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ORIGINAL ARTICLE

Characterization and Valuation of the Geological Heritage Identified in the Peró Dune Field, State of Rio de Janeiro, Brazil

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Abstract The Peró dune field is one of the largest in southeastern Brazil. Besides possessing Quaternary eolic records relating to the semiarid climate of the region, it also contains archaeological sites and functions as a haven for endemic animal and plant species, some of which are endangered. The dune field is of hydrogeological and pedological importance, not to mention being a site of undeniable natural beauty. The area has been targeted by the real estate industry and could disappear due to international tourism-based projects. The aim of the study reported here is to demonstrate the relevance of this site as a geological and geomorphological heritage site according to international methodologies used for such evaluations and through a comparison of the results obtained here with those in the inventory of the other geosites contained in the Cabo Frio Tectonic Domain. The results show that the area is relevant in four key areas, namely, science, culture, education and tourism. They also highlight the frailty of this geodiversity unity, which was constructed through the actions of the wind and which has an important ecological function as a biodiversity substrate and aquifer. The ultimate goal of the study is to use these results as arguments for the preservation of the area.

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Keywords Valuation of geological heritage · Geoconservation · Quantification of geoheritage

Introduction

The Peró dune field (Fig. 1) is an important record of eolic activity in the state of Rio de Janeiro and southeastern Brazil. To date, most of the field has been protected from urban occupation, with the exception of an area in the Peró district, the southwestern part of which has been developed, beginning in the 1970s. This dune field covered approximately 3.5 km^2 in 1958, with only 2.6 km^2 remaining at the present time. It is divided into two parts: a well-preserved one to the north (2.4 km^2), and a second, also well-preserved, part encompassing a little more than 0.1 km^2, located between the Peró urbanized center and the beautiful Conchas Beach (Fig. 2). The field in its totality falls under the administrative jurisdiction of the Pau Brasil Environmental Protection Area (APA), created by State Decree 31346 on June 6th, 2002.

This region, known as Costa do Sol (Sun Coast), is the main target of urban developers outside the metropolitan area of Rio de Janeiro. Deforestation, irregular demarcation of lots and real estate speculation are worrying problems in the region (Farah 2009). Furthermore, together with Angra dos Reis and Paraty, this region is one of the two centres of national and international tourism in the state of Rio de Janeiro, being also one of the most important in the country. Since the tragic landslides caused by the torrential rains in Angra dos Reis during the 2009–2010 New Year festivities, the Costa do Sol region has become the destination of an ever-increasing number of tourists. Therefore, one cannot rule out an increase in the pressure from residential development for the region of Cabo Frio, Armação dos

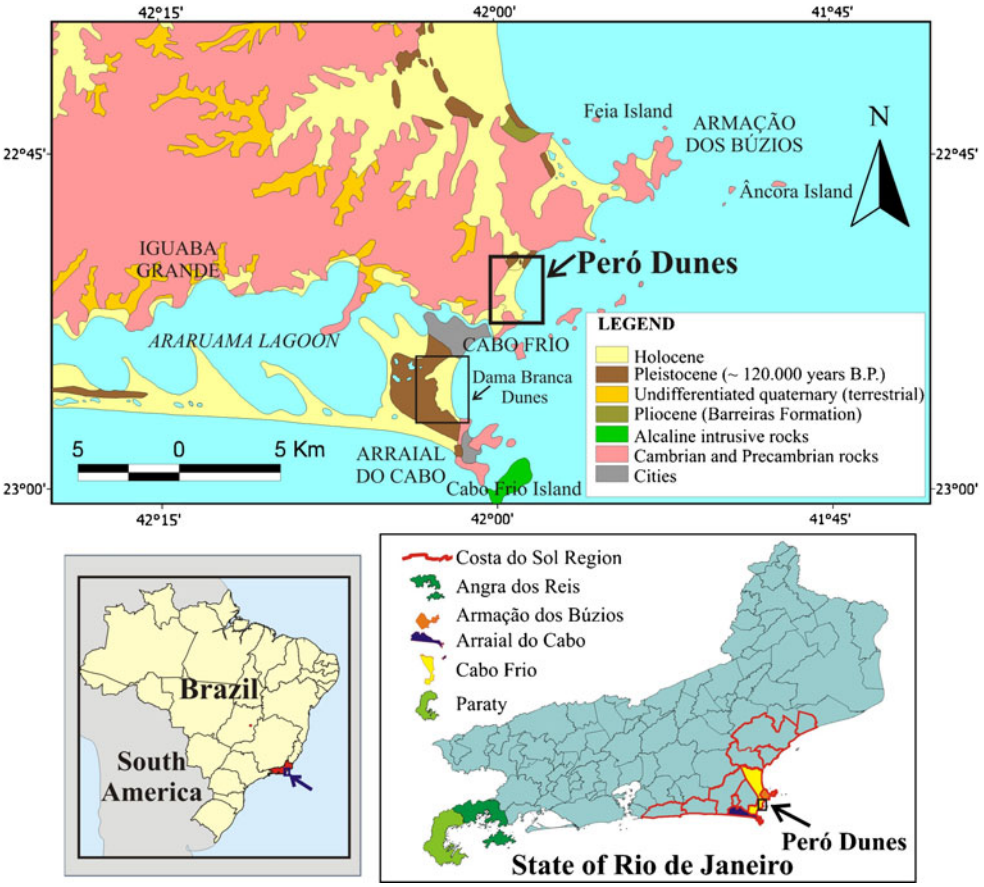

Fig. 1 Simplified geological map of part of the Costa do Sol Region (modified from Martin et al. 1997; Morais and Mello 2003). The localities cited in this paper are shown in the Rio de Janeiro state map

Búzios and Arraial do Cabo in the upcoming years, especially in those areas that contain the dune fields and have been preserved to date. In Cabo Frio alone, there are reports of the eradication of almost 21% of the original vegetation between 1960 and 2000 (Bohrer et al 2009).

Since 2006, the state of Rio de Janeiro's environmental licensing system has been discussing and analyzing a project for constructing hotels and real estate projects that would occupy the area as a whole, including the surrounding wetland zone, with the exception of a portion of the mobile dunes. This project has already acquired a preliminary license from the state environmental agency and has recently been conceded a construction license for one of its six resorts (Fig. 3). The project also contemplates commercial zones, clubs, entertainment areas, golf and polo fields and approximately 1000 houses.

Protected areas are divided into two groups according to Brazilian Law 9985 (July 18, 2000). The first one, called integral protection, allows little to none human interference and is usually refers to publicly owned properties. The second group, called sustainable use, refers to private lands and establishes use restrictions, which are based on a zoning project approved by a public authority. The APAs, such as the Pau-Brasil one, in which the Peró dune field is located, belongs to the latter group.

According to the APA's Master Plan zoning (Decree 32517, from December 23rd, 2002; Fig. 4a), the dune field was divided into wildlife conservation (ZCVS) and preservation zones (ZPVS) (mobile dunes) as well as controlled occupation zones (ZOC) (stationary dunes and adjacent wetland areas). With the formalization of these types of use, the resort project was planned so that: (1) the wildlife conservation area was assigned to the hotel complex; (2) the wildlife preservation zone, the smallest area among them all, was reserved for preservation; (3) the controlled occupation zone was assigned to lots and golf and polo fields (Fig. 4b). The dunes are also protected by the Brazilian Forest Code (Law 4771, from September 15th, 1965) as an APP (Permanent Preservation Area). However, a directive from a lower legal instance (CONAMA Resolution 341, from September 25th, 2003) allows the implementation of touristic projects in these environments, with a few restrictions.

IBAMA (2008), the Brazilian environmental agency, analyzed the construction plan for the resorts based on the zoning plan of the Pau Brasil APA and on the existence of the Permanent Preservation Area (APP). This report concluded that there would be significant alterations to the environment, which should be protected, according to the law.

