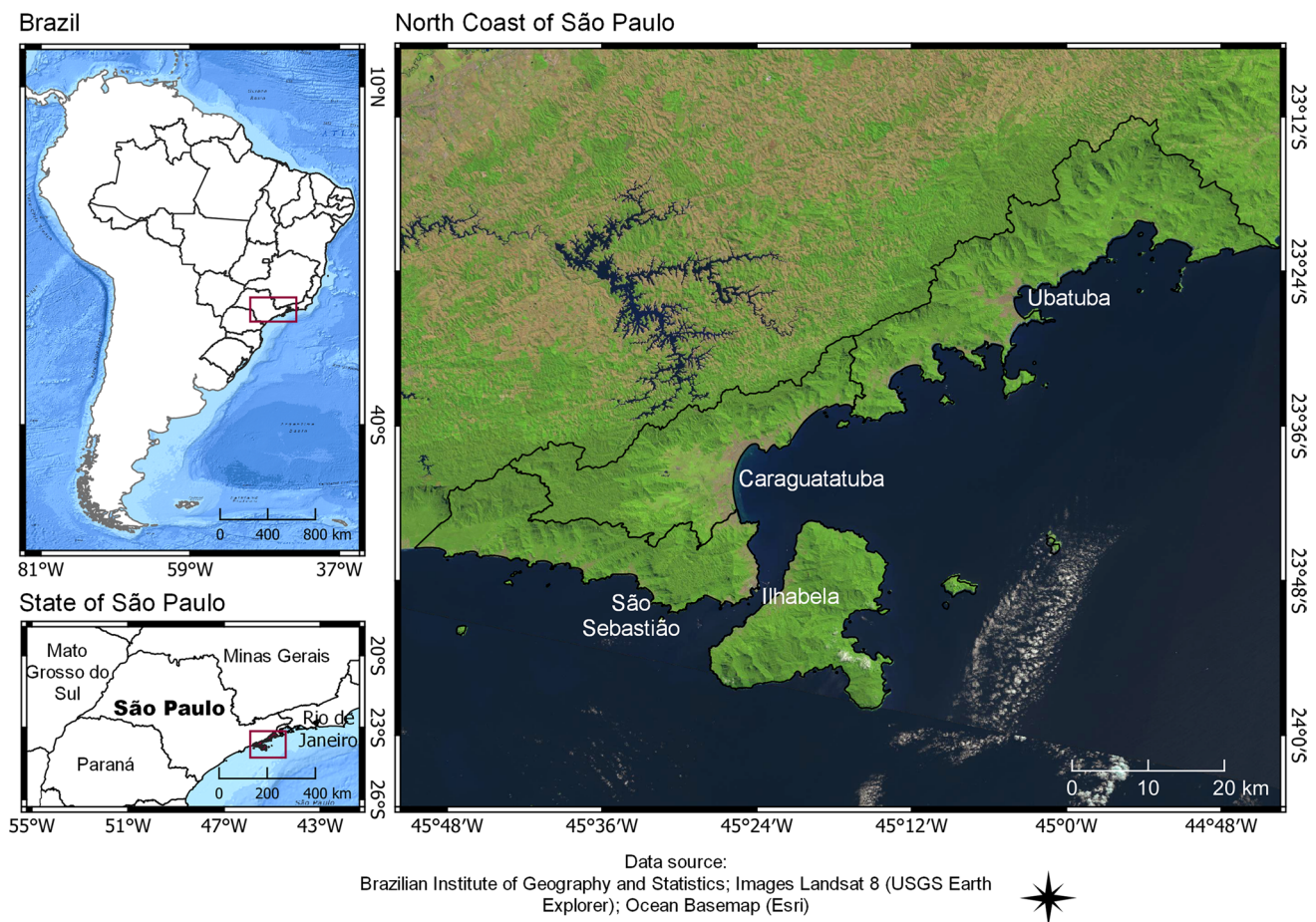


Fig. 1 Localisation map of the study area

contrast, the city of Ubatuba has 91,824 estimated inhabitants, and the central coastal plain has approximately 3 km of extension. This municipality has a dispersed occupation on pocket beaches and Serra do Mar slopes.

The current socio-economic aspects of the study area are marked by extensive preserved areas in contrast with the advancement of the urbanisation process. The creation and expansion of these municipalities occurred historically on coastal plains and, more recently, on the slopes of the Serra do Mar Escarpment. Thus, the pressure on the environment results mainly from the lack of land use and occupation planning, mass tourism, construction of summer houses, and expansion of occupation in protected and risky areas (Mazucato 2017). Garcia (2019) stresses the extreme real-estate speculation and the accelerated urbanisation and action it intended to bypass the legislation.

Many researchers have identified the geological heritage of this region (Garcia 2012; Prochoroff 2014; Santos 2014; Reverte and Garcia 2016; Arruda et al. 2017a; Jorge 2017; Rodrigues 2018; Garcia et al. 2018, 2019a). The framework of these inventories is related to the amalgamation, evolution

and fragmentation of the West Gondwana Supercontinent, and the geological history covers the Neoproterozoic to the present (Garcia et al. 2019a).

Garcia et al. (2019a) reviewed the first inventories drawn up in the area and defined 43 geosites distributed on the following specific frameworks: (i) geomorphology and landscape evolution, (ii) Quaternary evolution, (iii) Late Cretaceous alkaline magmatism, (iv) Jurassic-Cretaceous magmatism, (v) Cambro-Ordovician post-tectonic magmatism, (vi) strike-slip tectonics and shear zones, (vii) syn-tectonic granitic magmatism, and (viii) Costeiro Complex Terranes.

Palaeoenvironmental Aspects of the Coastal Zone

The interactions between geological, geomorphological, climatic, and oceanographic processes are essential factors in the genesis and evolution of coastal plains. The main characteristic of the North Coast of the State of São Paulo is a high relief in Southern Brazil (Dominguez 2009). The Serra do Mar Mountain range reached the coastline in almost all its extensions and originated the most indented coastline in

Brazil (Ab'Sáber 2000). The geomorphology of this region presents a scarped coastal range that formed the mostly heterogeneous coastline of the State of São Paulo and contains various embayments, bays, coves, and smaller and sheltered beaches (Souza 1997, 2012).

The current physiography of the coastal zone results from a sequence of events and geological, geomorphological, climatic, and oceanographic processes that determined the evolution of its basement (Serra do Mar Mountain range), the genesis and development of the watershed basins and coastal plains, and the consolidation of the current coastline and beaches (Souza 2015). After the breakup of the Gondwana supercontinent, triggering continental drift supported by a system of horsts and grabens, and the formation of the Southern Atlantic Ocean (Jurassic–Cretaceous), the coastal zone physiography has been influenced by two main sets of events (Souza 2015; Garcia et al. 2018). The first one is related to the formation of the Serra do Mar Mountain range, starting in the Upper Cretaceous, due to late tectonism and continual uplifting of the continental margin. The second set refers to climatic variations, RSL oscillations, and tectonic pulses during the Quaternary and represents a fundamental step in the development of coastal plains.

The Serra do Mar Mountain Range is, in fact, an escarpment ranging from 800 to 1000 m of elevation. Comprises Precambrian granites and granitoid bodies, high-grade metamorphic rocks, Jurassic basaltic dikes and sills, and Cretaceous alkaline intrusive bodies (e.g. Souza 2015). The genesis and evolution of the coastal plains comprise relevant records of Quaternary geological-geomorphological evolution, including sedimentary deposits, tectonic structures, the landscape, the coastline, and beaches. Morphogenesis presents a particular interest in palaeoenvironmental aspects of climate changes, RSL variations, and neotectonics during the Quaternary.

According to Suguio et al. (1985), reconstructions of fluctuations of SL in Brazil during the Quaternary have been made since the XIX century, as pointed out by Hartt (1870), Freitas (1951), and Bigarella (1965). Furthermore, the analyses of marine palaeolevels in the state of São Paulo have increased since 1974 (Martin and Suguio 1975, 1976, 1978; Suguio and Martin 1976a, b, 1978; Suguio et al. 1980).

Suguio and Martin (1978) and Martin et al. (2003) defined two main Quaternary transgressive–regressive events in the state of São Paulo. The first episode occurred at 120,000 years BP (Pleistocene) and is defined as Cananéia Transgression. The second episode had a maximum transgressive at 5600 cal year BP (calibrated years Before Present) (Holocene) and is called Santos Transgression.

According to Suguio et al. (1985), during the Cananéia Transgression, the SL would have been 8 ± 2.0 m higher than the present. The SL change curve to Santos Transgressions is marked by SL oscillations (Suguio and Martin

1978; Suguio et al. 1980; Martin et al., 1979, 2003): (i) two phases of higher SL (transgressions) occurred between 5650 and 5450 cal year BP when mean SL reached 4.0 ± 0.5 m above current position for Cananéia region and of 4.5 ± 0.5 m for Bertioga region, and around 3700–3600 year BP of 3.0 ± 0.5 m; (ii) at 2000 years BP, the SL would have been about 1.5 m higher than the present; (iii) a negative oscillation was detected between 4200 and 3700 cal year BP, with mean SL around or a little below the present level.

