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ORIGINAL ARTICLE

Inventory and Assessment of Palaeontological Sites in the Sousa Basin (Paraíba, Brazil): Preliminary Study to Evaluate the Potential of the Area to Become a Geopark

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Abstract The Rio do Peixe rift basin developed during the Lower Cretaceous (Neocomian) and comprises the Sousa, Uiraúna-Brejo das Freiras, Pombal and Vertentes basins. In these basins, there is an abundant ichnofauna mainly composed of theropod, sauropod and ornithopod dinosaur trackways that represent the palaeontological heritage of the region. As the majority of the fossiliferous areas are located in the Sousa basin, an inventory and assessment of the scientific, educational and touristic values, together with the vulnerability of 25 palaeontological sites, is here presented and discussed. The aims of the study are to guide the strategies of geoheritage protection in the Sousa basin and to evaluate the scientific potential of the area as a geopark. In general, the geosites of the Sousa basin have low scientific and touristic values, moderate educational value and high vulnerability. The fossiliferous areas are suffering from strong natural and anthropic threats and are at high risk of degradation. For these reasons, based on the quality of the palaeontological sites, the region currently has little potential to become a geopark.

Keywords Sousa basin · Dinosaur tracks · Palaeontological heritage · Geoconservation strategies · Geopark

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Introduction

The Rio do Peixe rift basin in NE Brazil comprises the Sousa, Uiraúna-Brejo das Freiras, Pombal and Vertentes basins. These basins originated in the Lower Cretaceous (Neocomian), along preexisting structural lineaments of the basement, during the opening of the Atlantic Ocean. The basins are located almost entirely in the western region of the Paraíba state, comprising a total area of 1250 km^2.

In the Rio do Peixe basin, there is an abundant ichnofauna composed of theropod, sauropod and ornithopod dinosaur trackways. In addition, there are invertebrate trace fossils produced by arthropods and annelids, fossils of ostracods, conchostracans, plant fragments, palynomorphs, fish scales and crocodylomorph bone fragments (Moraes 1924; Leonardi 1979a, 1979b, 1987, 1989; Leonardi et al. 1987a, 1987b, 1987c; Godoy and Leonardi 1985; Lima and Coelho, 1987; Santos and Santos 1987a, 1987b; Carvalho 1989, 1993, 1996a, 1996b, 2000a, 2000b, 2004; Carvalho and Carvalho 1990; Carvalho et al. 2013a; Fernandes and Carvalho 1997; Leonardi and Santos 2004; Leonardi and Carvalho 2007). However, the majority of the sites are located in the Sousa basin where dinosaur tracks are the main aspect of the local geological heritage (Siqueira et al. 2011).

The sedimentary rocks of the Rio do Peixe basin belong to the Rio do Peixe Group, which comprises the Antenor Navarro, Sousa and Rio Piranhas formations (Fig. 1). During the Lower Cretaceous, the region had a warm climate,

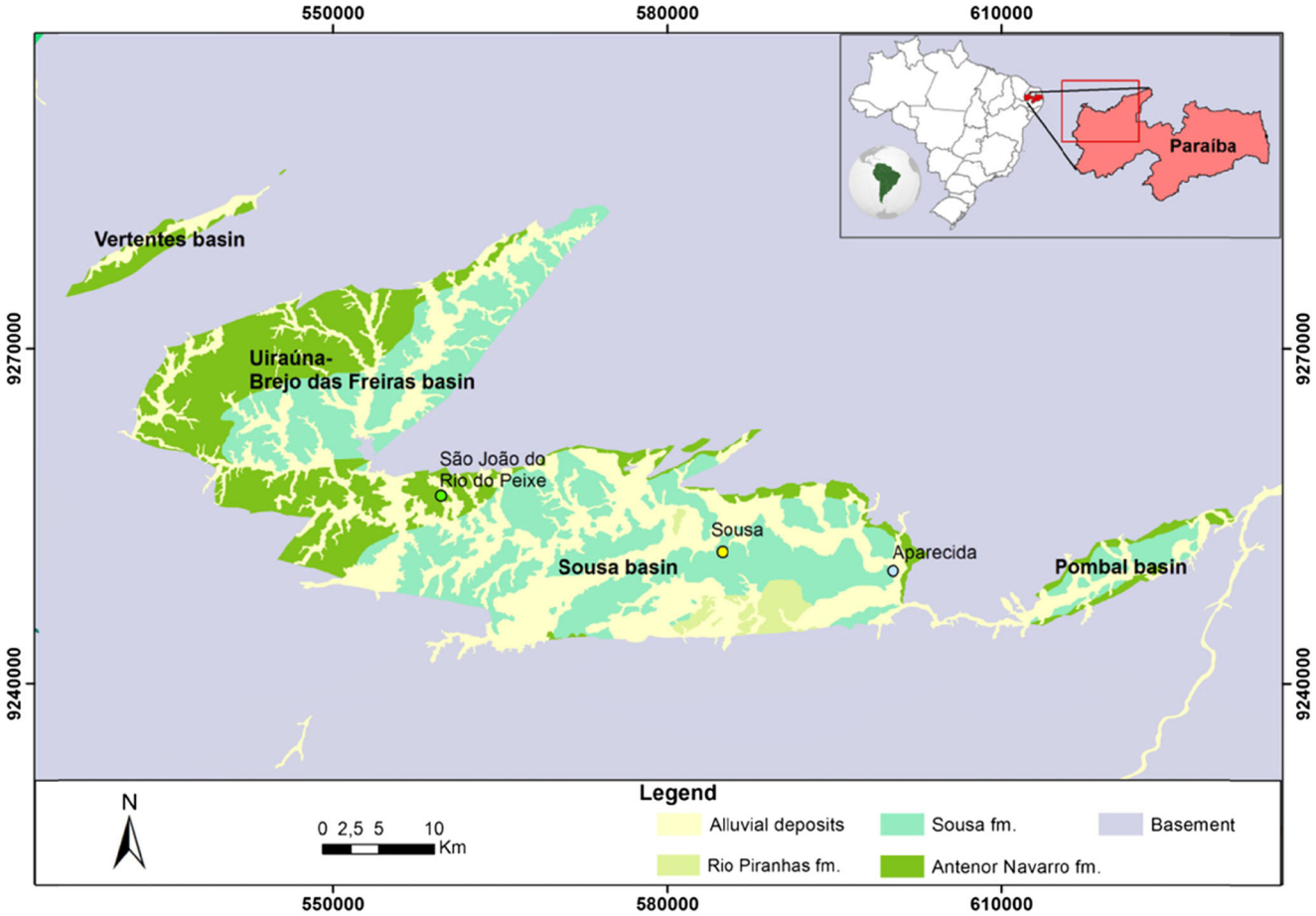

Fig. 1 Geological map of Rio do Peixe basin (including Sousa, Uiraúna-Brejo das Freiras, Pombal and Vertentes basins) with emphasis on the Rio do Peixe group. The Sousa, São João do Rio do Peixe and Aparecida municipalities are also represented (modified from CPRM–Geological Survey of Brazil, sheet Sousa SB.24-ZA)