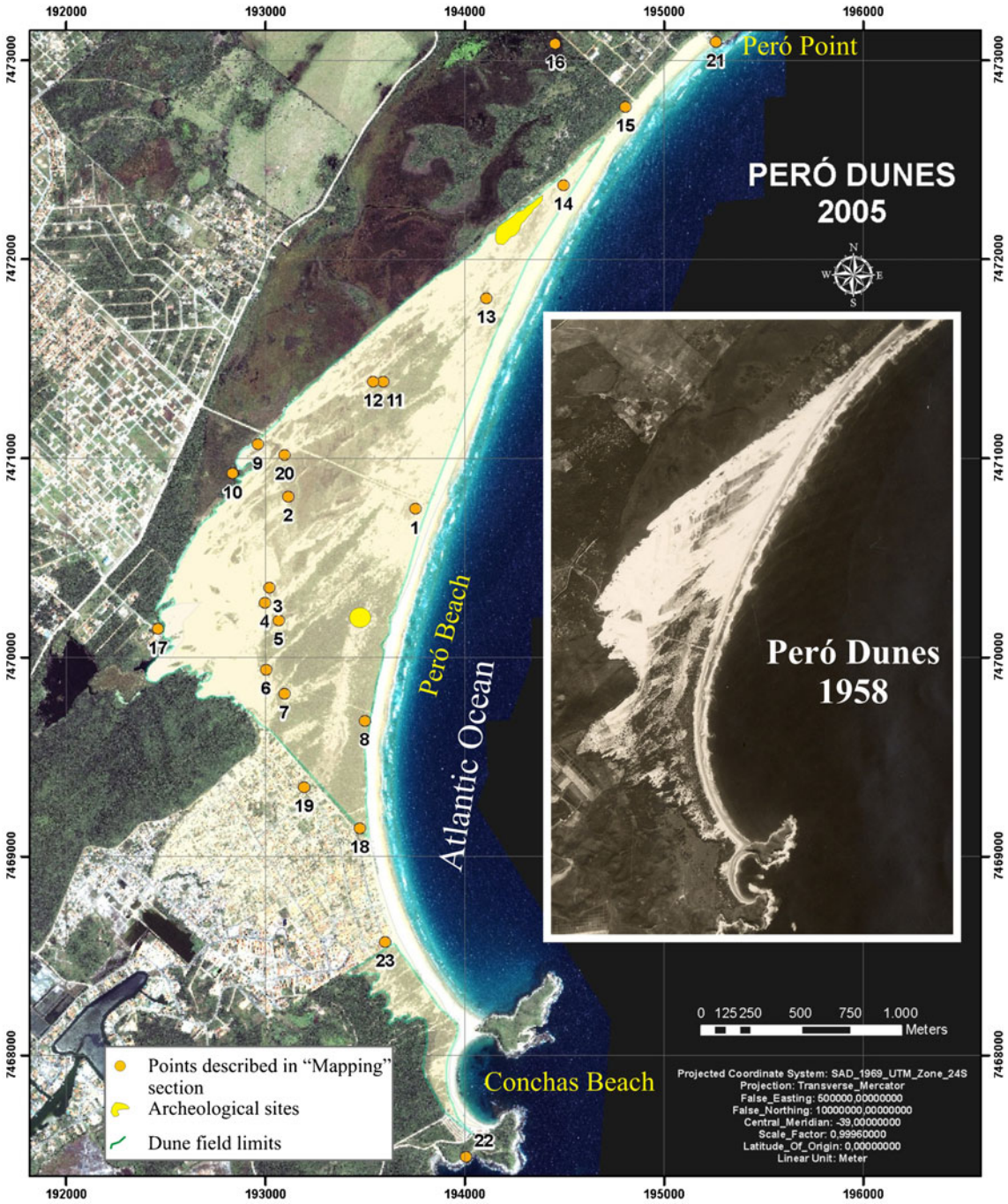

Fig. 2 Satellite image of the Peró dune field in 2005. Note the urban growth that has segmented the field into two parts. The map displays all the points described in the Mapping section and all known archaeological sites. Source: IKONOS image 2005. *Inset* A detailed aerial photograph from 1958 (DRM-RJ archive) in which it is possible to observe the low urban occupation

The goal of the study reported here is to make an inventory of the site features and then assess these within the framework of a potential geological heritage site in order to justify a geoconservation strategy. A much broader aim is to inform public institutions, nongovernmental organizations (NGOs) and the general population of the geological importance of the area, from a geoconservation point of view, given the imminent threat of its destruction.

Area Characterization

The Peró dune field is part of the Cabo Frio Tectonic Domain (CFTD) (Heilbron et al. 2000), whose palaeoproterozoic basement holds rocks and sediments from the Neoproterozoic, Paleozoic, Cretaceous, Paleogene, Neogene and Quaternary ages. Within the Quaternary record, there are at least four dune fields that can be

Fig. 3 **a** Pau Brasil Environmental Protection Area (APA) zoning plan in the dune field area; *yellow line* represents the resort's limits. *ZCVS* Wildlife conservation zone, *ZPVS* wildlife preservation zone (both referring to mobile dunes), *ZOC* controlled occupation zones (stationary dunes and adjacent wetland areas). **b** Resort's master plan. Note the total occupation of the fixed dunes and of the adjacent wetland area; *yellow line* indicates the area of Club Med already licensed for construction. Image source: Project's Environmental Impact Study (modified from SERVEC 2007)

mapped down to a scale of 1:50,000, with the Cabo Frio/Dama Branca fields and the Peró field being the two largest and containing the most important eolic deposits of southeastern Brazil (Castro and Rangel 2005). This singular characteristic is due to the local climate with low pluviometric precipitation, where the average rain volume in the area between Arraial do Cabo and Armação dos Búzios is 800 mm/year. According to Köppen-Geiger's classification (Barbiére 1994, cited in Bohrer et al. 2009; Araujo et al. 2009), it is a hot semi-arid climate (BSh). In the neighboring areas, especially in the mountain scarps, the average precipitation can reach 1,500 mm/year.

The combination of a markedly dry season, a regimen of winds that blow predominantly in one direction (from the northeast quadrant) and an income of sandy sediments from the shelf and the coastal massifs promotes the necessary conditions for the existence of these important eolic deposits (Castro and Rangel 2005). According to Pereira et al. (2008a, b) and Fernandez et al. (2009), the wind-remobilized sand comes from quaternary sandy transgres-

Fig. 4 Location of climbing dunes and aquifer-discharge areas forming lakes and wetlands (Image: Google Earth)

sive barriers upon which the dune fields develop. There are both mobile and stationary dunes in the region, with the latter having been fixed by native vegetation.

The Peró dune field extends from Peró Point to Conchas Beach (Fig. 2). Both places are rocky shores formed by felsic orthogneisses of paleoproterozoic age, intruded by cretaceous basic dykes. Eolic sediments cover the coastal plain, whose origin is associated with successive alterations in the relative sea level during the last 120 thousand years (Turcq et al. 1999; Dias et al. 2009).

Castro and Rangel (2005) divide Peró's sedimentary system into five morphological compartments: beach, foredunes, deflation basin and oblique and climbing dunes. According to these authors, this is one of the three Brazilian dune fields that display climbing dunes. These features are accumulated on ramps under the lee of a mountain front (Fig. 4). Dune shapes in Peró fields include barchans, barchanoids and transverse.

A 2.5-m-deep core was collected by the percussion method in the deflation basin of the dune field, a distance of 570 m from the current beach line (Point 12 in Fig. 2) (Dias et al. 2009). This study revealed the presence, at the bottom of the core, of coal that resulted from the burning of a *Laguncularia racemosa* trunk, a typical mangrove species, whose age was radiocarbon dated to between 6348 and 6374 cal BP. Valves of *Anomalocardia brasiliana* were also found at a depth of 0.8 m and dated to 3373–3000 cal BP. Their presence shows that there was a progradation of the coast line during that period. Turcq et al. (1999) had already identified three main events of relative sea level increase in the last 7,000 years on the coast of the state of Rio de Janeiro: from 7000 to 5100, 3900 to 3600 and 2700 to 2500 years AP.

At least four levels of palaeosoils and water table level-variation indicator spots were observed by Dias et al. (2009) in the core interval. Given the characteristics of the eolic deposits, a type of soil that develops over stationary dunes and which is very rare in other parts of the state can be found in the Peró and Dama Branca fields, namely, spodosols. These appear as a slightly hardened iron crust and give rise to the formation of B horizons. Such soils are pedological rarities in southeastern Brazil, made possible only due to the existence of dunes.