The Cananéia Transgression is correlated to Marine Isotope Stage (MIS) 5e (Souza 2015). The MIS 5e is recognised as the Last Interglacial period and resulted in 1.5 °C of global temperature warming (Rovere et al. 2016). Records to reconstruct SL changes in this period are fundamental to predicting changes in the face of current global warming (Rovere et al. 2016), considering that the Earth's temperature has increased approximately 1.1 °C since 1950, and predictions of a low emissions scenario indicate 1.5 °C until 2040 (Lee et al. 2021). The Santos Transgression is related to MIS 1 and is known as the final transgression (Souza 2015).

The characterisation of Quaternary units on the coastal plain provides information about these SL variations. Firsts mapping of Quaternary units of the North Coast of the State of São Paulo was provided by Suguio and Martin (1976b, 1978) and Souza (1990, 1992). Then, Souza and Luna (2008), Souza et al. (2009) and Souza (2015) proposed a mapping of Quaternary unities, integrating geological, geomorphological, pedological, and native vegetation cover criteria, for the Northern Littoral and the Bertioga coastal plains. Then, thirteen units that contain registers and dating of this evolution were defined:

- i) Current Beach: current beach deposits (medium, fine and very fine sands) at 0–2 m above the current mean SL (CMSL);
- ii) Current Tidal Flat: Late Holocene to the present estuarine deposits (sandy pelitic sediments) at –0.5 to +1.5 m above the CMSL;
- iii) Holocene to Current Fluvial Plain: fluvial deposits (sands, silty sands, and gravels) on floodplains, low terraces, bars, and bed depositional environments, at 2 to 5.0 m above the CMSL;
- iv) Holocene to Current Mixed Deposit (fluvial and colluvial): undifferentiated mixed deposits, formed by Holocene alluvial sediments reworked and buried by Late Holocene to current colluvial sediments, at 5.0 to 7.0 m above the CMSL;
- v) Holocene Palaeolagoon–Estuarine Depression: estuarine-lagoon deposits overlaid by lacustrine-palustrine sediments (silty-clayey-sandy and organic sediments), at 1.0 to 1.5 m above the CMSL;

- vi) Holocene Beach Ridge Plain: Early Holocene marine beach deposits (fine to very fine sands and bioterritic gravels), represented by regressive beach ridges, at 1.5 to 2.5 m above the CMSL;
- vii) Holocene Marine Terrace: Late Holocene marine beach deposits (very fine and medium sands), represented by lower marine terraces, at 3.0 to 4.0 m above the CMSL;
- viii) Pleistocene Marine Low Terrace: Early Pleistocene marine beach deposits (very fine and fine sands), at 4.5 to 9.0 m above the CMSL;
- ix) Pleistocene Marine High Terrace: Late Pleistocene marine beach deposits (very fine sands), forming irregular terraces, between 4.5 to 13.0 m above the CMSL;
- x) Pleistocene to Holocene Fluvial Terrace: fluvial deposits (sands, silty sands, and gravels) formed into floodplains, beds, and bars environments, at 7.5 to 10 m above the CMSL;
- xi) Pleistocene Marine High Terrace/Holocene Palaeoestuarine-Lacustrine Depression, and
- xii) Pleistocene Marine High Terrace/Pleistocene Fluvial Terrace: isolated and irregular remnants of marine terraces (very fine sands) bordered by either small and shallow palaeolagoonal-estuarine-lacustrine depressions or fluvial terraces remnants, at 4.5 to 8.0 m above the CMSL;

- xiii) Pleistocene to Current Slope Deposit: slope deposits (colluvial, talus, and alluvial) on low slopes of the Serra do Mar foothills, at > 10 m above the CMSL.

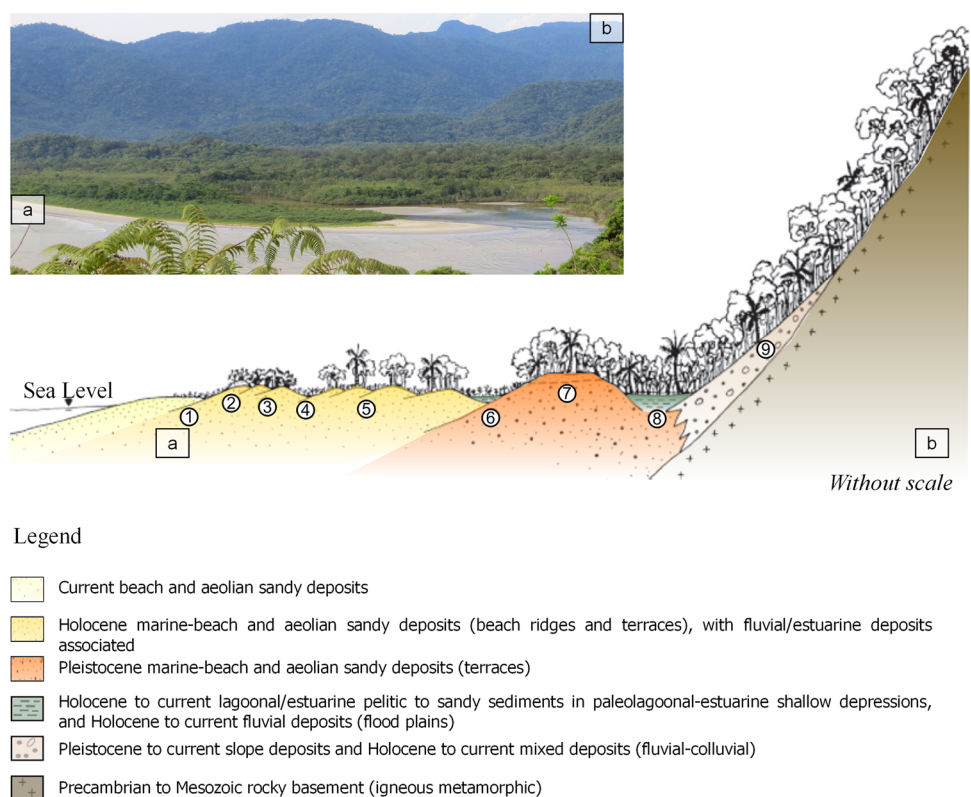
Mapping these units is also very important for understanding the evolution and development of the different coastal ecosystems (Souza et al. 1997, 2009; Souza 2015).

The association between these Quaternary units and the vegetation is illustrated in Fig. 2. In Brazil, Restinga is a general term used to refer to the native vegetation of coastal plain ecosystems (except mangroves), despite the very controversial linguistic origin of this term, which was formerly used to refer to modern coastal sandy deposits such as spits, bars, barriers and tombolos (Souza et al. 2008, 2009).

Material and methods

The methodological procedures of this study follow three main approaches: (a) inventory of geomorphosites of the study area; (b) selection of geomorphosites on coastal contexts that represent past and current climate changes; (c) analysis and discuss the relevance of this geomorphosites and their management implications.

Fig. 2 Section-type of geological and geomorphological Quaternary units present in the coastal zone of São Paulo and its association with *Restinga* phytophysionomies. The photo on the left illustrates vegetation variation through the profile (a-b) on the Mouth of Picinguaba River (Fazenda Beach-Ubatuba). 1. Beach vegetation; 2. Dune vegetation; 3. Scrub; 4. Vegetation between beach ridges; 5. *Restinga* Low forest (seaward migrating to *Restinga* High forest (landward); 6. Swamp of *Restinga*; 7. *Restinga* High forest; 8. *Restinga* Wet-High forest and Paludal forest; 9. *Restinga*-Slope Transition forest; 10. Atlantic Rainforest. Modified from Souza et al. (1997, 2008, 2009)



The inventory of Geomorphosites

The inventory of geomorphosites of the north coast of the state of São Paulo was based on the method of Reynard et al. (2016) because (i) it is a specific method for geomorphological heritage inventory with scientific and additional values (aesthetic, ecological and cultural), (ii) contain a proposition for regional scale inventories, including protected areas and others, and (iii) set an integrated approach, including the inventory and management of the sites.

According to Reynard et al. (2016), the inventory has two steps: selecting and assessing geomorphosites. The selection includes (i) definition of the main geomorphological contexts, (ii) elaboration of a preliminary list, (iii) classification of landforms, (iv) final list of geomorphosites, and (v) site documentation. The assessment covers (i) assessment of intrinsic value (scientific, ecological, aesthetic, and cultural values), (ii) characterisation of the protection and promotion of the sites, and (iii) synthesis. In this paper, it will be stressed the selection steps.

The inventory proposed initiated with the definition of the aim, which according to Lima et al. (2010), includes the

topic (the typology to be inventoried), the value (types of use), the scale (the geographical area of the study), and use (the purpose of the study). So, the objective of this inventory was to select geomorphosites with scientific and additional values (ecological, cultural, and aesthetic) on the north coast of the state of São Paulo to support educational, scientific, and touristic activities and, to contribute to the geoconservation strategies of the region. The procedures for the inventory of geomorphosites following Reynard et al. (2016) on the study area will be described below.