with a wide variation of wet conditions with ephemeral rivers and shallow lakes as the main ecosystems. The Antenor Navarro and Rio Piranhas formations are composed of conglomerates, coarse sandstones and sandstones intercalated with siltstones which were deposited in fan deltas, alluvial fans and fluvial braided environments. The Sousa Formation is composed of sandstones, shales and mudstones deposited in lacustrine, meandering rivers and swampy environments. As footprints are better preserved in fine sediments, tracks are most likely to occur in the rocks of the Sousa Formation (Carvalho and Leonardi 1992; Leonardi and Carvalho 2002).

The palaeontological sites of the Sousa basin not only are mostly within the Sousa municipality, but are also present in smaller number in São João do Rio do Peixe and Aparecida counties. A brief characterization of these administrative areas is presented in Table 1—all have a medium human development index and low demographic density.

The inventory carried out in these three municipalities generated a list of 25 palaeontological sites. The most important locality in terms of the distribution of fossil footprints is known as Passagem das Pedras (in the municipality of Sousa). On 20 December 1992, this area was designated as

Table 1 Area, inhabitants, demographic density and Human Development Index (HDI) of Aparecida, Sousa and São João do Rio do Peixe municipalities

General characterization of Sousa, Aparecida and São João do Rio do Peixe municipalities

Municipalities	Area (km^2)	Inhabitants	Demographic density (inhabitants/km^2)	HDI
Aparecida	229	5.894	25.73	0.628
Sousa	842	62.635	74.38	0.658
São João do Rio do Peixe	474	17.661	37.25	0.595

Adapted from IBGE (2010a, 2010b) and PNUD (2000)

Table 2 Criteria, indicators and numeric parameters to quantify the scientific, educational and touristic values, together with vulnerability of the Sousa basin palaeontological sites

Criteria, indicators and numeric parameters for assessing of the scientific, educational and touristic values and vulnerability of Sousa basin palaeontological sites	
1. Representativeness (SVW=30; EVW=0; TVW=0; VUW=0)	Points
The geosite is the best known example in the study area	4
The geosite is a good example in the study area	2
The geosite is a reasonable example in the study area	1
2. Local-type character (SVW=20; EVW=0; TVW=0; VUW=0)	Points
Geosite used, of the scientific point of view, as an international reference	4
Geosite used, of the scientific point of view, as a national reference	2
Geosite used, of the scientific point of view, as a regional and/or local reference	1
3. Integrity (SVW=15; EVW=0; TVW=0; VUW=0)	Points
Geosite well conserved and practically intact	4
Geosite with deterioration, but that does not affect, crucially, its geological features	2
Geosite with deterioration that does not allow the perception of some important geological features	1
4. Rarity (SVW=15; EVW=0; TVW=0; VUW=0)	Points
The geosite is the only or one of few known examples at national level	4
The geosite is the only known example in the area under analysis	2
The geosite is one of the few examples known in the area under analysis	1
5. Scientific knowledge (SVW=10; EVW=0; TVW=0; VUW=0)	Points
There are scientific publications of international character dedicated to geosite (theses, papers, books, etc.).	4
There are scientific publications of national character dedicated to geosite or there are references to geosite in scientific publications of international character	2
There are references to geosite in scientific publications of national character	1
6. Geological diversity (SVW=10; EVW=0; TVW=0; VUW=0)	Points
Geosite with more than three geological interests with scientific value (mineralogical, palaeontological, geomorphological, sedimentological/stratigraphic, etc.)	4
Geosite with three geological interests with scientific value	2
Geosite with two geological interests with scientific value	1
7. Didactic potential (SVW=0; EVW=20; TVW=0; VUW=0)	Points
Illustrates products and geological processes in a clear and expressive way for all levels of the educational system	4
Illustrates products and geological processes in a clear and expressive way to classes from elementary school onwards	3
Illustrates products and geological processes in a clear and expressive way to classes from high school onwards	2
Illustrates products and geological processes in a clear and expressive way only for higher education	1
8. Geodiversity elements (SVW=0; EVW=15; TVW=5; VUW=0)	Points
The geosite presents more than three types of geodiversity elements (invertebrates fossils, bioturbations, dinosaur footprints, ripple marks, mud cracks, etc.)	4
The geosite presents three types of geodiversity elements	3
The geosite presents two types of geodiversity elements	2
The geosite presents one type of geodiversity elements	1
9. Observing conditions (SVW=0; EVW=15; TVW=5; VUW=0)	Points
All geological contents are readily observable in all seasons	4
There are obstacles that hinder the observation of some geosite content at certain times of year	3
There are obstacles that hinder the observation of the main geosite contents at certain times of year	2
There are obstacles that impede the observation of the main geosite contents in all seasons	1
10. Vulnerability (SVW=0; EVW=10; TVW=10; VUW=0)	Points
Without possibility of content deterioration by anthropic activity (students or tourists)	4
Possibility of secondary content deterioration by anthropic activity (students or tourists)	3
Possibility of main content deterioration by anthropic activity (students or tourists)	2
Possibility of all content deterioration by anthropic activity (students or tourists)	1
11. Accessibility (SVW=0; EVW=10; TVW=10; VUW=0)	Points
Geosite less than 100m of a paved road and with bus parking	4
Geosite less than 500m of a paved road	3
Geosite only accessible by unpaved road, but travelled by bus	2
Geosite without direct access by road, but less than 1km from a passable route	1
12. Safety (SVW=0; EVW=10; TVW=15; VUW=0)	Points
Geosite with safety equipment (fences, walls, stairs, railings, etc.), mobile phone network coverage and less than 5km of assistance means	4
Geosite with safety equipment (fences, walls, stairs, railings, etc.), cellular network coverage and less than 25km of assistance means	3
Geosite without safety equipment, but with cellular network coverage and less than 50km of assistance means	2
Geosite without safety equipment, without cellular network coverage and more than 50km of assistance means	1