The Peró dune field is a porous aquifer. The discharge of freshwater from saturated sands toward adjacent areas produces groundwater flows to form lakes and wetlands (Fig. 4). This aquifer discharge allows the development of humid ecosystems, such as temporary or permanent freshwater lakes and flooding areas, which are of great environmental significance and whose existence is directly associated with the hydrogeological characteristics of the sandy deposits. The presence of freshwater in the area is important because there are no rivers to supply the population and watering livestock. For many centuries, the only source of freshwater was the groundwater extracted from sandy deposits along the coast and the water found in intra-dune lakes and in the peripheral areas of the dune fields.

Dune fields are common in northeastern Brazil due to the combination of sand supply and climatic factors, particularly the hot semi-arid climate. On the other hand, a tropical climate with summer rains dominates the southeast, where the state of Rio de Janeiro is located. Dune fields should not occur there, given this climatic profile. However, a portion of the Costa do Sol region has a hot semi-arid climate as well, with a hydric deficit (Freitas

2006) and a dry season in winter, mostly with winds from the NE quadrant. This special climate is explained by the resurgence of cold waters from the Malvinas Current (South Atlantic Central Water) in the region of Cabo Frio Island. Resurgence is a process by which deep-water masses in the ocean rise to the surface bringing with them a large amount of nutrients. The location of this phenomenon seems to be the result of a combination of several factors, such as the sudden change in direction of the Brazilian coast line and the position of the Brazil Current axis. However, according to Turcq et al. (1999) and Bohrer et al. (2009), the NE winds originating from the South Atlantic Semi-permanent Anticyclone seem to be a determining factor because they carry away the warm surface oceanic mass, thereby favoring the vertical migration of the cold water. This process prevents the formation of cumulus clouds responsible for convective rains.

Two archaeological sites, as well as the presence of lithic material, have been identified in the Peró dune field. Highlighted in Fig. 3, these two sites contain chipped quartz, pot shards, possibly of Tupi-guarani tradition, and pecked pebbles (lithic artefacts) that functioned as hammerstones. Anvils and scrapers have also been found in the largest site, to the north (Venturini and Gaspar 2007; IBAMA 2008). There is another archaeological site at Conchas Beach.

Another important aspect is the occurrence of native biota, whose existence reinforces the uniqueness of the area and the role its geological substrate plays in the development of species. Thus, one can find endangered animal species endemic to the state of Rio de Janeiro, such as the bird formigueiro-do-litoral (*Formicivora littoralis*), the reptile lagartixa-da-praia (*Liolaemus lutzae*; Fig. 5c) and the annual fishes (*Sympsonichthys constanceae* and *Nematolebias whitei*) (IBAMA 2008). One can also find plant species native to the coastal areas, such as *Jacquinia armillaris* (Fig. 5d), classified as Vulnerable in IBAMA's Official List of Endangered Plants (http://www.ibama.gov.br/flora/extincao.htm). Orchids, bromeliads and cactuses (Fig. 5e) form vegetation classified as herbaceous and bushy restinga (Bohrer et al. 2009), and even locally arboreal (Fig. 5f).

Methodology

State Inventory and the Insertion of the Peró Dune Field

The inventory is a tool used to list the heritage assets, recognize their value and subsequently publicize them. Singularity and/or monumentality are attributes that one tries to identify in each inventoried asset in order to enhance its value and justify its protection.

The Peró dune field is one of the geosites chosen for the geological heritage inventory of the state of Rio de Janeiro, which is in its final phase of deployment. Therefore, the methodology presented below is the same as that used for the state inventory one, which is based on:

1) International Scientific Committee on Cultural Landscapes of ICOMOS (International Council on Monuments and Sites): Cultural Landscape inventory sheet proposal (http://www.icomos.org/landscapes/inventory_card.htm);
2) International Union for Conservation of Nature (IUCN): among other topics, it discusses the role of national inventories (http://cmsdata.iucn.org/downloads/geology.pdf) and the importance of comparative analysis for the identification of "exceptional universal value" as described by the Convention Concerning the Protection of the World Cultural and Natural Heritage, adopted by the UNESCO General Conference, Paris, 1972. It also advances the characterization of the typology associated with geological heritage, used in several countries to inventory and valuate geological and geomorphological sites.
3) SIGEP (Brazilian Commission of Geological and Palaeobiological Sites; *Comissão Brasileira de Sítios Geológicos e Paleobiológicos*): one of its goals is to organize and manage a database of Brazilian geological sites, as well as publicize it through specific publications and the Internet (http://e-groups.unb.br/ig/sigep/).
4) Lima et al. (2010) discusses a proposal for an unified methodology for the Brazilian inventory assuming the Geological Survey of Brazil (CPRM) as the organizing and managing institution and the collaboration of state governments and scientists. The author lists the strong points found among the inventories featured in her research: (a) participatory activities involving researchers; (b) the use of qualitative criteria for the selection of geosites; ©) the use of geological context or frameworks to systematize the inventories. As negative points, she lists difficulties in involving government officials and even scientists.

Following IUGS orientation (Wimbledon 1996), the Rio de Janeiro state area was divided into frameworks (Mansur 2010). Since this state comprises a vast majority of metamorphic and magmatic rocks, tectonic domains were used, according to Trouw et al. (2000), Heilbron et al. (2000), Heilbron and Machado (2003) and Schmitt et al. (2008) as frameworks for the geological heritage inventory. Thus, Rio de Janeiro state is divided into four parts: Cabo Frio Tectonic Domain, Oriental Terrain (comprising the Coastal Domain and the Rio Negro Magmatic Arch), Occidental Terrain and *Klippe* Paraíba do Sul. Therefore, these are the selected frameworks to group the inventoried