- i) Definition of the Main Geomorphological Contexts: This step was carried out based on a bibliographic review that highlighted the frameworks defined by Garcia et al. (2019a) and the quaternary unities by Souza (2015). The classification was based on the dominant processes related to the morphogenesis and morphodynamics of the study area. Table 1 details the contexts defined.
- ii) Elaboration of a Preliminary List: The potential geomorphosites survey was developed considering a bibliographic review, analysis of geological and geomorphological cartography, fieldwork, specialist consultation,

Table 1 Geomorphological contexts of the study area

Geomorphological contexts (processes)	Description	Categories related to (a)Garcia et al. (2019a) and (b) Souza (2015)
Tectonic	<p><i>Genesis and dynamic:</i> late tectonism and uplifting of the continental margin with the formation of the Serra do Mar Mountain range and the resulting action of tectonic adjustments, weathering, and erosional processes along the time</p> <p><i>Landforms:</i> Escarpments, peaks and hills, hills testimonies, islands and islets continentals, and structural landforms (such as triangular and trapezoidal facets on the escarpments)</p>	<p>(a) Geomorphology and landscape evolution (b) Pleistocene to current slope deposits</p>
Coastal	<p><i>Genesis and dynamic:</i> coastal processes influenced by the SL oscillations (mostly on Pleistocene and Holocene) interacting with the geological, geomorphological, and meteorological conditioners. Recently, the SL rising, and anthropogenic factors are modifying these features</p> <p><i>Landforms:</i> sandy beaches, estuaries, lagoons, bars, berms, beach cusps, beach ridges, rip currents, spits, tombolos, mangrove swamps, bedforms, and features on rock outcrops</p>	<p>(a) Quaternary evolution (b) Current Beach deposits; Current Tidal Flat; Holocene beach ridge plain; Holocene marine terrace; Pleistocene Marine Low Terrace</p>
Fluvial	<p><i>Genesis and dynamic:</i> the action of superficial water is directly related to the structural conditioners and the climatic patterns, mainly concerning the Holocene to the present</p> <p><i>Landforms:</i> V-shaped valleys, waterfalls, headwaters, mouths, channel and drainage patterns, drainage anomalies, palaeochannels</p>	<p>(a) Quaternary evolution (b) Holocene to current fluvial plain</p>
Gravitational movements	<p><i>Genesis and dynamic:</i> mass movements are influenced by the intense slopes, soil vulnerability, climatic patterns, and land use</p> <p><i>Landforms:</i> landslide scars, features of mass movements, talus, and colluvium deposits</p>	<p>(a) Quaternary evolution (b) Pleistocene to current slope deposits</p>

and the authors' knowledge. The bibliographic review mentioned above includes the analysis of the previous geological heritage inventories of the region (Garcia 2012; Santos 2014; Prochoroff 2014; Arruda et al. 2017a, b; Jorge 2017; Reverte and Garcia 2016; Rodrigues 2018; Garcia et al. 2018, 2019a) and the consultation of the management plans of the protected areas and the touristic materials.

- iii) Classification of Landforms: The sites were classified according to spatial (representatives and rare forms) and temporal criteria (ancient and current features and processes). In this sense, the temporal criteria illustrate the active, passive (Reynard 2004) and evolving passive geomorphosites (Pelfini and Bollati 2014).
- iv) The Final List of Geomorphosites: This selection occurred after the fieldwork based on representativeness and rarity criteria related to the geomorphological context defined in the study area. Another criterion applied was accessibility, including only geomorphosites with some open access, such as the trails in the natural protected area.
- v) Site Documentation: The site description was based on the general and descriptive cards based on Reynard et al. (2016) and Santos et al. (2020). The observed aspects were as follows: localisation; landforms, and process; morphogenesis and morphodynamics; accessibility; level of protection; state of conservation; potential uses; threats and impacts; assessment of scientific, ecological, aesthetic, and cultural values; and other management settings. This description was made in the fieldwork and complemented with bibliographical information.

Selection and Interpretation of Geomorphosites on Coastal Contexts That Represent Past and Current Climate Changes

This step was carried out to highlight the climate change records and the coastal zone vulnerability in the study area, selecting some ones from the inventory of geomorphosites of the North Coast of São Paulo.

The proceedings to select geomorphosites from the inventory for this analysis followed the criteria: (i) geomorphosites from coastal context and (ii) features and processes that registered the SL fluctuations, considering the Pleistocene and Holocene transgressive–regressive events that allow the reconstruction of the palaeoclimate history of the study area, and the current SL rise, both measured by the existence of scientific publications.

The evolution of the geomorphosites interpretation was carried out to highlight aspects such as: SL fluctuations, Quaternary units and related ecosystems, current erosional

processes associated with the SL rise, and to connect the evolution of the sites with the anthropogenic factors, for example, the coastal structures used to minimise the SL rise impacts. The geomorphosites were classified into active, passive, and evolving passive geomorphosites (Reynard 2009; Pelfini and Bollati 2014).

Analysis of the Management Implications of These Geomorphosites

This analysis was based on Brocx and Semeniuk (2019), which shed light on the management of sites, especially in coastal areas. According to the authors, there are many use possibilities for geological sites, such as educational, geotouristic, and scientific, and the management needs to protect fragile or vulnerable features.

The authors pointed out that the management includes concerns about the safety of visitors and actions to protect the sites. Some considerations related to safety were physical hazards associated with coastal zones (for example, rocky shores, sandy beaches, tidal flats, wave dominating coastal zones) and biological hazards (for example, dangerous biota such as cone shells, stone fish, sharks, venomous jellyfish). Concerning protection issues, some aspects cited were direct degradation (trampling), impacts of activities that can lead to degradation (excessive walking), destruction or degradation by hammering, and overcollection of rock samples.

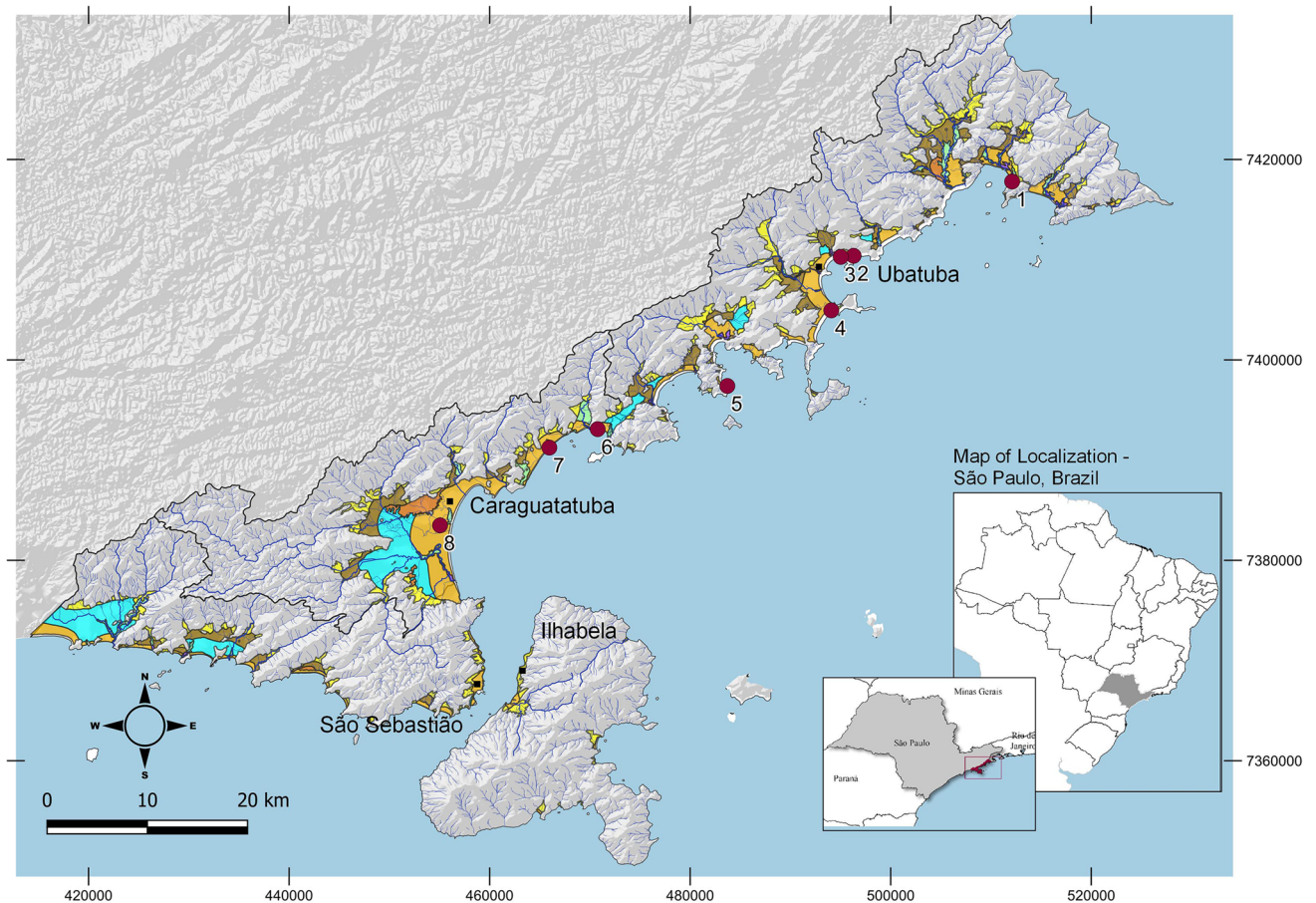
In this work, such aspects were identified in the study area, based on a bibliography review and fieldwork observations. Then, a correlation was carried out between the type of features present on the geomorphosites highlighting the sensitivity factors (according to Garcia-Ortiz 2014), the natural and anthropic threats, and the security. In addition, analysis based on the integration of those aspects led to answer the question: “how to maintain the integrity of coastal geomorphosites since they are more fragile and are subject to anthropic and natural threats?”.