Table 2 (continued)

13. Logistics infrastructure (SVW=0; EVW=10; TVW=5; VUW=0)	Points
Accommodation and restaurant for groups of 50 people at less than 10km	4
Accommodation and restaurant for groups of 50 people at less than 20km	3
Accommodation and restaurant for groups of 50 people at less than 30km	2
Accommodation and restaurant for groups of 50 people at less than 40km	1
14. Association with other values (SVW=0; EVW=5; TVW=10; VUW=0)	Points
Presence of various ecological and cultural values in a radius of 5km	4
Presence of various ecological and cultural values in a radius of 10km	3
Presence of one ecological and one cultural value in a radius of 10km	2
Presence of a unique ecological or cultural value in a radius of 10km	1
15. Scenic beauty (SVW=0; EVW=5; TVW=20; VUW=0)	Points
Geosite habitually used in touristic documentation at national level	4
Geosite occasionally used in touristic documentation at national level	3
Geosite habitually used in the touristic documentation at regional or local level	2
Geosite occasionally used in touristic documentation at regional or local level	1
16. Outreach potential (SVW=0; EVW=0; TVW=15; VUW=0)	Points
Illustrates products and geological processes in a clear and expressive way for the general public	4
Illustrates products and geological processes in a clear and expressive way to the public with some geological knowledge	3
Illustrates products and geological processes in a clear and expressive way to the public with solid geological knowledge	2
Illustrates products and geological processes in a clear and expressive way to the specialist public in geology	1
17. Proximity to recreational areas (SVW=0; EVW=0; TVW=5; VUW=0)	Points
Geosite situated less than 5km from a recreational area	4
Geosite situated less than 10km from a recreational area	3
Geosite situated less than 15km from a recreational area	2
Geosite situated less than 20km from a recreational area	1
18. Deterioration by natural and anthropic action (SVW=0; EVW=0; TVW=0; VUW=35)	Points
Possibility of all geological item deterioration by anthropic and natural action	4
Possibility of main item deterioration by anthropic and natural action	3
Possibility of secondary item deterioration by anthropic and natural action	2
Without possibility of geological item deterioration by anthropic and natural action	1
19. Proximity to potentially degrading zones (SVW=0; EVW=0; TVW=0; VUW=25)	Points
Geosite located close to four or more potentially degrading zones (residential areas/ human trampling, mining activities, river flooding, construction of dams, recreational areas, rock fracturation, cattle treading, uncontrolled growth of vegetation and proximity to railways).	4
Geosite located close to three potentially degrading zones	3
Geosite located close to two potentially degrading zones	2
Geosite located close to one potentially degrading zone	1
20. Protection regime (SVW=0; EVW=0; TVW=0; VUW=25)	Points
Geosite situated in an area without protection regime and none access control	4
Geosite situated in an area without protection regime but with access control	3
Geosite situated in an area with protection regime and none access control	2
Geosite situated in an area with protection regime and access control	1
21. Accessibility for vulnerability analysis (SVW=0; EVW=0; TVW=0; UVW=15)	Points
Geosite at less than 100m of paved road, with parking for buses or outcropping on a dirt road	4
Geosite at less than 100m of paved road	3
Geosite at less than 100m of road without asphalt or geosite located between 100 and 500m of paved road	2
Geosite to more than 100m of dirt road or over 500m of paved road	1

Each criterion has a specific weight for the value and vulnerability: scientific value weight (SVW), educational value weight (EVW), touristic value weight (TVW) and vulnerability weight (VUW) (adapted from Brilha 2015)

the 'Dinosaur Valley Natural Monument' (Decree No. 14.833); however, geoconservation strategies for other geosites of the basin have not yet been carried out (Santos 2014). Scientific, educational and touristic values, together with a vulnerability index, were assessed for these 25 sites. This study contributes to the establishment of strategies to assure geoheritage protection in the Sousa basin.

The study area is included in a geopark project proposed by the Brazilian Geoparks Programme lead by CPRM, the Geological Survey of Brazil (Ferreira et al. 2014). A geopark, according to UNESCO (2014), is a territory with well-defined limits, which is large enough area to allow local economic development. The geopark should comprise a certain number of sites associated with geological heritage with a special scientific importance, rarity or beauty or be representative of an

Table 3 Classification of scientific, educational and touristic values and vulnerability into four classes: very low, low, moderate and high

Range	Value and vulnerability
0–100	Very low
101–200	Low
201–300	Moderate
301–400	High

Adapted from Brilha (2015)

area and its geological history, events or processes. In addition, a geopark should have ecological, archaeological, historical or cultural values. The current study carried out on the palaeontological heritage of the area is intended to contribute to this project by evaluating if the scientific relevance of the included fossil sites can justify such a project.

Materials and Methods

For the inventory and quantification of palaeontological sites in the Sousa basin, the method of Brilha (2015) was used with adaptations to the local situation. There is a specific method to quantify the values of dinosaur ichnite sites proposed by Mampel et al. (2009). However, the method of Brilha (2015) is the most current and a compilation of the best practices described in the literature, in association with the experience of the author, creates an integrated proposal for the quantitative assessment of all types of geosite and geodiversity site.

A detailed description and photographic record of potential geosites were completed in 2013 during fieldwork. The characterization of these potential geosites included their geographical coordinates, the municipality and geological formation in which the palaeontological elements occur, as well as the main features and threat, and information about what action is needed to protect the fossils. Subsequently, the palaeontological sites of Sousa basin were numerically assessed for their scientific, educational and touristic values, together with their vulnerability.

For the quantification process, 21 criteria were used, with numerical parameters ranging from 1 to 4. The value