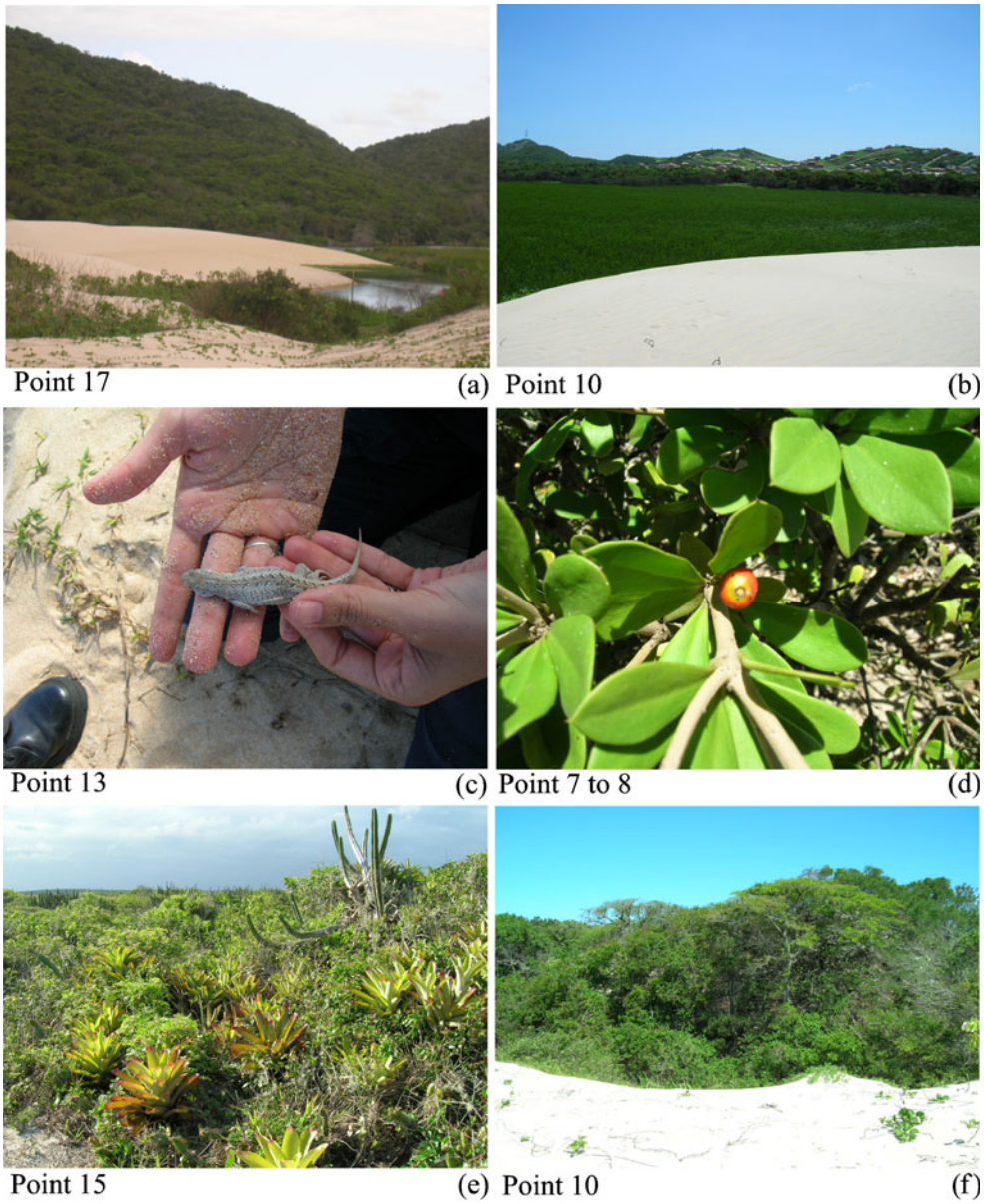

Fig. 5 Ecological value of geodiversity. **a** Lake in the frontal portion of the dune field, **b** aquifer discharge zone in the NNE portion, **c** *Liolaemus lutzae*, **d** *Jacquinia armillaris*, **e** bush vegetation (bromeliads, orchids, cactuses, among others), **f** arboreal vegetation. *Numbers* (*Point*) refer to the numbers on the map in Fig. 2, and indicate the locality where the picture was taken

sites in Rio de Janeiro state. The different soils, the Cenozoic clastic, chemical and biogenic deposits, the Meso-Cenozoic alkaline rocks and the Mesozoic diabasic dykes were assessed within the context of their location.

The cataloging data contained in the geosites' sheets were based on the Spanish [García-Cortés 1996; García-Cortéz and Carcavilla 2009, Comissão Brasileira de Sítios Geológicos e Paleobiológicos do Brasil (SIGEP), International Scientific Committee on Cultural Lanscapes (ICOMOS), ProGEO–Portugal (http://www.progeo.pt/progeo_pt.htm)] and UK (Greater London Authority 2008) inventories. The classification by content can and should be adapted to the local reality. Thus, many authors use a typology adapted to their country or region, adopting several contents, such as geomorphological, geochemical, geophysical, geological history, palaeontology and/or palaeobiological, pedological, palaeoclimatic, impact crater, marine, submarine, metalogenetic, metamorphic, sedimentary and igneous, among others. For the work reported here, inventory structures and proposals created for Brazil (SIGEP 2009; Lima et al. 2010; Mansur and Erthal 2004), Portugal (ProGEO 2009), Argentina (Leynaud 2003), Colombia (Molina and Mercado 2003), Cuba (Lacaba et al. 2003), Peru (Rivas et al. 2001) and the UK (Ellis 2008) were consulted, in addition to the typology used in Spain (García-Cortés 1996).

The forming processes of geological heritage have been identified for the state of Rio de Janeiro (www.caminhosgeologicos.rj.gov.br). They include the following typology according to content: Sedimentary, Geomorphological, Tectonic, Petrological, Pedological, Mineralogical, Palaeontological/Palaeobiological, Hydrogeological,

Geoenvironmental and Stratigraphical. Additionally, the History of Geology and Mining and Museums and Collections typologies were considered for incorporation of the existing historical and museological aspects.

Archaeological heritage (associated with the geological one), either prehistorical or industrial, has also been identified, such as the sambaqui records that are used as indicators of relative sea level variation, the presence of lithic workshops employed by prehistoric men to craft tools and ancient mining activities and its equipments.

In addition to material heritage, one can add immaterial heritage to the list, such as the one related to salt pond operations, a crafting activity that is disappearing from the state of Rio de Janeiro. Traditional folk wisdom linked to salt production is threatened due to the closure of salt ponds and the development of the territory by real estate projects.

Due to the eolic environment dynamics, the dimensions of the geosite, the variety of geological aspects and the threats to the Peró dune field, 23 points within its area were chosen for mapping, description and monitoring. The scientific, educational and/or touristic value of these sites (points) were also taken into consideration. A broad literature search on geodiversity and biodiversity was conducted, as well as interviews with researchers who work in fields associated with heritage typologies. Historical and prehistorical aspects, iconography, maps from the 18th to 20th century and current images were also researched. Special attention was given to scientific and educational field trips. The scientific and educational value of the geosite has been described in PhD theses, Master's dissertations, undergraduate monographs, national and international papers, scientific tours and in at least eight annual educational field trips (verbal information from Prof. João Wagner Castro, National Museum/Federal University of Rio de Janeiro, and from Prof. Guilherme Fernandez, Fluminense Federal University).

The visited sites in the dune field were located on a map and photographed. Due to their dynamics and the threats to their integrity, they are periodically visited for status monitoring. Consequently, sites inside and around the dune field were selected as much for their vulnerability to human occupation and natural phenomena as for their scientific, educational, touristic and ecological importance.

According to an assessment conducted by the DRM-RJ (2006) and Mansur and Castro (2008), the Peró dune field fits the following types of heritage:

1) Sedimentary, because its eolic deposits are rare for the southeastern region of Brazil, and it is one of the only three sites in the country with climbing dunes;
2) Geomorphological, due to the scenic beauty of the dunes, beaches and associated coast;
3) Hydrogeological, due to the accumulation of freshwater within and around the field, which results from the discharge of the granular aquifer, in a region of semiarid climate that lacks rivers;
4) Archaeological, due to the existence of three archaeological sites (sambaquis);
5) Geoenvironmental, due to the interaction between the geo- and biodiversity aspects, which contribute to the existence of typical fauna and flora in the dune field area, some of which are endangered, thus confirming the ecological function of the geological site, and
6) Pedological, due to the occurrence of soil types that develop over sandy substrates and which are characteristic of a restinga eolic environments semiarid climate.

According to criterion related to its utilization (García-Cortés 1996), the Peró dunes possess the following importance: (1) scientific, due to research already conducted or in progress in its area; (2) educational, due to the frequent field trips taken by Brazilian geography and geology undergraduate and graduate courses; (3) touristic/economic, because the Cabo Frio region visitors use its beaches for strolls and contemplation (Fig. 6). The latter is enhanced by the presence of bilingual (Portuguese and English) interpretative panels that describe the dune field (Fig. 7) and invite visitors to discover and understand the dynamics of the existing eolic processes. The ecological importance is also worth noting, given the variety of ecosystems and endemic species that occur there.

Due to its dynamic characteristic, this geosite is constantly (re-)building itself. Perhaps this is one of its main intrinsic values: the possibility of evolving in human time, which makes it unique from other geosites, which evolve in thousands or millions of years. What one sees at the Peró dune field is an ongoing geological process.

It is worth highlighting that Peró is one of the suggested visitation sites in Brazil's Ministry of Tourism publication "Roteiros do Brasil 2010 94 Belos Motivos para viajar pelo Brasil" (www.turismo.gov.br). Still according to García-Cortés' (1996) methodology, it has a national influence because it is one of the largest dune fields of southeastern Brazil and is one of the three places in the country where climbing dunes can be found.