Results

Representative Geomorphosites of Climate Changes

The representative geomorphosites of climate change are part of the geomorphosites inventory on the North Coast of São Paulo. This selection focused on the coastal landforms and processes, resulting in the selection of eight geomorphosites (Fig. 3).

To interpret SL variations since the Quaternary up to the present, the testimonies observed in the study area are related to (i) coastal plain evolution, including Pleistocene marine terraces, Holocene beach ridges (Suguio and Martin 1978; Souza 1997; Souza and Luna 2008), and Holocene



Legend

- North Coast of the State of São Paulo
 - Municipality
 - Geomorphosite
 - Drainage network
- Quaternary unities (Souza and Luna 2008)
- Current marine-fluvial deposits
 - Current fluvial deposits
 - Holocene to current mixed deposits (aluvial and colluvial)
 - Holocene to current colluvial and paleolagunar deposits
 - Holocene marine deposits
 - Pleistocene marine deposits
 - Pleistocene to current colluvial, talus and alluvial fans deposits

Fig. 3 Representative geomorphosites of climate changes on the North Coast of State of São Paulo related to the Quaternary unities: (1) Ancient channel of Ubatumirim River; (2) Pleistocene marine terrace of Vermelha do Norte Beach; (3) Severe erosion on Barra Seca

Beach; (4) Beachrock at Tenório Beach; (5) Rocky shores at Fortaleza Beach; (6) Accelerated erosion of Tabatinga Beach; (7) Severe erosion on Massaguaçu Beach; (8) Marine terraces, beach ridges and palaeolagoon of Caraguatatuba coastal plain

onshore beachrocks (Souza 2013; Souza and Sobrinho 2015); (ii) biological evidence, including bands of palaeoburrows of sea urchins (Vilano 2013; Vilano et al. 2013; Souza and Vilano 2015; Teles 2016); and (iii) coastal processes and features such as beach erosion (Souza and Luna 2010) and wave-cut terraces (Teles 2016).

Table 2 summarises the description of the eight geomorphosites identified according to the bibliography, highlighting features and processes observed and morphogenesis and morphodynamic interpretations. In addition, the geomorphosites were classified into active, passive, and evolving passive geomorphosites.

Table 2 Synthesis of the eight geomorphosites with past and current climate changes records on the North Coast of São Paulo

Geomorphosite (number on the map)	Municipality	Features	Process	Brief description	Category	References
Ancient channel of Ubatumirim River (1)	Ubatuba	The mouth of the Ubatumirim River; palaeochannel; freshwater ecosystems	River siltation; coastal erosion; anthropogenic processes	The original channel of the Ubatumirim River was silted after changes in the drainage system caused by the construction of the BR-101 Highway. Consequently, the beach has become starved of sediments and started to erode. Since then, this process has been accentuated by the current SL rising and coastal dynamics processes. Also, the former mangrove was substituted by freshwater ecosystems	Active geomorphosite	A; B
Pleistocene marine terrace of Vermelha do Norte Beach (2)	Ubatuba	Cliffs on marine terraces from the Cananéia Formation	Coastal processes (active and inactive); SL oscillations; beach erosion; anthropogenic processes	The formation of the marine terraces is related to the Cananéia Transgressive–Regressive event (Pleistocene). Since then, deposits have been eroded as an effect of both transgressive–regressive and neotectonic events during the Holocene and current SL rising	Evolving passive geomorphosite	A; C; D; E
Severe erosion on Barra Seca Beach (3)	Ubatuba	Severe shoreline recession, destruction of natural vegetation (<i>Restinga</i> and mangrove), and anthropic constructions	Chronic coastal erosion; anthropogenic processes	Severe coastal erosion results from changes in the drainage system due to the construction of the BR-101 Highway summed to dynamic coastal processes and the current SL rising	Active geomorphosite	A; B

Table 2 (continued)

Geomorphosite (number on the map)	Municipality	Features	Process	Brief description	Category	References
Beachrock at Tenório Beach (4)	Ubatuba	Onshore beachrock outcropping at the upper shoreface; sea urchin palaeoburrows	Physical–chemical–biological coastal processes	This occurrence is significant in the context of high-frequency SL oscillations (beach former and cementations (high temperatures and high concentration of CaCO ₃ in seawater), and neotectonic pulses that occurred during the mid-to-late Holocene. In addition, after the beachrock formation, its surface was excavated by sea-urchins in a condition of SL-rising	Evolving passive geomorphosite	F; G
Rocky shores at Fortaleza Beach (5)	Ubatuba	Three bands of palaeoburrows excavated by sea-urchin above the superior limit of the living homologous on rocky shores and correlated wave-cut platforms; fossil vermetids	Biological and physical marine processes	The formation of three bands of palaeoburrows excavated by black-sea urchins and their correlated wave-cut platforms are associated with the medio Holocene high-frequency SL fluctuations. Therefore, they indicate palaeolevels of the sea. Ages of bands were obtained from radiocarbon dating of remains of fossil vermetids incrustations associated with each one	Evolving passive geomorphosite	H; I; J; K
Accelerated erosion of Tabatinga Beach (6)	Caraguatatuba	Pleistocene marine deposits at backshore zone recently covered by beach sands; intense shore line recession	Coastal processes; coastal erosion and anthropic processes	The origin of marine deposits is related to the Cananúa Transgression. The erosion is mainly associated with the beach rotation process and rising in SL in the last century	Evolving passive geomorphosite	A; L

Table 2 (continued)

Geomorphosite (number on the map)	Municipality	Features	Process	Brief description	Category	References
Severe erosion on Massaguaçu Beach (7)	Caraguatatuba	Severe erosion of the beach and the BR-101 Highway	Coastal erosion and anthropogenic processes	Severe coastal erosion results from natural coastal processes (presence of a divergence centre of longshore drift cells) that has been intensified due to inadequate coastal defence structures, as well as the increase in frequency and magnitude of intense storm surges, and SL rising	Active geomorphosite	A; L
Marine terraces, beach ridges and palaeolagoon of Caraguatatuba coastal plain (8)	Caraguatatuba	Pleistocene and Holocene marine deposits; palaeolagoon deposits on the coastal plain	Erosion process; anthropic processes; slope processes	Pleistocene and Holocene marine deposits and palaeolagoon deposits are testimonies of the genesis and evolution of the biggest coastal plain in the study area, representing the two main Quaternary marine transgressive–regressive events, and the Holocene system lagoon–barrier	Evolving passive geomorphosite	A; M; N

A: Souza (1997); B: Souza and Luna (2009); C: Souza and Luna (2008); D: Garcia et al. (2018); E: Garcia et al. (2019a); F: Souza (2013); G: Souza and Sobrinho (2015); H: Vilano (2013); I: Vilano et al. (2013); J: Souza and Vilano (2015); K: Teles (2016); L: Souza and Luna (2010); M: Souza (1990); N: Souza (1992)

The Relevance and Management Implication of the Geomorphosites

The management of the conservation and use of geomorphosites in the study area needs to consider the particularities related to

the natural and anthropogenic factors to ensure the protection and use of the geomorphosites. Based on Brocx and Semeniuk (2019), Table 3 describes the geomorphological features of the geomorphosites correlated with their fragilities, threats, and security settings. Some examples are shown in Fig. 4.