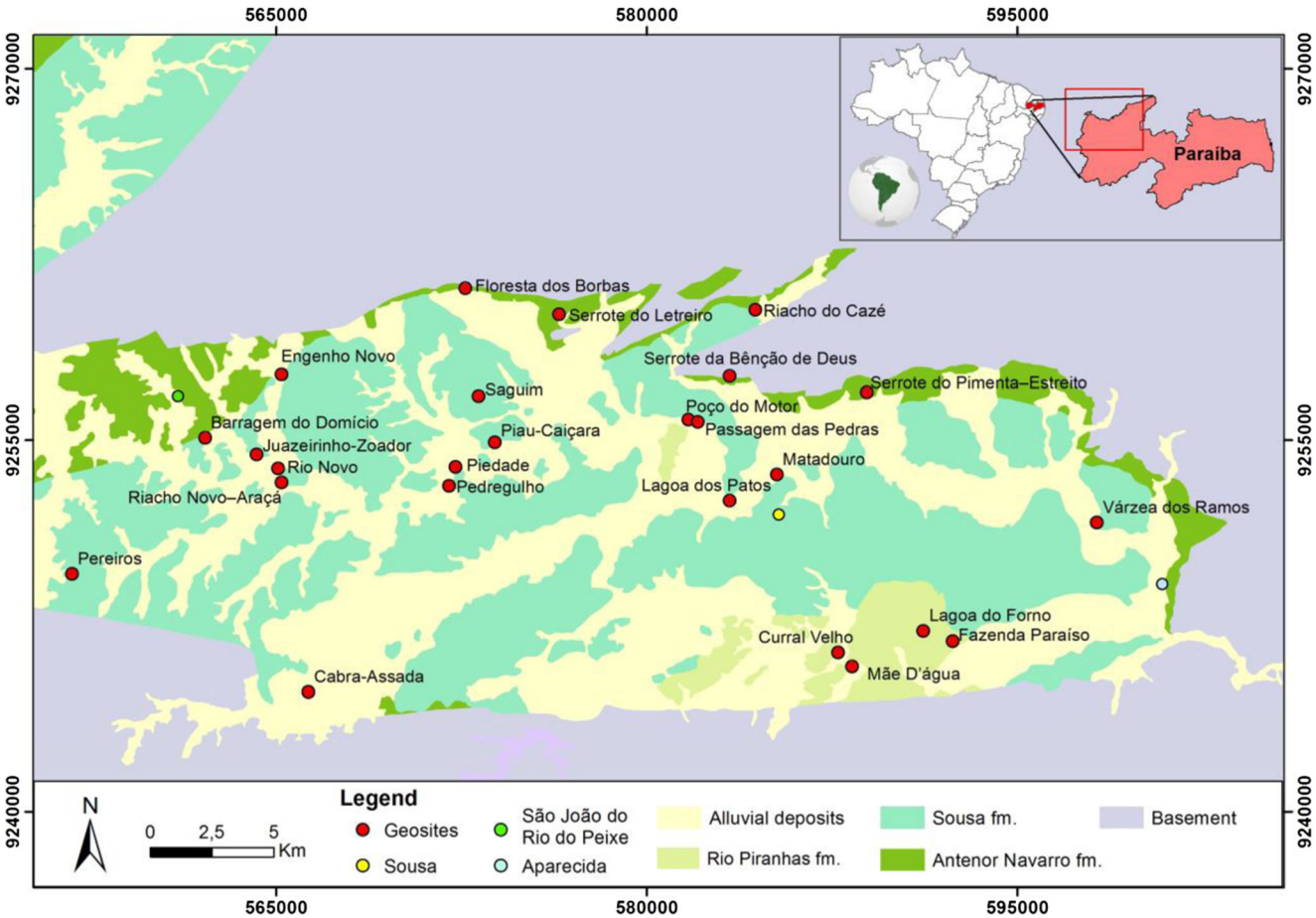

Fig. 2 Simplified geological map of the study area with location of palaeontological sites (after CPRM–Geological Survey of Brazil, sheet Sousa SB.24-ZA)

Table 4 Brief characterization of 25 inventoried palaeontological sites of Sousa basin

Geosites	Municipality and coordinate	Geological formation	Main features	Main threats	Notes
Passagem das Pedras	Sousa 06° 44.031′ S 038° 15.657′ W	Sousa fm.	There are an iguanodontian trackway and some theropod trackways. On 20 December 1992, the geosite was designated as "Dinosaur Valley Natural Monument" (Decree No. 14.833) (Fig. 3).	Mining activities; cattle treading; rock fracturation; river flooding; human trampling.	The Dinosaur Valley underwent a revitalization process (2012–2013). These works included the refurbishment of the local infrastructure. However, these developments did not include any measures in order to prevent the flooding of Peixe river and the continuous erosion of tracks (Fig. 3).
Lagoa dos Patos	Sousa 06° 45.688′ S 038° 14.751′ W	Sousa fm.	Occurrence of flimsy conchostracans with microcracking (Fig. 4).	Mining activities; cattle treading; rock fracturation; river flooding; human trampling; railway.	It is necessary to remove the remaining fossils to be protected ex situ in collections of museums and scientific institutions in order to avoid the total loss of these fossils.
Piau-Caiçara	Sousa 06° 44.413′ S 038° 19.908′ W	Sousa fm.	Some trackways and footprints of large and small theropods and sauropods (Fig. 5).	River flooding; rock fracturation.	Five footprints were removed from the outcrop because they were in imminent risk of total loss. Presently, there is a judicial process related to the withdrawal of footprints.
Pedregulho	Sousa 06° 45.371′ S 038° 20.911′ W	Sousa fm.	Probable theropod footprint and possible invertebrate traces.	River flooding; rock fracturation; cattle treading; residential area.	The outcrop has high vulnerability and is practically degraded. Nothing can be done to recover it.
Piedade	Sousa 06° 44.927′ S 038° 20.954′ W	Sousa fm.	One trackway with two deteriorated theropod dinosaur footprints and traces of invertebrates.	River flooding; rock fracturation.	The removal of the remaining palaeontological elements for ex situ protection is recommended.
Serrote do Pimenta-Estreito	Sousa 06° 43.309′ S 038° 11.736′ W	Antenor Navarro fm.	Trackways and isolated footprints of large theropods and sauropods (Fig. 6).	Rock fracturation.	This is the most well-protected site of the region. The in situ conservation of the tracks is very important.
Matadouro	Sousa 06° 45.113′ S 038° 13.716′ W	Sousa fm.	Trackways of large bipedal dinosaurs (theropods) were described in the literature, but not observed during the fieldwork.	Cattle treading; river flooding; rock fracturation; residential area.	It was noticed the presence of open sewage with dump directly in Peixe river and exposed garbage everywhere. Currently, this is a completely degraded area.
Riacho do Cazé	Sousa 06° 41.801′ S 038° 13.958′ W	Antenor Navarro fm.	Uncertain large sauropod footprints and some low quality theropod trackways have been described in literature, but not observed during fieldwork.	Construction of dams.	More fieldwork is necessary to detect fossils previously described.
Serrote da Bênção de Deus	Sousa 06° 42.829′ S 038° 14.636′ W	Antenor Navarro fm.	Some few silicified trees trunks were found in the locality in the 1980s, however the exact location remains uncertain.	Recreational area (Frei Damião monument).	Panoramic view over Sousa city and the whole sedimentary basin.
Floresta dos Borbas	Sousa 06° 41.034′ S 038° 20.558′ W	Antenor Navarro fm.	Large theropod footprints and sauropods trackway (Fig. 7).	Mining activities; cattle treading; rock fracturation; human trampling.	Ichnofossils are under quick erosion and located in the middle of a private gravel road.
Saguim	Sousa 06° 43.404′ S 038° 20.267′ W	Sousa fm.	Footprints of large theropods and one iguanodontian track, which were collected and stored in Dinosaur Valley.	Cattle treading.	Potential touristic and educational uses due to the occurrence of oil exudation (Fig. 8) (Mendonça-Filho et al. 2006; Carvalho et al. 2013b).
	Aparecida	Sousa fm.			The tracks were not found.