Another relevant aspect to take into consideration is how it fits the Cultural Landscape category. The National Historical and Artistic Heritage Institute (IPHAN) published Directive 127 on April 30th, 2009, which describes the Brazilian Cultural Landscape. This legislation defines the Brazilian Cultural Landscape as a distinctive portion of the national territory that represents the interaction process between humans and nature, to which life and human science make their mark or attribute value. The State

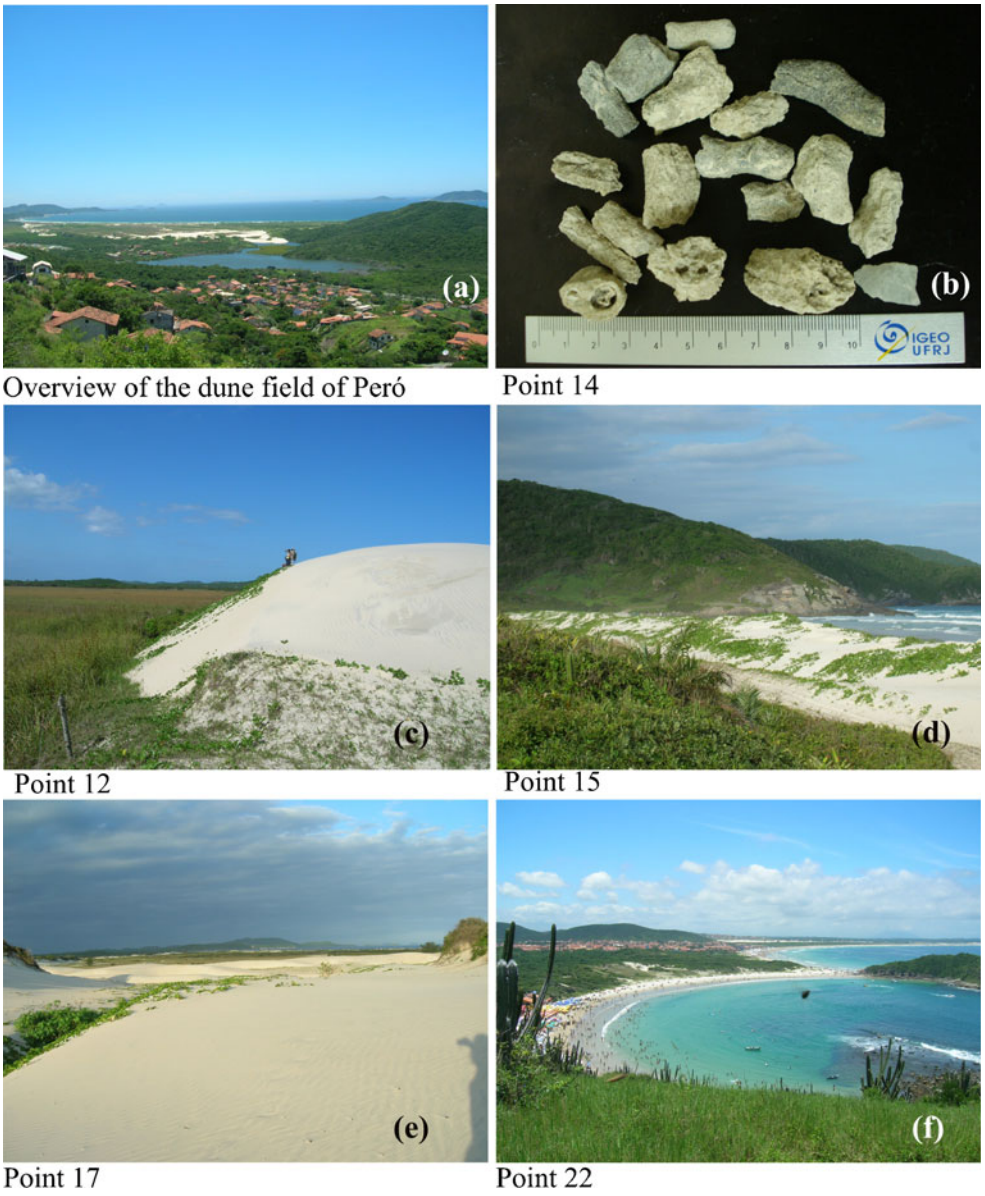

Fig. 6 Scenic beauty that characterizes the geomorphological heritage and sites with hydrogeological and archaeological value. **a** View of the dune field, highlighting the lake formed by the dune aquifer and the climbing dunes covering the base of the Piaçava Hill, **b** chipped quartz, plant fragments and, possibly, human bones found next to point 14, **c** deflation basin and the wetland areas formed by the dune aquifer discharge, **d** foredunes and Peró Point, where the dune field begins, **e** oblique dunes, **f** Conchas Beach and, in the background, Peró Beach. *Numbers (Point)* refer to the numbers on the map in Fig. 2, and indicate the locality where the picture was taken

Cultural Heritage Institute (INEPAC) (2006) reported to the State Public Ministry (MPE) that the landscape in the Peró dune field, due to its rarity, is a fundamental element of local and regional identity and that the construction plans there can put the cultural content of that landscape at risk.

Valuation of the Geological and Geomorphological Heritage

Is this dune field truly a geological heritage site? From a conceptual point of view, researchers are trying to answer that question using several methods, especially through attributing value to these sites so as to be able to confirm their importance by comparing them by means of a heritage ranking value.

Fig. 7 Interpretative panel posted by the Caminhos Geológicos Project in Peró Beach that explains the origin of the dune field

For Cendrero Uceda (1996), the geological heritage includes rock formations, structures, sedimentary accumulations, shapes, mineral or palaeontological deposits and collections of geological objects of scientific, cultural or educational value and/or landscape or recreational interest. Brilha (2005) defines geological heritage as the group of geosites of a specific region where there are one or more geodiversity element of exceptional scientific, educational, cultural, touristic or other value. Thus, according to these classical concepts, and due to the already described scientific, educational, cultural and touristic values of the Peró dunes, this site can be considered a geological heritage. However, in addition to the above, it is necessary to demonstrate its values by means of its possible or effective utilization. To that end, it is necessary to have both a large body of scientific knowledge on the site and a selection of elements to attribute value, so that one can evaluate each geosite objectively, with little or no subjectivity.

The first premise for conducting this study was that this dune field is relevant for both the state and national spheres. The Cabo Frio Tectonic Domain (CFTD) was used as a regional entity for comparison, being employed as a framework according to the methodology for the national inventory of geosites proposed by the IUGS (Wimbledon 1996; Brilha et al. 2005). The second premise is that the Peró dune field fulfills two aspects: it is both a geological and geomorphological heritage site.

Thus, an analysis of the various assessment methods for geological and geomorphological heritage was conducted. Some of these were chosen to be applied to the Peró dune field.

The literature on geological heritage valuation is restricted to a few studies. Cendrero Uceda (1996) presented one of the first valuation systems for geological heritage. This system has been followed by several authors and institutions to date, such as ProGEO (2009) and Brilha

Table 1 Points described in the Peró dune field with intrinsic geological value (World Geodetic System Datum: revision WGS84)

Point (Fig. 2)	UTM X-coordinate	UTM Y-coordinate	Description
1	193753	7470744	Beach—point in the road that cuts through the dune field
			Value: geomorphological
5	193066	7470184	Depression between ridges—bushy and herbaceous restinga
			Value: geomorphological and geoenvironmental
6	193004	7469937	Beginning of the area with bushy vegetation
			Value: geomorphological and geoenvironmental
9	192963	7471068	Sandy ridge that separates the dune field from the wetland
			Value: hydrogeological, geomorphological and geoenvironmental
10	192835	7470922	Mobile dune with ripple marks next to the arboreal vegetation
			Value: hydrogeological, sedimentological and geoenvironmental
12	193540	7471385	Mobile dune with ripple marks—wetland view—bushy and herbaceous restinga
			Value: geomorphological, pedological, sedimentological and geoenvironmental
14	194496	7472370	Quartz chips and sand tubes: look like plant remains and/or bones
			Value: archaeological and geomorphological
15	194806	7472764	Beginning of the dune field in the northern portion of Peró Beach
			Value: hydrogeological, geomorphological, sedimentological and geoenvironmental
16	194453	7473083	Flooding area
			Value: hydrogeological and geoenvironmental
17	192460	7470141	Acquadunas Condominium—dunes burying houses and condominium equipment
			Value: hydrogeological, geomorphological, sedimentological and geoenvironmental
21	195176	7473081	Peró Point—orthognaisse with granitic texture, no foliation
			Value: geomorphological and petrologic
22	194008	7467487	Conchas Beach—orthogneisses and orthoamphibolites from basement and Mesozoic dikes. Dunes. Archaeological site.
			Value: geomorphological, petrologic and archaeological
23	193602	7468567	Panel—Caminhos Geológicos Project
			Value: tourism and educational

UTM, Universal Transverse Mercator geographic coordinate system

(2005). Molina and Mercado (2003) presented another model and used it to test Colombian geotouristic areas. In both of these cases, the geosites are scored according to selected criteria. Other models have been proposed by Scott et al. (2007), the Greater London Authority (2008) and Reis and Henriques (2009). García-Cortés and Carcavilla (2009) of the Instituto Geológico y Minero de España, wrote a proposal for the methodological update of the Spanish Inventory for Places of Geological Interest (IELIG).