Table 3 Contents of features, fragility, threats and security of geomorphological heritage of the study area to management conservation

Geomorphology (type of geomorphological features)	
	Cliffs on marine deposits
	Rocky shores
	Sand ridges
	Palaeochannels
	Beaches
	Erosional features
	Beachrocks
Sensitivity (According to García-Ortiz (2014), refers to the intrinsic factor being damaged or destroyed)	
	Sand marine deposits
	Active geomorphosites
	Evolving passive geomorphosites
Threats (vulnerability to extrinsic factors-natural and anthropic)	
<i>Natural</i>	
	Climate change (influencing SL rise, increasing the frequency and magnitude of high magnitude events such as storms, floods, meteorological tides, El Niño and La Niña)
	Coastal morphodynamics (dynamic equilibrium between sedimentary erosion and depositions, beach rotation)
	Fluvial erosion
	Siltation
	Loss of vegetation (generated by natural processes)
	Intense weathering of humid tropical climate
<i>Anthropic</i>	
	Inadequate occupation (snack bars, parking areas, residences) (Figs. 4a, b)
	Urban infrastructure (marinas, ports, highways, artificial stream flows)
	Inadequate coastal defence structures (seawalls, jetties, groynes, breakwaters)
	Mining (beach sand and irregular rock exploitation)
	Water pollution
	Beach pollution
	Introduction of exotic species (damaging the <i>Restinga</i> such as <i>Terminalia catappa</i> and <i>Labramia bojeri</i>)
	Loss of vegetation (generated by anthropic processes)
	Mass tourism (Fig. 4a)
	Illiteracy
	Graffiti on rocky shores and cliffs
	Scientific research (inadequate collection and sampling holes) (Fig. 4c)
Security	
	Slippery moss and dangerous benthonic communities on rocky shores (such as venomous sea urchins and barnacles)
	Breaking waves on rocky shores and beaches
	Igneous and metamorphic rock cliff collapse
	High magnitude events (storms, extratropical cyclones)
	Rip currents
	Flash flooding
	Snakes in rocky and sedimentary terrain
	Tree trunks and remains of artificial structures on the beach

Fig. 4 Threats and security aspects of coastal geomorphosites on the North Coast of the State of São Paulo. **a** Mass tourism on Fortaleza Beach (Ubatuba); **b** parking areas on the marine terraces at Vermelha do Norte Beach (Ubatuba); **c** sampling holes observed in various rocky shores and dikes on coastal zone; **d** benthonic organisms on the rocky shore may cause cuts, scrapes, and other injuries



Discussion

The eight geomorphosites selected in the study area allowed the reconstruction of the Quaternary history of the North Coast of the State of São Paulo. Figure 5 illustrates palaeoclimatic records representing Cananéia and Santos Transgression and the current processes. In the study area, those records are considered “evolving passive geomorphosites” because they testify to inherited features being modified by current coastal processes.

Palaeoclimate geomorphosites represent Marine deposits from Cananéia and Santos Transgression. According to Souza and Luna (2008), while few Pleistocene marine deposits are conserved to the present (3,01% of the study area), Holocene marine deposits are more frequent (26,6% of the study area). Furthermore, the presence of beach ecosystems, such as the *Restinga* low forest and the pioneer scrub vegetation, show a relevant interaction between those deposits and the biodiversity (Figs. 2 and 3).

The marine terrace on Vermelha do Norte Beach (Fig. 5a, b) can be considered one of the best examples of the Cananéia Transgressive–Regressive event on the North Coast, showing cliffs ranging up to 4 m high. On the other hand, correlated deposits may appear as intensely eroded outcroppings in some beach profiles, such as in Tabatinga and Barra Seca beaches. Until the early 2000s, remains of marine terraces used to be exposed in the backshore zone of Tabatinga Beach (Souza and Luna 2010) during a phase of beach rotation. However, after that, they have been recovered by beach sands. In turn, in Barra Seca Beach, these deposits have been recently exposed due to the action of chronic erosional processes (Fig. 5c).

The Beachrock on Tenório Beach (Fig. 5d) is the only beachrock occurrence in the State of São Paulo. It is a great palaeoindicator of SL oscillations during the Holocene, particularly a negative oscillation. This geomorphosite reinforces the date of the Holocene transgression maximum (about 5000 years B.P.) for the region. After this period, the beachrock indicates the occurrence of a rapid negative sea-level oscillation (about -0.4 m above the current SL), followed by a new SL rising (Souza 2013; Souza and Sobrinho 2015).

The complex evolution of the Caraguatatuba coastal plain is the most studied in the study area (Suguio and Martin 1976b; Souza 1990; Souza and Luna 2008); therefore, it has been considered a model for understanding the genesis of coastal plains on the Northern Coast (Souza and Luna 2008). The geomorphosite Marine terraces and beach ridges of Caraguatatuba coastal plain contain vestiges of a barrier-beach system, such as sand ridges and palaeolagoons (Souza 1990) (Fig. 5e). Nevertheless, those records are intensely eroded because of the natural erosion, historical occupation of the coastal plains, livestock activity development, and expansion of urbanisation.

The Rocky shores at Fortaleza Beach in Fig. 5f provide further evidence of SL fluctuations during the Holocene. According to Vilano et al. (2013), this rocky shore has three segments with palaeoburrows of sea urchins above their present living level, and their analysis contributes to understanding how the SL went to the current rates. The authors interpreted that the higher palaeoburrow level occurred about 4.48–4.58 m above the present level during Holocene, the middle palaeoburrow level occurred at around

Fig. 5 Testimonies of Quaternary palaeo-SL in the study area. **a** and **b** Pleistocene marine terraces at Vermelha do Norte Beach (Ubatuba); **c** remains of Pleistocene marine terraces on Barra Seca Beach (Ubatuba) (photo: Celia R. Gouveia Souza, 2021, May); **d** Beachrock at Tenório Beach with remains of palaeoburrows (Ubatuba) (photo: Celia R. Gouveia Souza, 2014, April); **e** Marine terraces and beach ridges at Caraguatuba coastal plain (Caraguatuba); **f** Rocky shore of Fortaleza Beach (Ubatuba), showing palaeoburrows of sea urchin, the diameter of the burrows ranges between 6 to 16 cm and are strongly weathered (photo: Celia R. Gouveia Souza, 2013, January)



3.36–3.46 m and the lowest palaeoburrow level, around 2.06–2.16 m above the present. The presence of narrow levels of free burrows intercalating that palaeolevel probably indicates that the SL decline occurred with oscillations and negative levels.

The active geomorphosites (Fig. 6) are representative of retrograding coastal processes. According to Souza and Luna (2009), these phenomena result from natural and anthropogenic factors. Natural factors include the elevation of SL and changes in the coastal dynamics. In the State of São Paulo, the rates of this increase have been about 30 to 40 cm in the last century (Mesquita 2003). Anthropogenic processes highlight interventions on the coastal plain, for instance, barrier constructions, the implementation of inadequate drainage systems, the occupation of the seafont and coastal plains, and sand removal for civil construction (Souza and Luna 2009). The “Severe erosion on Massaguaçu Beach” composes a significant example of these processes. In some stretches of this Beach, an intense erosion process has been occurring, constantly damaging and collapsing the pedestrian sidewalk and the highway (BR-101) (Fig. 6b). These processes are related to the occurrence of a divergence

centre of longshore drift cells. However, the installation of hard artificial defence structures (Fig. 6a, b) to minimise the impacts on the BR-101 highway has increased natural erosion.

The geomorphosite accelerated erosion of Tabatinga Beach (Fig. 6c, d) illustrates coastal erosion associated with the beach rotation process. In this way, Fig. 6c, d show the section representing the erosional processes. This coastal plain has an intense use and occupation changing the landscape and the evolution of the processes, mainly through the alteration of natural vegetation, installation of a private residential complex since 1977, mass tourism, the introduction of barriers for erosion control (such as sandbags on Fig. 6c), and others.

The geomorphosite on Barra Seca Beach (Fig. 6e, f) concerns mainly anthropogenic coastal erosion processes promoting retrogradation. The coastal erosion indicators of the geomorphosite include the absence of the backshore zone, shoreline retrograding, the concentration of heavy minerals in the beach sands, loss of natural vegetation and exposure of remains of Pleistocene marine terraces on the foreshore zone.

Fig. 6 Coastal erosion records related to the current increase in SL and anthropic processes in the study area. **a** Severe erosion and inadequate coastal protection built on Massaguaçu Beach (Caraguatatuba) (photo: Celia R. Gouveia Souza, 2016, January); **b** collapse of pedestrian pavement and artificial structures on Massaguaçu Beach (Caraguatatuba) (2022, October); **c** coastal protection work on Tabatinga Beach (Caraguatatuba) (photo: Celia R. Gouveia Souza, 2019, November); **d** intensified anthropic occupation and shoreline retrograding on Tabatinga Beach (Caraguatatuba) (photo: Celia R. Gouveia Souza, 2021, May); **e** remnants of a containment wall on Barra Seca Beach (Ubatuba) (photo: Celia R. Gouveia Souza, 2021, May); **f** a huge tree trunk fallen by coastal erosion and exposed roots on Barra Seca Beach; **g** siltation of the ancient channel of the Ubatumirim River (Ubatuba) (2020, November); **h** Ancient channel of the Ubatumirim River and severe beach erosion (Ubatuba) (photo: Celia R. Gouveia Souza, 2015, December)



Concerning the Ancient channel of Ubatumirim river geomorphosite, the feature observed at the mouth of the Ubatumirim River indicates a channel originated from a river of higher erosion capacity. According to Souza and Luna (2009), the Ubatumirim River changed its natural course due to BR-101 highway construction, on 1970th. Nowadays, the landform observed is a silted palaeochannel (Fig. 6g, h). This process also has been altering the dynamic sedimentary balance on the beach since the deposition of sediments at this mouth was drastically reduced, intensifying erosive processes.