Table 4 (continued)

Geosites	Municipality and coordinate	Geological formation	Main features	Main threats	Notes
Várzea dos Ramos-Tapera	06° 46.158′ S 038° 06.673′ W		Tracks of theropods, sauropods and possible impressions of the crocodile tail (Fig. 9).	River flooding; rock fracturation; cattle treading.	Potential educational and touristic uses but urgent conservation measures are necessary.
Lagoa do Forno	Sousa 06° 48.535′ S 038° 10.488′ W	Rio Piranhas fm.	Some footprints of theropod dinosaurs highly deteriorated.	Residential area; railway.	The footprints were almost destroyed with the opening of a gravel road.
Fazenda Paraíso	Sousa 06° 48.765′ S 038° 09.840′ W	Rio Piranhas fm.	Tracks of theropod dinosaurs in high relief and in different directions (Fig. 10).	Human trampling; railway; rock fracturation; weathering.	Fossils need in situ protection measures.
Mãe D'água	Sousa 06° 49.320′ S 038° 12.045′ W	Rio Piranhas fm.	Footprints with deterioration of theropod and ornithopod dinosaurs (Fig. 11).	Cattle treading; rock fracturation; human trampling.	In situ protection is probably impossible due to high fossil degradation.
Curral Velho	Sousa 06° 49.013′ S 038° 12.357′ W	Rio Piranhas fm.	Footprints of theropods and ornithopods with low integrity were described in the literature, but not registered during fieldwork.	Residential area; construction of dams.	The tracks may have been completely destroyed. More fieldwork is necessary.
Rio Novo	São João do Rio do Peixe 06° 45.301′ S 038° 24.595′ W	Sousa fm.	Dinosaur tracks and bioturbations mentioned in the literature but not found during fieldwork.	Recreational area (football field); river flooding; cattle treading.	Footprints have been illegally removed. More fieldwork is necessary.
Riacho Novo-Araçá	São João do Rio do Peixe 06° 44.995′ S 038° 24.673′ W	Sousa fm.	Trackway of a small theropod, still with high integrity (Fig. 12).	River flooding; cattle treading; uncontrolled growth of vegetation; human trampling.	The rock blocks containing the trackway need to be urgently removed and transported to a museum or scientific institution.
Juazeirinho-Zoador	São João do Rio do Peixe 06° 44.685′ S 038° 25.144′ W	Sousa fm.	It was found a theropod dinosaur footprint, conchostracans and bioturbations. These fossils present low integrity.	River flooding; cattle treading; rock fracturation; human trampling.	There is the imminent risk of loss of all remaining fossils. Ex situ conservation is recommended.
Barragem do Domício	São João do Rio do Peixe 06° 44.165′ S 038° 26.288′ W	Sousa fm.	New trackway of a large sauropod dinosaur (Fig. 13).	River flooding; cattle treading; rock fracturation; human trampling; construction of dams.	Ex situ conservation is recommended.
Engenho Novo	São João do Rio do Peixe 06° 42.870′ S 038° 24.737′ W	Sousa fm.	Eroded footprints of theropods in different directions; sauropod footprint with detail of the anatomical characteristics and invertebrate traces (Fig. 14).	Cattle treading; rock fracturation; human trampling.	The site is constantly deteriorating but has potential to be conserved in situ. Blocks with footprints were already illegally removed.
Pereiros	São João do Rio do Peixe 06° 47.311′ S 038° 29.197′ W	Sousa fm.	Trackway of a theropod dinosaur, with the mark of the claws (Fig. 15).	Cattle treading; rock fracturation; recreational area (football field); mining activities.	Ex situ conservation is recommended.
Poço do Motor	Sousa 06° 44.129′ S 038° 15.507′ W	Sousa fm.	Sauropod dinosaur trackways but usually submerged by Peixe river.	River flooding; rock fracturation; mining activities.	Poço do Motor is close to Passagem das Pedras geosite but does not have a regime protection. The best option for this site is to remove the tracks and to store them in Dinosaur Valley.
Serrote do Letreiro	Sousa 06° 41.602′ S 038° 18.498′ W	Antenor Navarro fm.	Theropod tracks, many in high relief, associated with archaeological features (rupestrian petroglyphs) (Fig. 16).	Cattle treading; rock fracturation; mining activities.	Geoconservation strategies are recommended, because this is the only site in the world with the association dinosaur tracks and petroglyphs.
Cabra-Assada	São João do Rio do Peixe 06° 49.892′ S 038° 23.999′ W	Rio Piranhas fm.	Possible isolated theropod footprint, in an advanced state of deterioration.	Residential area.	The footprints are in constant degradation and are difficult to be found in flagstones. Some footprints of ornithopod and theropod dinosaurs were collected and are stored in Câmara Cascudo museum (Rio Grande do Norte, Brazil).

Fig. 3 Passagem das Pedras geosite. **a**, **b** Trackway of ornithopod dinosaur and footprint of theropod dinosaur. Note the presence of mud cracks (August 2010). **c** Overview of the geosite completely flooded, causing degradation of the trackways (March 2012). **d** Construction of a dinosaur replica in Dinosaur Valley (March 2013). **e**, **f** External and internal view of the museum. New exhibition with dinosaur replicas and interpretative panels (photographs by Tatiane Santos, June 2014)

zero was assigned when a particular criterion did not reach the minimum score of 1. Specifically for the scientific value (criteria 1 to 6 of Table 2), there is no score 3 in order to emphasize the results obtained from fossiliferous areas with score 4 (Brilha 2015). The final value for each geosite derives from the weighted sum of each criterion, with a maximum score of 400 points. Each criterion has a specific weight for the scientific value (SVW), educational value (EVW), touristic value (TVW) and vulnerability (VUW) (Table 2). Based on the numerical result, the scientific, educational and touristic values, and the vulnerability, of palaeontological sites were classified into one of four classes: very low, low, moderate and high (Table 3).