Assessment of geomorphological heritage, on the other hand, has a wide assortment of published methodologies. Pereira (2006) evaluated various methods, including those published by Grandgirard (1999), Panizza (2001), Rivas et al. (1997), Restrepo (2004), Bruschi and Cendrero Uceda (2005), Coratza and Giusti (2005), Serrano and González-Trueba (2005) and Pralong (2005). Based on this evaluation, Pereira (2006) proposed a new method aimed at merging all of the various approaches into one integrated proposal. In our study, we used Pereira's method to evaluate the Peró dune field as a geomorphological heritage site (Pereira 2006; Pereira et al. 2007).

However, to assess the Peró dune field in terms of its potential classification as a geological heritage site, the following methods were selected for use in this study:

1) García-Cortés and Carcavilla's (2009) method is influenced by the pioneering works of Cendrero Uceda (1996). The proposed method is an update of the Spanish inventory model almost 30 years after its first survey, in accordance with Law 42/2007, which deals with that country's Natural and Biodiversity Heritage. It also presents a valuation model that still uses Cendrero Uceda's criteria (1996), which define the heritage value classes as: (a) intrinsic, use potential and need of protection. This was changed to four classes within two larger groups: (a) Interest: Scientific, Educational and Touristic/Recreational; and (b) Protection: Vulnerability. In our study, most of the analysis criteria were kept, and a more objective approach to heritage value was sought;
2) Greater London Authority's (2008) method, which has a strong focus on community and educational use of the

Table 2 Points described in the Peró dune field map (World Geodetic System Datum: revision WGS84)

Point (Fig. 2)	UTM X-coordinate	UTM Y-coordinate	Description
2	193116	7470805	Restinga vegetation: herbaceous and bushy
			Value: geoenvironmental
3	193020	7470349	Restinga vegetation: herbaceous, separated from the bushy one by a higher sandy belt—*Mimus gilvus* observed, an endangered bird species
			Value: geoenvironmental
4	192996	7470274	Casuarina (exotic species) amid native plants
			Threat: introduction of exotic species
7	193095	7469815	*Jacquinia armillaris*—thicket with orchids, cactuses and bromeliads. Brazilian cherry native to the restinga
			Value: geoenvironmental
8	193500	7469680	Peró Beach—trail exit; *Liolaemus lutzae* observed
			Value: geoenvironmental
11	193590	7471385	Bushy vegetation
			Value: geoenvironmental
13	194109	7471803	Placement of equipment for monitoring the amount of sand brought by the wind. *Liolaemus lutzae* and lair photographed
			Value: geomorphological, sedimentological and geoenvironmental
18	193473	7469138	Beach—vegetation whose form has been altered by the wind; biazomorphosis
			Value: geomorphological, sedimentological and geoenvironmental
19	193193	7469345	Placement of installed lamp posts - without electrical power yet in the ClubMed Project area
			Threat: destruction of biodiversity and construction of obstacles for sand transport. The introduction of electrical power in the dune field is a major threat because it allows invasion and occupation of the area
20	193095	7471016	Staking —demarcation of future lots?
			Threat: destruction of biodiversity and construction of obstacles for sand transport

sites. The method used in the elaboration of the Action Plan for London Geodiversity comprises the inventory and evaluation of Regionally Important Geological/Geomorphological Sites (RIGS) and Locally Important Geological Sites (LIGS);

3) Reis and Henriques' (2009) method contains a special methodology and does not use a quantitative ranking system, unlike the others. These authors do not propose a comparative ranking system for the evaluated sites; rather, the method is a simple and objective way to visually show the qualitative relevance of the geological heritage. Each site is plotted on graph where the *X*-axis represents the abstract perception of the heritage, classified as Material, Demonstrative, Cognitive and Social, and the *Y*-axis represents the degree of relevance of the heritage in terms of its Local, Regional or Global importance. Curves are drawn to establish a domain of value for each evaluated heritage. Finally, three inclined vectors are plotted on the graph to represent the strategic approach for geoconservation according to the social, scientific or integrated influence of the evaluated heritage. The position of the geosite in the graph will yield its value in a ranking system comprised of four categories: "*A lower rank refers to indicial contents. Documental, iconographic, and symbolic contents represent a content value of rank II. Rank III refers conceptual and scenic contents. In this analysis, a rank IV content can be virtually attributed to a very special entity of singular meaning to mankind*" (p. 9).

Points Selected Due to their Intrinsic Value or for Monitoring Threats to the Integrity of the Geosite

The dune field was mapped down to a scale of 1:20,000. Geology, zoology (bird and reptile fauna), botany, forest engineering and cultural heritage professionals from institutions such as IBAMA, Rio de Janeiro Botanical Garden, INEPAC, State University of Rio de Janeiro (UERJ) and DRM-RJ took part in one of the steps.

The points described in the mapping process are presented in the maps in Fig. 2 and in Tables 1 and 2. Some of the places visited are recorded in the pictures of Figs. 5 and 6. Aspects related to eolic activity, aquifers and existing geological risks and those that might be affected by the occupation of this area were observed and considered from the point of view of the area's geology (Fig. 8). Two points in the bedrock area on the beach, in the dune field's extremities, were also visited: one in the Conchas Beach area, to the south, and another at Peró Point, to the north. Due to the dynamics of the eolic process, these 23 points are monitored at least twice a year. Table 1 lists the

Fig. 8 Geological risk associated with the Peró dune field. The construction of houses/building in the direction of the dunes' movement reveals the consequences of occupation without any prior technical risk evaluation. **b**, **c**, **d** Successive engulfment of a lamp post by sand (*encircled*)

representative points of the geosite's intrinsic geological value and Table 2 shows which points were used for monitoring. Such monitoring is necessary due to the intrinsic characteristics of this type of geosite, whose main characteristic is being dynamic, as opposed to the vast majority of geosites, which are static.

Quantitative and Qualitative Assessment

Quantitative Assessment as a Geomorphological Heritage Site

For Pereira (2006), the scientific value (VCi) and additional value (VAd) indicators together form the geomorphological value (VGm) of the site, and the use value (VUs) and preservation value (VPr) indicators reveal its management value (VGt). The Total Value (VT) is a group indicator that represents the sum of the scores obtained for all of the criteria. According to this methodology, the Peró dune field obtains the following score (Table 3):

Assessment as a Geological Heritage Site

Quantitative Assessment Using the Proposed Method for the Spanish Inventory

According to García-Cortés and Carcavilla (2009), the Peró dunes had the following score (Tables 4, 5):

Table 3 Valuation of geomorphological heritage according to Pereira (2006) and Pereira et al. (2007)