The management for conservation and use of these geomorphosites is a complex issue because of their intrinsic dynamic aspect. Changes in coastal landforms occur on a faster time scale than in other environments.

The conservation strategies must be adapted to the characteristics of geomorphosites and the study area. The high touristic frequency of these geomorphosites is an assumption that needs attention due to the natural fragility of the risks associated with climate change and SL rising and the necessity to explain and prepare the population for their

consequences. The proposals to face these threats are integrating Geoconservation issues on the Protected Areas on the north coast and developing activities to promote the sites. Some examples of Protected Areas in this region are the Marine Environmental Protection Area of the north coast, the Serra do Mar State Park, the Ilhabela State Park, the Ilha Anchieta State Park, and others.

In this sense, an achievement was made in the Marine Environmental Protection Area of the central coast of São Paulo in 2019 as an approach developed after the inventory of geosites in the region (Garcia et al. 2018). As a result, five geosites were included in the Management Plan as areas with historical and cultural interest, and a new zoning category was created, named geobiodiversity protection zone. This example represents the first time that geosites were included in the management of protected areas in Brazil (Garcia et al. 2019c).

The Centre for Research Support in Geological Heritage and Geotourism (GeoHereditas) at the Geosciences Institute of the University of São Paulo (IGc-USP) has promoted some initiatives for training courses with environmental monitors, teachers, and the community (Garcia et al. 2019b; Mazzucato et al. 2018) based on systematic geological heritage inventories on the region. The courses intended to promote the popularisation of Geosciences and the awareness to the need for the conservation of geological heritage. These previous experiences were responsible for consolidating a partnership between GeoHereditas and some Protected Areas (Serra do Mar State Park and Marine Environmental Protection Area of the North Coast of the State of São Paulo). Also, it is important to highlight that through the works promoted by GeoHereditas, twelve interpretative panels with geosites information were installed in the region (Garcia et al. 2019b). In the following steps, the climate changes issues and geomorphosites could be integrated into those actions.

Concerning training courses, it is also important to mention the initiative aimed at guiding civil defence officials, traders, public managers, teachers, and the local community of the coast of São Paulo against coastal risks (Souza et al. 2022).

Coastal geomorphosites are characterised by a high educational and geoturistic potential because their records include morphogenesis and morphodynamics that can be observed on a human time scale. Besides, accessibility is an advantage due to the proximity of roads, the availability of public transport, and parking areas. In general, there are no significant topographic variations, and the access does not need a forest trail. Then, the perception of the dynamic of past and current processes concerning SL oscillations and climate change contributes to raising awareness about global warming and its impacts on the ecosystem's services (e.g. Garcia 2019).

Conclusion

The emphasis given to climate change on coastal zones in the inventory of geomorphosites aims to contribute to the incorporation of this topic in geoconservation strategies. The selection of eight geomorphosites was a primary step to reconstituting past and current climate changes in the coastal zone of São Paulo. The geomorphological registers illustrate the Pleistocene to the present geological phenomena bringing an innovative perspective to the inventory of the north coast of the State of São Paulo. Furthermore, focusing on the Quaternary framework to actual and climate changes is essential to new education policies, geotourism and land use planning.

The geomorphosites identified represent evolving passive and active categories and consist of challenges to discussing conservation needs. The evolving passive geomorphosites are especially relevant to promote reconstructions of palaeoenvironmental aspects and show a morphodynamic relative to the current SL rising. Furthermore, these geomorphosites summarise the dynamic characteristic concerning the genesis and evolution of coastal geomorphosites. On the other hand, active geomorphosites exemplify the current morphodynamics concerning global warming and anthropogenic processes (considering the long, medium, and short terms to modify landforms).

The conservation criteria for these two categories are different. In evolving passive geomorphosites, the central management objective is to preserve the geological register of quaternary conditions and enable scientific research to improve palaeoenvironmental reconstructions. On the other hand, the management objectives of active geomorphosites are to promote actions to minimise the effects of climate fluctuations and SL elevation on coastal plains using active geomorphosites as an example of hazards and promote the integration of socioenvironmental context to Geoconservation.

It is also noted that the categories observed in the study area represent a potential resource to improve the knowledge about palaeoenvironmental processes in the coastal zone and the evolution of the patterns of climate oscillation through time. Therefore, it is an increased step to sensibilise the public to Geoconservation and coastal management.

Acknowledgements We are grateful to the organisers of the I Oxford Geoheritage Virtual Conference, convened by the Oxford University Museum of Natural History, 2020, for the opportunity to write this paper. In addition, we thank the two anonymous reviewers for their helpful comments on the manuscript.

Funding Financial support was received from the National Council for Science and Technological Development of Brazil (CNPq) for the doctoral scholarship (Process n. 140331/2019–0), the São Paulo Research Foundation (BIOTA-FAPESP) (Process n. 2019/19527–5), and the Coordination for the Improvement of Higher Education Personnel (CAPES).

Declarations

Conflict of Interest The authors declare no competing interests.