García-Ortiz et al. (2014) conducted a detailed description of the terms that evaluate the risk of degradation of a geosite: sensitivity, fragility, natural and anthropic vulnerability. To

Fig. 4 Lagoa dos Patos geosite (March 2013). **a** Overview of Peixe river. **b** Fragile conchostracan with a microcracking. **c** Ruminant animal carcass and railway bridge near the site

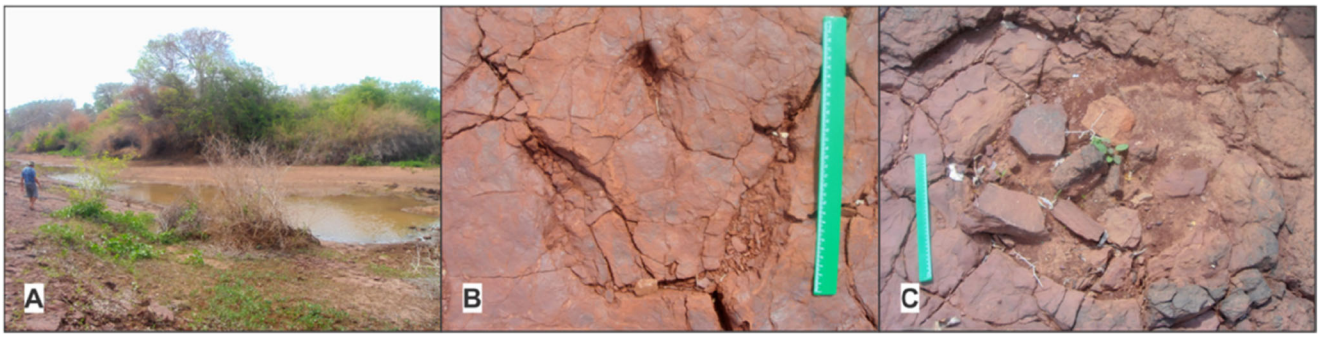

Fig. 5 Piau-Caiçara geosite (March 2013). **a** Overview of the geosite in the bed of Peixe river. **b** Theropod dinosaur footprints. **c** Sauropod dinosaur footprint

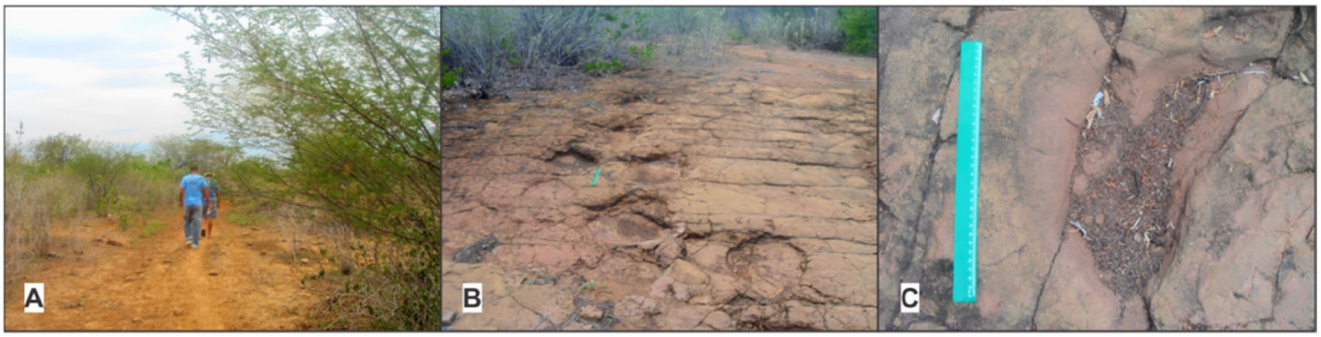

Fig. 6 Serrote do Pimenta-Fazenda Estreito geosite (March 2013). **a** Dirt road to access the geosite. **b** Sauropod dinosaur trackway. **c** Theropod dinosaur footprint

test the use of these terms, García-Ortiz et al. (2014) carried out an analysis of geosites in La Rioja (Spain), where more than 100 outcrops bearing exceptional dinosaur footprints are located. Thus, we use these terms to verify, in a general context, the risk of degradation of the palaeontological sites in Sousa basin.

Inventory of Palaeontological Sites

Twenty-five fossiliferous areas in the Sousa basin were inventoried: 17 in the Sousa municipality, 7 in São João do Rio do Peixe county and 1 in Aparecida county. Of those 25 geosites, 15 are outcrops of Sousa formation, 5 of Antenor

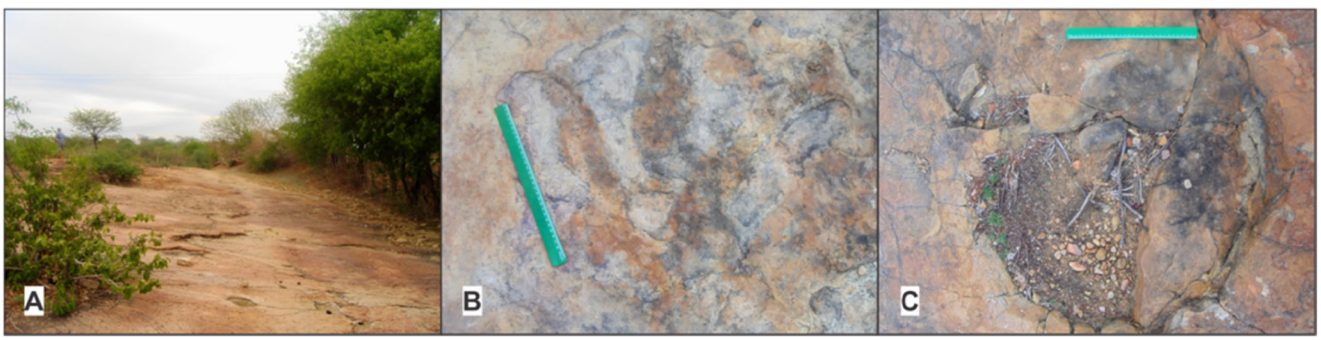

Fig. 7 Floresta dos Borbas geosite (March2013). **a** Private road where the fossil tracks occur. **b** Large theropod dinosaur footprint damaged by human and natural action. **c** Sauropod dinosaur footprint

Fig. 8 Saguim geosite (March 2013). **a** General vision of the private property where the geosite is located. **b, c** Exudation of oil

Navarro formation and 5 of Rio Piranhas formation (Fig. 2 and Table 4). Geoconservation strategies for fossiliferous areas of the Sousa basin are not yet established, except for Passagem das Pedras geosite that is under a protection regime (Santos and Carvalho 2011). A brief description of all 25 inventoried palaeontological sites is presented in Table 4 (Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16).