Valuation of geomorphological heritage	
Scientific value (VCi)=4.09 (81.8% of total possible score=5.00)	Additional value (VAd): 4.25 (94.4% of total possible score=4.50)
Abundance/rarity: 0.50 (one of the most important three)	Cultural: 1.25 (relevant material cultural features related to landforms)
Integrity: 1.00 (No visible damage)	Aesthetic: 1.50 (high—"subjective value. Aspects to be considered: visual singularity of landforms; panoramic quality; objects and color diversity and combination; presence of water and vegetation; absence of human-induced deterioration; proximity to the observed features" (Pereira et al. 2007, p 162)
Representativeness: 1.00 (good example of processes and/or good pedagogical resource)	Ecological: 1.50 [Geomorphological features are crucial for the ecosystem (s)]
Number of interesting geomorphological features (diversity): 1.00 (>3)	
Other geological features with heritage value: 0.17 (other geological features but without relation to geomorphology)	
Scientific knowledge on geomorphological issues: 0.25 (medium: presentations, national papers)	
Abundance/rarity at national level: 0.17 (between 3 to 5 occurrences)	
VGm (Geomorphological value)=VCi+VAd=4.09+4.25=8.34 =87.8% of total score	
Use value (VUs): 6.79 (97% of total possible score=7.00)	Preservation value (VPr): 2.50 (83.3% of total possible score=3.00)
Accessibility: 1.29 (By bus on local roads and less than 50 m by footpath)	Integrity: 1.00 (no visible damage)
Visibility: 1.50 (excellent for all relevant geomorphological features)	Vulnerability of use as geomorphosite: 1.50 (damage can occur only in/along the access structures)
Present use—geomorphological interest:1.00 (promoted/used as geomorphosite or geosite)	
Present use of other natural and cultural interests: 1.00 (with other interests, with promotion and use)	
Legal Protection and use limitations:1.00 (with protection but without use restriction or with very low use restriction)	
Equipments and support services: 1.00 (hostelry and support services are less than 5 km away)	
VGt (Management Value)=VUs+VPr=6.79+2.50=9.29=92.9% of total score	
Total Value=VT=90.% of total possible score	

Table 4 Valuation of geological sites of interest based on their scientific, educational and touristic importance according to García-Cortés and Carcavilla (2009)

Valuation parameters of geological sites of interest	Score	Scientific	Educational	Touristic or recreational
Representativity	4	100	20	0
Type Locality	1	20	5	0
Scientific knowledge degree of the site	4	60	0	0
State of conservation	4	40	20	0
Observation conditions	4	20	20	20
Rarity	1	15	5	0
Diversity	4	40	40	0
Educational Content/Educational Use	1	0	20	0
Logistics Infrastructure	4	0	60	20
Population density (potential demand)	2	0	10	10
Accessibility	2	0	30	20
Intrinsic frailty	2	0	0	30
Other elements of the natural/cultural heritage	4	0	20	20
Beauty	4	0	20	80
Popularization content/use	4	0	0	60
Potential for touristic and recreational activities	4	0	0	20
Proximity to recreational areas (potential)	4	0	0	20
Socioeconomic sphere	0	0	0	0
Total Possible score/scire obtained		400/295	400/270	400/300
Percentage		74%	67.5%	75%

Maximum score: 4

Quantitative and Qualitative Assessment Applying the Method used in the Action Plan for London Geodiversity

The scores given the Peró dunes according to the Greater London Authority (2008) are presented in Table 6.

Qualitative Assessment through the Method that Analyzes Content type of the Geological Objects with Heritage Value

According to Reis and Henriques (2009), the Peró dune field would score as Rank III because of its regional importance and the material, iconographic, symbolic, documental and scenic types of abstract perception. It is positioned between vectors 1 and 3 in the graph, i.e., between that of social influence and that integrated with scientific ones (Fig. 9).

The Peró Dune Field in the Context of the Cabo Frio Tectonic Domain

Mansur (2010) used the methodology of García-Cortéz and Carcavilla (2009) to assess the 78 inventoried points of the Cabo Frio Tectonic Domain, the tectono-stratigraphic terrain where the Peró dune field is installed. The geosites that scored higher in each category are listed in Tables 7, 8 and 9.

An analysis of the results reported in Table 7 shows that the Peró dunes, in comparison with the other 77 geosites inventoried in the CFTD, is one of the nine locations with the highest score for scientific value and one of the ten for educational value. Furthermore, it is one of the three sites with highest touristic value and one of the four that is most vulnerable.

Table 8 shows the score of the Peró dunes in terms of protection priority according to scientific, educational and touristic interest, with this site occupying the first, third and first positions, respectively. Table 9 shows the final result for protection priority, with the Peró dunes occupying the first position among the 78 inventoried sites.

Its terms of Global Protection Priority, the rank of the Peró dunes also indicates that it is the most threatened geosite in the framework, be it for its natural fragility or for the pressure on it. It is worth noting that the three most threatened geosites all have an intrinsic fragility due to erosion. In the case of both dune fields, this is a natural phenomenon. At the other site (Geribá beach), pressure from luxury residential resorts and an old mining site has resulted in coastal erosion as well, even though Geribá

Table 5 Valuation of geological sites of interest based on their scientific, educational and touristic importance, according to García-Cortés and Carcavilla (2009)

Valuation parameters of the vulnerability of geological interest sites	Score	Value
Anthropic threats	1	15
Interest for mineral exploitation	0	0
Natural threats	4	30
Intrinsic frailty	1	10
Site's protection regimen	4	40
Indirect Protection	4	40
Accessibility (potential aggression)	2	20
Site's property regimen	4	20
Population density (potential aggression)	2	10
Proximity to recreational zones (potential aggression)	4	20
Total Possible Score/Obtained Score	400	205
Percentage	51.25%	
Protection Priority	Value	
PPc—Protection Priority due to Scientific Interest	500	
PPd—Protection Priority due to Educational Interest	475	
PPt—Protection Priority due to Touristic-Recreational Interest	505	
PPG—Global Protection Priority	493.33	
SPECIFIC PROTECTION FIGURE		
Obtained classification: Urgent need of protection	PPc, PPd, PPt or PPG≥501	

beach is a rocky coast and should, therefore, be less vulnerable such stresses.

The Dama Branca dune field has greater legal protection than Peró because it's a state heritage nature site. Even so, it already displays signs of degradation caused by human occupation of the area that supplies sand to the field (Mansur and Nascimento 2007b).

The potential fragility of the eolic environments to the occupation of the dune field feeding areas and to obstacles that prevent the advance of the sand is clear. The results of the studies corroborate the answer of the valuation method to the high natural vulnerability of these types of nature sites.

According to these results, it is evident that the Peró dune field is a geomorphological–geological heritage site of undeniable importance in terms of science, culture, education and tourism. One must also highlight its fragility, since its landscape is a result of wind action and requires space to evolve and adequate conditions to perform its ecological role as a substrate for biodiversity, as well as its importance as an aquifer in a semiarid region.

Discussion and conclusions

The methodologies analyzed here show, in general, a trend to score sites in a ranking system. The analysis is conducted using parameters related to scientific, educational and touristic importance, as well evaluation criteria for vulnerability and visitor reception. Reis and Henriques's (2009) proposal is an exception, in which the main innovation is in the placement of the site according to a graph that approaches the same basic questions. The importance given to community use in the sites assessed according to the London methodology is also highlighted.

The high value attributed to the Peró dune field, when analyzed through the lens of its classification as a geomorphosite, should be adequate to show its touristic importance and reinforces its potential for educational and cultural use. The high total score for the site's assessment as geomorphological heritage (90%), according to Pereira (2006) and Pereira et al. (2007), mainly reflects the

Table 6 Valuation of geological heritage according to the Greater London Authority (2008)

Criterion	Score or description
Rarity	National=8 points
Quality	National=8 points
Literature/collections	Detailed studies=10 points
Educational value	Regional=8
Community value	Daily local use=10 points
Access and security	
Access road and parking	Existent
Access security	Existent
Exposition security	Existent
Permission to visit	Not necessary
Condition	Preserved
Existence of conflicting activities	Proposed real state project can lead to deterioration
Restriction condition	Only walks should be allowed
Exposition nature	Dune field
Multiple expositions/fliers	Interpretative panel at the beach and at the Cabo Frio Airport
Culture, heritage and economy	
Historical, archaeological and literary associations	10
Scenic beauty	10
History of Natural Sciences	1
Economic geology	NA
Geodiversity value	
Specific scientific interest	10

Scoring: 1–2, very poor; 3–4, poor; 5–6, acceptable/usable; 7–8, reasonably good; 9–10, very good/excellent; NA, not applicable; NS, not known