References

- Ab`Saber AN (2000) Fundamentos da Geomorfologia Costeira do Brasil Inter e SubTropical. *Rev Bras Geomorfol* 1:27–43 <https://doi.org/10.20502/rbg.v1i1.67>
- Arruda KEC, Garcia MGM, Del Lama EA (2017a) Inventory and quantitative assessment of geological heritage of the town of Caraguatatuba, São Paulo. *Geociências (São Paulo)* 36:447–462
- Arruda KEC, Garcia MGM, Del Lama EA, Mucivuna VC, Reverte FC (2017b) Método de seleção e propostas de uso dos sítios da geodiversidade: Exemplo do litoral norte do estado de São Paulo, Brasil. *Anuário do Inst Geociências* 40 (3):24–47 https://doi.org/10.11137/2017b_3_24_47
- Bardach JE (1989) Global warming and the coastal zone. *Clim Change* 15:117–150. <https://doi.org/10.1007/BF00138849>
- Berred S, Berred K (2021) Climate change issues, challenges, and impacts in terms of rural geo-biological and cultural tourism activity development in semiarid areas: a case study from Tata, Bani Geopark (Anti-Atlas, South Morocco). *Geoheritage* 13:110 <https://doi.org/10.1007/s12371-021-00640-1>
- Bigarella J (1965) Subsídios para o estudo das variações do nível oceânico no Quaternário brasileiro. *An Acad Bras Cienc* 37:263–278
- Brazier V, Bruneau PMC, Gordon JE, Rennie AF (2012) Making space for nature in a changing climate: the role of geodiversity in biodiversity conservation. *Scott Geogr J* 128:211–233. <https://doi.org/10.1080/14702541.2012.737015>
- Brocx M, Semeniuk V (2019) The ‘8Gs’—a blueprint for Geoheritage, Geoconservation, Geo-education and Geotourism. *Aust J Earth Sci* 66:803–821. <https://doi.org/10.1080/08120099.2019.1576767>
- Brown EJ, Prosser CD, Stevenson NM (2012) Geodiversity, conservation and climate change: key principles for adaptation. *Scott Geogr J* 128:234–239. <https://doi.org/10.1080/14702541.2012.725859>
- Čekada TM, Rodovan D, Lipuš B et al (2020) Very small glaciers as geoheritage: combining a spatio-temporal visualisation of their development and related effects of climate change. *Geoheritage* 12:85. <https://doi.org/10.1007/s12371-020-00511-1>
- Cooley S, Schoeman L, Bopp L, et al (2022) Oceans and coastal ecosystems and their services. In: Pörtner HO, Roberts DC, Tignor M, et al (eds) (2022). *Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge UK and New York, NY, USA, pp. 379–550. <https://www.ipcc.ch/report/ar6/wg2/>. Accessed 15 September 2022
- Coratza P, Hobléa F (2018) The specificities of geomorphological heritage. In: Reynard E, Brilha J (eds) *Geoheritage: Assessment, Protection and Management*. Elsevier, Amsterdam, pp 87–106. <https://doi.org/10.1016/B978-0-12-809531-7.00005-8>
- Crofts R, Gordon JE, Brilha J, et al (2020) Guidelines for geoconservation in protected and conserved areas. *Best Practice Protected Area Guidelines Series N° 31*. IUCN, Gland, Switzerland
- Crofts R, Gordon JE, Santucci V (2015) Geoconservation in protected areas. In: Worboys GL, Lockwood M, Kothari A et al (eds) *Protected area governance and management*. Australian National University Press, Canberra, pp 531–568
- Dominguez JML (2009) The Coastal Zone of Brazil. In: Dillenburg SR, Hesp PA (eds) *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*. Springer, Berlin, Heidelberg, pp 17–51. https://doi.org/10.1007/978-3-540-44771-9_2
- Freitas RO de (1951) Ensaio sobre a Tectonica moderna do Brasil. *Boletim da Faculdade de Filosofia, Ciências e Letras, Universidade de São Paulo. Geologia* (6), 7–107. <https://doi.org/10.11606/issn.2526-3862.bffcluspgeologia.1951.121701>
- Garcia MGM (2012) Gondwana geodiversity and geological heritage: examples from the North Coast of São Paulo State, Brazil. *Anuário do Inst Geociências* 35:101–111 https://doi.org/10.11137/2012_1_101_111
- Garcia MGM (2019) Ecosystem services provided by geodiversity: preliminary assessment and perspectives for the sustainable use of natural resources in the coastal region of the State of São Paulo, Southeastern Brazil. *Geoheritage* 11:1257–1266. <https://doi.org/10.1007/s12371-019-00383-0>
- Garcia MGM, Del Lama EA, Martins L, et al. (2019a) Inventory and assessment of geosites to stimulate regional sustainable management: the northern coast of the state of São Paulo, Brazil. *An Acad Bras Cienc* 91 <https://doi.org/10.1590/0001-37652019a20180514>
- Garcia MGM, Reverte FC, Mucivuna VC, et al (2019b) Geoconservação em áreas protegidas: contribuição de cursos para monitores ambientais no Litoral Norte do estado de São Paulo, Brasil. *Terrae Didat* 15:e019028 <https://doi.org/10.20396/td.v15i0.8652390>
- Garcia MGM, Lanza MCT, Silva IL, Mucivuna CV, Costa JA, Queiroz DS (2019c) Geossítios como áreas de interesse em planos de manejo de unidades de conservação: exemplos da APA Marinha Litoral Centro, estado de São Paulo. In: *Anais do V Simpósio Brasileiro de Patrimônio Geológico. Geopark Araripe, Crato, Ceará*, pp 40–41. http://www.urca.br/vsbgp/?page_id=2420. Accessed 09 Nov 2022.
- Garcia MGM, Brilha J, de Lima FF et al (2018) The inventory of geological heritage of the State of São Paulo, Brazil: Methodological Basis, Results and Perspectives. *Geoheritage* 10:239–258. <https://doi.org/10.1007/s12371-016-0215-y>
- Gordon JE, Tormey D, Wignall R, Brazier V, Crofts R (2022) Climate change will challenge the management of geoheritage in protected and conserved areas. *Parks Stewardship Forum* 38(1) <https://doi.org/10.5070/P538156119>
- Hartt C (1870) *Geology and physical geography of Brazil*. Fields, Osgood & Co., Boston
- Henriques MH, dos Reis RP, Brilha J, Mota T (2011) Geoconservation as an emerging geoscience. *Geoheritage* 3:117–128. <https://doi.org/10.1007/s12371-011-0039-8>
- IBGE. Instituto Brasileiro de Geografia e Estatística (2011) *Atlas geográfico das zonas costeiras e oceânicas do Brasil*. IBGE: Diretoria de Geociências, Rio de Janeiro
- IBGE. Instituto Brasileiro de Geografia e Estatística (2020) *IBGE cidades*. <https://cidades.ibge.gov.br/>. Accessed 22 Dec 2020
- IUCN (2008) Resolution 4.040: conservation of geodiversity and geological heritage. In: *Resolutions and recommendations*. IUCN, International Union for Conservation of Nature, Gland, pp 44–45
- Jorge M do CO (2017) *Potencial geoturístico e estratégias de geoconservação em trilhas situadas na região sul do município de Ubatuba-SP*. PhD thesis, Federal University of Rio de Janeiro
- Lee JY, Marotzke J, Bala G, et al (2021) Future global climate: scenario-based projections and near-term information. In: Masson-Delmotte V, Zhai P, Pirani A, et al (eds). *Climate change 2021: the physical science basis. Contributions of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672. <https://www.ipcc.ch/report/ar6/wg1/>. Accessed 16 September 2022
- Lima FF, Brilha JB, Salamuni E (2010) Inventorying geological heritage in large territories: a methodological proposal applied to Brazil. *Geoheritage* 2:91–99. <https://doi.org/10.1007/s12371-010-0014-9>

- Lozar F, Clari P, Dela Pierre F et al. (2015) Virtual tour of past environmental and climate change: the Messinian succession of the Tertiary Piedmont Basin (Italy). *Geoheritage* 7:47–56. <https://doi.org/10.1007/s12371-014-0098-8>
- Martin L, Suguio K (1975) The state of São Paulo coastal marine Quaternary geology. *An Da Acad Bras Ciência* 47:249–263
- Martin L, Suguio K (1976) O quaternário marinho do litoral do Estado de São Paulo. In: *Anais do 29º Congresso Brasileiro de Geologia*, vol 1, Ouro Preto, SBG, pp 281–294. <http://www.sbggeo.org.br/home/pages/44#Anais%20de%20Congressos%20Brasileiros%20de%20Geologia>. Accessed 09 Nov 2022.
- Martin L, Suguio K (1978) Excursion route along the coastline between the town of Cananéia (State of São Paulo) and Guaratiba outlet (State of Rio de Janeiro). In: *International Symposium on Coastal Evolution in the Quaternary*. São Paulo.
- Martin L, Dominguez JML, Bittencourt ACSP (2003) Fluctuating Holocene sea levels in eastern and southeastern Brazil: evidence from a multiple fossil and geometric indicators. *J Coast Res* 19(1):101–124
- Martin L, Suguio K, Flexor J-M (1979) Le Quaternaire marin du littoral brésilien entre Cananéia (SP) et Barra de Guaratiba (RJ). In: Suguio K, Fairchild TR, Martin L, Flexor JM (eds) *Proceedings of the International Symposium on Coastal Evolution in the Quaternary*, São Paulo, pp 296–331. <https://repositorio.usp.br/item/001661105>. Accessed 09 Nov. 2022
- Mazzucato E (2017) *Estratégias de geoconservação no Parque Estadual da Serra do Mar - Núcleos Picinguaba e Caraguatatuba (SP)*. Dissertation, University of São Paulo
- Mazzucato E, Bacci D de LC, Santos VMN dos (2018) Educação para a geoconservação: reflexões da experiência no Parque Estadual da Serra do Mar (SP). *Terrae Didat* 14:417–426 <https://doi.org/10.20396/td.v14i4.8654191>
- Mazzucato E, Mucivuna VC, Bacci DC, Garcia MGM (2021) Inventories of geomorphological heritage: a review of the Brazilian scientific publications. In: Lozano G, Luengo J, Cabrera A, Vegas J (eds) *Abstract book of the X International Online ProGEO Symposium*, Spain, p 19–20
- Mesquita AR (2003). Sea-level variations along the Brazilian coast: a short review. *Journal of Coastal Research*, Special Issue 35, p 21–31 <https://www.jstor.org/stable/40928745>. Accessed 26 September 2022
- UN. United Nations (2022) The sustainable development goals report. <https://unstats.un.org/sdgs/report/2022/>. Accessed 23 September 2022
- Pelfini M, Bollati I (2014) Landforms and geomorphosites ongoing changes: concepts and implications for geoheritage promotion. *Quaest Geogr* 33:131–143. <https://doi.org/10.2478/quageo-2014-0009>
- Prochoroff R (2014) *O patrimônio geológico de Ilhabela - SP: estratégias de geoconservação*. Universidade de São Paulo. Dissertation, University of São Paulo
- Prosser CD, Burek CV, Evans DH, Gordon JE, Kirkbride VB, Rennie AF, Walmsley (2010) Conserving geodiversity sites in a changing climate: management challenges and responses. *Geoheritage* 3:123–136. <https://doi.org/10.1007/s12371-010-0016-7>
- Prosser CD, Bridgland DR, Brown EJ, Larwood JG (2011) Geoconservation for science and society: challenges and opportunities. *Proc Geol Assoc* 122(3):337–342. <https://doi.org/10.1016/j.pgeola.2011.01.007>
- Ravanel L, Bodin X, Deline P (2014) Using terrestrial laser scanning for the recognition and promotion of high-alpine geomorphosites. *Geoheritage* 6:129–140. <https://doi.org/10.1007/s12371-014-0104-1>
- Reverte FC, Garcia MGM (2016) Avaliação Quantitativa do patrimônio geológico: aplicação aos geossítios de São Sebastião, Litoral Norte do estado de São Paulo. *Anuário do Inst Geociências* 39:43–56 https://doi.org/10.11137/2016_2_43_56
- Reynard E (2004) Géotopes, géo(morpho)sites et paysages géomorphologiques. In: Reynard E, Pralong J-P (eds). *Paysages géomorphologiques*. Institut de Géographie, Lausanne, pp 123–136. https://serval.unil.ch/resource/serval:BIB_2B3783E15AB9.P001/REF.pdf. Accessed 09 Nov 2022
- Reynard E (2005) Géomorphosites et paysages. *Géomorphol Reli Process Environ* 11:181–188. <https://doi.org/10.4000/geomorphologie.338>
- Reynard E, Fontana G, Kozlik L, Scapozza C (2007) A method for assessing “scientific” and “additional values” of geomorphosites. *Geogr Helv* 62(3):148–158
- Reynard E (2009) Geomorphosites: definitions and characteristics. In: Reynard E, Coratza P, Regolini-Bissig G (eds) *GEOMORPHOSITES*. Pfeil Verlag, München, pp 9–20
- Reynard E, Perret A, Bussard J et al (2016) Integrated approach for the inventory and management of geomorphological heritage at the regional scale. *Geoheritage* 8:43–60. <https://doi.org/10.1007/s12371-015-0153-0>
- Rodrigues FH (2018) *Estudo da geodiversidade da região norte da Ilha de São Sebastião (SP): uma proposta de mapeamento geoambiental aplicado à estratégia de geoconservação*. PhD thesis, São Paulo State University
- Romão RMM, Garcia MGM (2017) Initiatives of inventory and quantification of geological heritage in Brazil: an overview. *Anuário do Inst Geociências - UFRJ* 40:250–265 https://doi.org/10.11137/2017_2_250_265
- Rovere A, Raymo ME, Vacchi M, Lorscheid T, Stocchi P, Gómez-Pujol L, Harris DL, Casella E, O’Leary MJ, Hearty PJ (2016) The analysis of Last Interglacial (MIS 5e) relative sea-level indicators: reconstructing sea-level in a warmer world. *Earth Sci Rev* 159:404–427. <https://doi.org/10.1016/j.earscirev.2016.06.006>
- Ruchkys UA, Mansur KL, Bento LCM (2017) A historical and statistical analysis of the Brazilian academic production, on master’s and PhD level, on the following subjects: Geodiversity, geological heritage, geotourism, geoconservation and geoparks. *Anuário do Inst Geociências - UFRJ* 40:180–190. https://doi.org/10.11137/2017_1_180_190
- Santos DS, Mansur KL, Seoane JCS, Mucivuna VC, Reynard E (2020) Methodological proposal for the inventory and assessment of geomorphosites: an integrated approach focused on territorial management and geoconservation. *Environ Manage* 66:476–497. <https://doi.org/10.1007/s00267-020-01324-2>
- Santos PL de A (2014) *Patrimônio geológico em áreas de proteção ambiental: Ubatuba-SP*. Dissertation, University of São Paulo
- Selmi L, Canesin TS, Gauci R, Pareira P, Coratza (2022) Degradation risk assessment: understanding the impacts of climate change on geoheritage. *Sustainability* 14(7):4262 <https://doi.org/10.3390/su14074262>
- Souza CRG (1990) *Considerações sobre os Processos Sedimentares Quaternários e Atuais na Região de Caraguatatuba, Litoral Norte do Estado de São Paulo*. Dissertation, University of São Paulo
- Souza CRG (1992) *Considerações sobre a origem de um depósito marinho pleistocênico no litoral norte do Estado de São Paulo*. *Bol IG - Univ Sao Paulo, Inst Geociencias* 23:43–54 <https://doi.org/10.11606/issn.2316-8986.v23i0p43-54>
- Souza CRG (1997) *As células de deriva litorânea e a erosão nas praias do Estado de São Paulo*. PhD thesis, University of São Paulo
- Souza CRG (2012) *Praias arenosas oceânicas do Estado de São Paulo (Brasil): Síntese dos conhecimentos sobre morfodinâmica, sedimentologia, transporte costeiro e erosão costeira*. *Revista do Departamento de Geografia*, pp 308–371. <https://doi.org/10.7154/RDG.2012.0112.0014>
- Souza CRG (2013) *The Ubatuba Beachrock (State of São Paulo, Brazil): A New Evidence of a Mid-Holocene Negative Sea-Level*. In: 8th International conference (AIG) on Geomorphology. Paris, p 917
- Souza CRG (2015) *The Bertioga Coastal Plain: an example of morpho-tectonic evolution*. In: Vieira BC, Salgado AAR, Santos LJC (eds)