Quantification of Palaeontological Sites

The results of the numerical quantification of the scientific, educational and touristic values and of the vulnerability of the 25 geosites of the Sousa basin are presented in Table 5. The numerical results allowed the classification of all the geosites into one of four classes: very low, low, moderate and high value and vulnerability (Fig. 17 and Table 6).

In general, Sousa basin geosites are characterized by a low scientific value. Ten geosites have very low scientific value, 12 low, two moderate and one high scientific value (Passagem das Pedras geosite). These results are justified by the low integrity of many fossil sites and by the fact that they are common in the study area (Sousa basin), have low fossil diversity (most sites have only dinosaur tracks) and absence of other geological features with significant relevance. However, the scientific importance of an area with more than 500 dinosaur tracks studied and mapped during approximately 40 years cannot be ignored. In addition, at the national scale of Brazil, the occurrence of dinosaur footprints is not so common, which is a justification for trying to understand the scientific importance of the study area in a national context.

The results of the assessment show that Sousa basin geosites are more suitable for an educational use when compared with a touristic use. A total of two geosites have a very low educational value, ten have low, 12 moderate and one high (Passagem das Pedras geosite), whilst four geosites have very low touristic value, 18 low and only three show moderate touristic value. Passagem das Pedras geosite, which already has had some geoconservation actions implemented and has the highest score for the scientific and educational values, did not reach a high touristic value.

In what concerns vulnerability, only one geosite has low vulnerability. Nine geosites have moderate, and 15 geosites have high vulnerability. The palaeontological

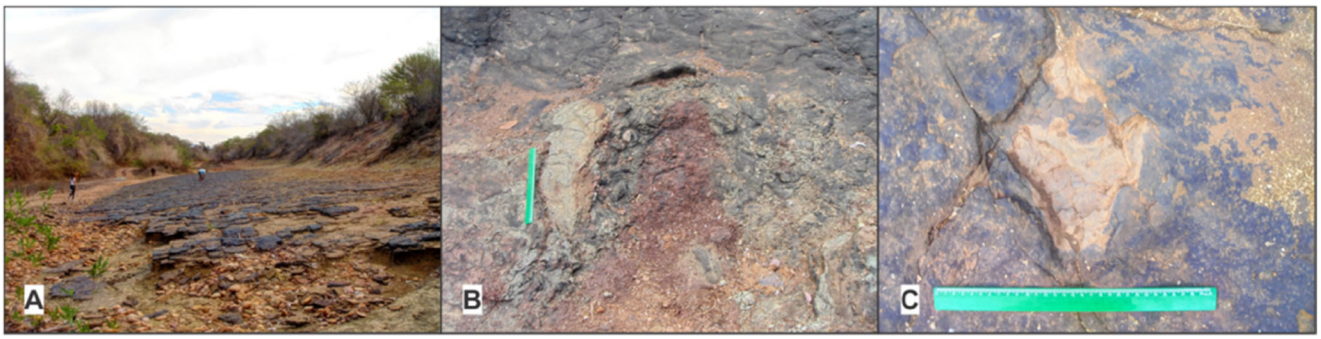

Fig. 9 Várzea dos Ramos-Tapera geosite (March 2013). **a** Overview of the outcrop containing ichnofossils and sedimentary structures. **b** Sauropod dinosaur footprint. **c** Theropod dinosaur footprint

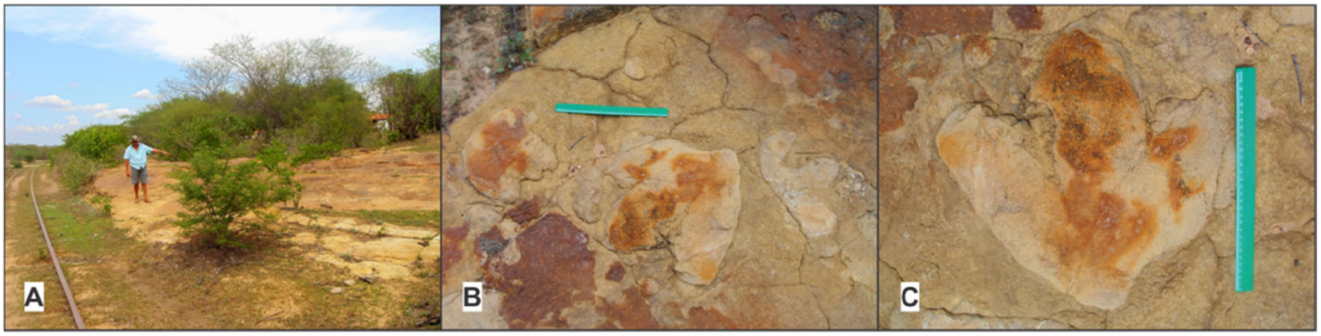

Fig. 10 Fazenda Paraíso geosite (March 2013). **a** Overview of the geosite close to the railway. **b**, **c** Theropod dinosaur footprints in high relief in sandstone slabs and in different directions. Note the evidences of oxidation processes

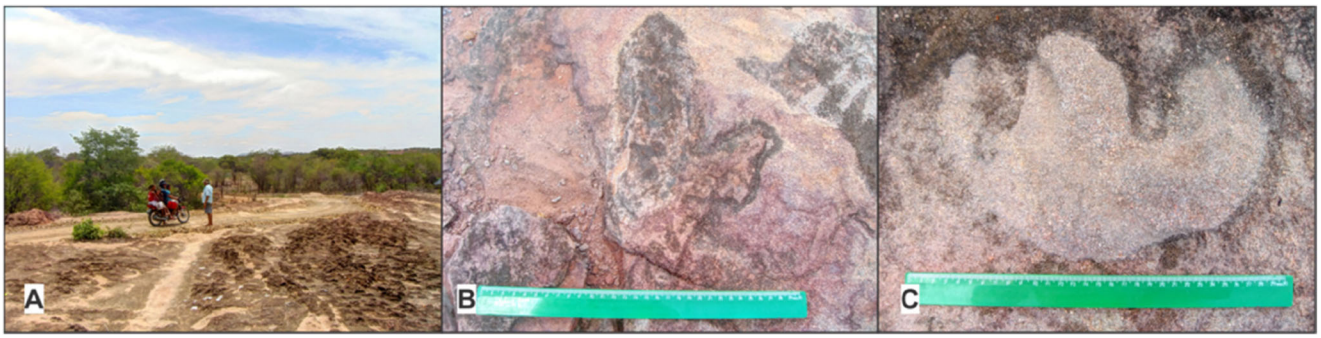

Fig. 11 Mãe D'Água geosite (March 2013). **a** Overview of geosite. **b** Theropod dinosaur footprint showing strong erosion effects. **c** Ornithopod dinosaur footprint (Iguanodonid)