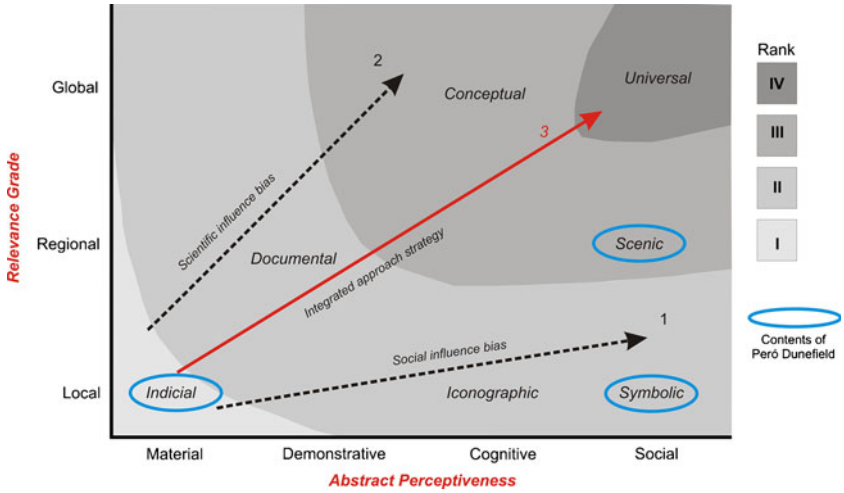

Fig. 9 Valuation system of the geological heritage according to Reis and Henriques (2009)

Additional and Use Values criteria, which scored 94 and 97%, respectively. The reasons for this score are: the site's easy access and observation capacity, the existence of nearby touristic infra-structure, the diversity of observable elements, the close proximity to beautiful beaches, the current touristic use, the existence of rare endemic animal and plant species and of archaeological sites and the associated eolic landscape, which is rare in Brazil's Southeast.

The other two criteria, Scientific Value (82% of the total possible score) and Preservation Value (83%), had lower scores. With respect to Scientific Value, it is important to stress that rarity, in a national context, was the lowest scoring criterion. In fact, northeastern Brazil has larger and more abundant dune fields due, mainly, to its semi-arid regional climate. However, the presence of active holocenic eolic deposits in the Southeast, including climbing dunes, elevates the Peró dunes to the level of national relevance.

The Preservation Value reflects the methodology employed, wherein only two criteria, Integrity and Vulnerability, are used for assessment. It is important to highlight the fact that the dune field is an extremely fragile environment, dependent on climatic and sedimentological aspects for its maintenance. Furthermore, anthropic alterations that prevent the transport of sediments to the dune group can, in a few decades, change its mobile pattern to a stationary one, threatening the field's very existence later on.

Table 7 List of some of the 78 inventoried geosites in the Cabo Frio Tectonic Domain framework and their scores for scientific, educational and touristic–recreational interest and vulnerability, according to García-Cortéz and Carcavilla's methodology (2009)

Geosite	Score/Rank			
	Scientific	Educational	Touristic	Vulnerability
Araruama lagoons	360/1	310/5	270/5	125/15
Lagoinha, Foca and Forno beaches	360/1	320/4	320/1	135/12
Brejo do Espinho (Espinho Marsh)	360/1	240/14	130/23	110/16
Forte Beach	340/2	335/2	245/9	140/11
Pai Vitório and Mangue de Pedra	310/3	255/12	215/11	60/23
Cabo Frio Island	310/3	225/17	300/2	35/26
Atalaia Point	310/3	260/11	245/9	115/10
Conchas Beach	295/4	290/7	235/10	145/10
Peró dunes	295/4	270/9	300/2	205/2
Tauá palaeolagoon	280/5	195/22	135/22	115/10
Geribá and Marisco points	275/6	340/1	280/3	190/4
Sapata and Manguinhos points	265/7	295/6	275/4	175/7
Saquarema Promontory	230/10	270/9	215/11	135/12
Dama Branca dunes	195/17	330/3	250/8	210/1
Imboassica Lake	170/20	280/8	260/7	145/10
Barreiras Formation—S.P. Aldeia	115/28	195/22	95/28	210/1
Tartaruga Beach—Rio das Ostras	95/32	235/15	185/15	205/2
Forno Beach—Arraial do Cabo	60/39	200/21	280/3	150/9

Sites listed scored higher than the Peró dune field in each category of the analysis

Table 8 List of the geosites from the Cabo Frio Tectonic Domain framework that scored higher for protection priority in terms of scientific, educational and touristic interest, according to García-Cortéz and Carcavilla's methodology (2009)

Geosite	Protection Priority by Interest		
	Scientific	Educational	Touristic
Peró dunes	500/1	475/3	505/1
Dama Branca dunes	405/11	540/1	460/3
Geribá and Marisco points	465/6	530/2	470/2

The Management Value (93% of the possible score) is derived from the scores for Use and Preservation Values, which reflect the current condition of the Peró dunes. This criterion's score may severely drop with the construction of the resort due to the change in use and occupation of the whole site. It shows, therefore, that the Management Value criterion, according to the methodology employed, is in tune with reality.

Therefore, the evaluation of the Peró dunes as a geological heritage must be understood according to the three methodologies used:

1) New Spanish inventory: the scientific and touristic values are higher than the educational one. This can reflect the difficulty of inserting geological themes in elementary and high schools in Brazil (Mansur 2009), since the Peró geosite is widely employed in university field trips. On the other hand, it is classified as urgent in terms of Global Protection Priority, being one of the three sites in this analysis that obtained this result.
2) London inventory: although this methodology is not totally based on scores, the site can be characterized as a good to excellent example of geological importance according to almost all criteria, except for not being part of the History of the Natural Sciences.
3) By content of the geological objects: this result shows its importance due to its scenic beauty, landscape representativity, cultural value and social and scientific influence, being placed at Rank III, outranked by sites of regional importance.

Despite being located within an APA, its imminent occupation and destruction by real estate projects and the growth of the city are a serious threat. One of the main functions of the valuation methodologies is to show—in an unerring way—the value associated with the sites that make them heritage material. In fact, the GATE (2007) advice on the real state project highlights the valuation exercise conducted by Mansur and Nascimento (2007a, b), according to Cendrero Uceda's methodology (1996), as a tool for the analysis of the impact of the project.

By comparing the Peró geosite with the other inventoried sites in the Cabo Frio Tectonic Domain, it becomes evident that Peró is a relevant site for the state of Rio de Janeiro. The application of the valuation methodologies showed the necessity of conserving it, both for its cultural value and its continuing touristic, educational and scientific uses.

Brazilian law allows the protection of this kind of site. However, there is a trend in the country to classify international tourism or high-income-oriented enterprises as promoters of local development, i.e., of public and social interest. Such a policy allows the occupation of still-preserved areas of the coast under the justification of economic and environmental gains, such as job and income generation, and the application of private resources in sanitation-related infrastructure improvement, like water delivery and sewage treatment for low-income communities located around the touristic complexes. This has also happened in Peró, specifically in terms of issuing environmental licenses for the project.

Thus, touristic use, in the format that has been allowed, is the greatest threat to the natural and cultural heritage associated with the Peró dunes.

The results of this study will be sent to NGOs, the Public Ministry and civil organizations as a way of demonstrating the value and importance of this heritage site and, hopefully, strengthen the fight for its preservation. The assessment methodology, with its clear and objective parameters that are applicable both at both the international and national levels, can be used as a scientific tool free of emotional elements to justify the preservation of endangered sites or to provide the elements to be used in organizing the use and occupation of the land that holds geological and geomorphological heritage sites.

Table 9 List of the five geosites from the Cabo Frio Tectonic Domain framework that scored higher for the criterion Global Protection Priority, according to García-Cortéz and Carcavilla's methodology (2009)

Rank	Geosite	Score	Protection Priority	Typology
1	Peró dunes	493.33	Urgent	Sedimentary
2	Marisco and Geribá points	488.33	Urgent	Stratigraphic
3	Dama Branca dunes	468.33	Urgent	Sedimentary
3	Lagoinha, Foca and Forno beaches	468.33	Medium term	Stratigraphic
4	Sapata and Manguinhos points	453.33	Medium term	Tectonic

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