- Landscapes and landforms of Brazil. World Geomorphological Landscapes. Springer, Dordrecht, pp 115–134
- Souza CRG, Galera RA, Oliveira ACA (2022) RedECOST – Uma areia para o futuro: Plataforma de comunicação de Riscos Costeiros para o Estado de São Paulo (Brasil). In: XIX Congresso Latinoamericano de Ciencias del Mar. Panamá, 2022.
- Souza CRG, Luna GC (2008) Unidades quaternárias e vegetação nativa de planície costeira e baixa encosta da Serra do mar no litoral norte de São Paulo. *Rev Do Inst Geol* 29:1–18. <https://doi.org/10.5935/0100-929x.20080001>
- Souza CRG, Luna GC (2009) Taxas de retrogradação e balanço sedimentar em praias sob risco muito alto de erosão no município de Ubatuba (Litoral Norte de São Paulo). *Q Environ Geosci* 1(1):25–41. <https://doi.org/10.5380/abequa.v1i1.14489>
- Souza CRG, Luna GC (2010) Variação da linha de costa e balanço sedimentar de longo período em praias sob risco muito alto de erosão do município de Caraguatatuba (Litoral Norte de São Paulo, Brasil). *Rev Gestão Cost Integr* 10:179–199
- Souza CRG, Sobrinho JMA (2015) Beachrock de Ubatuba (Litoral Norte de São Paulo): evidências de oscilações negativas e positivas do nível do mar no Holoceno Médio a Superior. In: XV Congresso da Associação Brasileira de Estudos do Quaternário (ABEQUA), Imbé, p 165
- Souza CRG, Vilano VF (2015). Utilização de bandas de paleolocas de ouriços-do-mar como indicadores de estabilização do nível do mar no Holoceno. In: VX Congresso da Associação Brasileira de Estudos do Quaternário – ABEQUA, Tramandaí/Imbé (RS). Abstracts (http://abequa.org.br/trabalhos/Anais_XVABEQUA.pdf). Accessed 23 September 2022
- Souza CRG, Bendazoli A, Sugiyama M, et al. (1997) A relação entre o meio físico e a biota no estudo da “Restinga” do Estado de São Paulo. In: VI Congresso da Associação Brasileira de Estudos do Quaternário (ABEQUA). ABEQUA, Curitiba, pp 367–372
- Souza CRG, Moreira MG, Lopes EA (2009) Coastal plain and low-medium slope sub-biomes: a new approach based on studies developed in Bertioiga (SP). *Braz J Ecol* 8:1–13
- Souza CRG, Hiruma ST, Sallun AEM, et al. (2008) “Restinga” Conceitos e empregos do termo no Brasil e implicações na legislação ambiental. Instituto Geológico, São Paulo
- Suguio K, Martin L (1976a) Presença de tubos fósseis de “Callianassa” nas formações quaternárias do litoral paulista e sua utilização na reconstrução paleoambiental. *Bol IG* 7:17 <https://doi.org/10.11606/issn.2316-8978.v7i0p17-25>
- Suguio K, Martin L (1976b) Brazilian coastline quaternary formations — the states of São Paulo and Bahia littoral zone evolutive schemes. *An Acad Bras Cienc* 48:325–334
- Suguio K, Martin L (1978) Quaternary marine formations of the state of São Paulo and Southern Rio de Janeiro. In: International Symposium on Coastal Evolution in the Quaternary, Special Publication, n. 1, São Paulo, IGCP/SBG, p 57. <https://repositorio.usp.br/item/003076219>. Accessed 09 Nov 2022
- Suguio K, Martin L, Bittencourt C et al (1985) Flutuações do nível relativo do mar durante o Quaternário Superior ao longo do litoral brasileiro e suas implicações na sedimentação costeira. *Rev Bras Geoc* 15:273–286
- Suguio K, Martin L, Flexor JM (1980) Sea level fluctuations during the past 6000 years along the coast of the State of São Paulo, Brazil. *Earth Rheol Isostasy Eustasy, Proc Symp, Stockholm* 471–486
- Teles RD (2016) Caracterização paleogeográfica de costões rochosos da porção sul do município de Ubatuba, SP. Dissertations, University of São Paulo
- Vilano WF (2013) Aspectos Biogeográficos e Paleogeográficos de Costões Aspectos Biogeográficos e Paleogeográficos de Costões Rochosos de Ubatuba - São Paulo. Dissertations, University of São Paulo
- Vilano WF, Souza CRG, Cantareli CV, Silva WWDB (2013) Sea urchin burrows in rocky shores as indicator of Holocene sea-levels at the northern coast of the State of São Paulo, Brazil. 8th International Conference on Geomorphology (AIG), Paris, 27–31/08/2013. Abstracts, p. 361. http://www.geomorph.org/wp-content/uploads/2019/11/ABSTRACTS_BOOK_IAG_PARIS_2013.pdf. Accessed 23 September 2022
- Wignall RML, Gordon JE, Brazier V, MacFadyen CCJ, Everett NS (2018) A qualitative risk assessment for the impacts of climate change on nationally and internationally important geoheritage sites in Scotland. *Proc Geol Assoc* 129(2):120–134. <https://doi.org/10.1016/j.pgeola.2017.11.003>

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.