sites of the Sousa basin are fragile because their fossils occur in fractured rocks and have natural vulnerability because they are located in areas under the influence of regular flooding caused by the rise of the Peixe river waters and by cattle trampling. In addition, these sites are under anthropic vulnerability due to mining and illegal collecting of fossils, together with the proximity of residential areas and roads, and not least that they oc-

Fig. 12 Riacho Novo-Araçá geosite (March 2013). **a** Overview of geosite highlighting the rocky blocks detached from the riverbed during the wet season. **b** Trackway of a small theropod dinosaur. **c** Fluidization structures

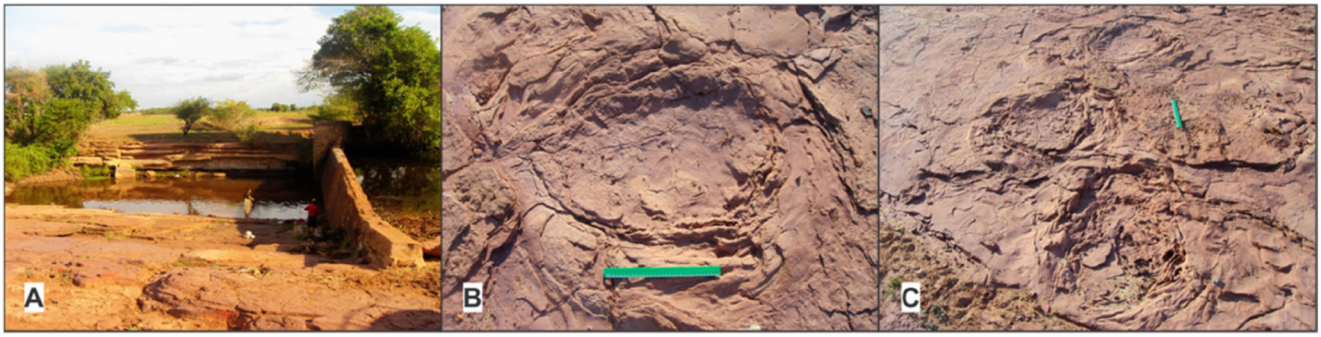

Fig. 13 Barragem do Domício geosite (March 2013). **a** View of the dam built to store water. **b**, **c** New sauropod dinosaur trackway discovered during fieldwork

Fig. 14 Engenho Novo geosite (March 2013). **a** General overview of slabs with footprints. **b** Theropod dinosaur footprints in three different positions. **c** Sauropod dinosaur footprint

cupy small areas, which is a risk factor as indicated by Fuertes-Gutiérrez and Fernández-Martínez (2010).

As observed by García-Ortiz et al. (2014), the smaller and shallower dinosaur tracks are more sensitive than larger and deeper. In the Sousa basin, there are large and shallow dinosaur tracks (Floresta dos Borbas), large and deep (Passagem das Pedras), small and deep (Riacho Novo-Araçá) and in diverse sizes and in high relief (Serrote do Letreiro). Another issue is that due to their occurrence in siliciclastic rocks, ichnofossils can suffer from microcracking (Lagoa dos Patos) and oxidation processes (Fazenda Paraíso). In general, the Sousa geosites were discovered between 1970 and 1980 and fossils were described as having a high integrity. Today, some geosites are already damaged, which suggests that the Sousa fossils are being degraded by anthropic and natural causes at a very high rate.

Fig. 15 Pereiros geosite (March 2013). **a** View of the slab with the trackway. **b** Theropod dinosaur footprint still intact and with the claw mark. **c** Theropod dinosaur trackway

Table 5 Quantification of scientific, educational and touristic values and vulnerability of the 25 palaeontological sites of Sousa basin

Quantification of scientific, educational and touristic values and vulnerability of geosites	Representativity	Local-type character	Integrity	Rarity	Scientific knowledge	Geological diversity	Didactic potential	Geodiversity elements	Observation conditions	Vulnerability	Accessibility
P. das Pedras	4	4	2	4	4	1	4	4	2	3	3
Lagoa dos Patos	1	1	0	1	2	1	1	3	2	1	2
Piau–Caiçara	2	2	1	1	4	1	3	2	2	1	1
Pedregulho	0	2	0	0	4	1	0	2	2	0	2
Piedade	0	2	1	2	2	1	1	4	2	2	1
S. do Pimenta	2	2	2	1	4	0	4	1	4	2	1
Matadouro	0	1	0	0	2	0	0	2	1	0	3
Riacho do Cazé	0	1	0	0	4	0	0	1	0	0	2
Bênção de Deus	0	1	0	0	1	0	0	0	0	0	4
F. dos Borbas	2	2	1	1	4	0	3	1	4	2	2
Saguim	4	2	1	2	4	0	4	1	4	2	2
V. dos Ramos	2	2	2	1	4	1	4	3	2	2	1
Lagoa do Forno	0	2	0	0	4	1	0	1	1	0	2
Fazenda Paraíso	2	2	2	1	4	0	4	1	4	1	2
Mãe D'água	1	2	1	1	4	1	2	2	2	1	2
Curral Velho	0	1	0	0	2	0	0	1	0	0	2
Rio Novo	0	1	0	0	2	0	0	1	0	0	2
Riacho Novo	1	1	2	1	2	1	3	4	2	2	1
Juazeirinho	1	2	1	1	2	1	2	4	2	2	1
B. do Domício	1	1	2	1	2	0	3	1	2	2	2
Engenho Novo	2	2	2	1	4	1	4	3	4	2	2
Pereiros	2	0	2	1	2	1	3	2	4	2	4
Poço do Motor	0	1	0	0	2	1	0	2	1	2	3
S. do Letreiro	2	4	2	2	4	0	4	2	4	2	3
Cabra-Assada	0	2	0	0	2	0	0	1	4	0	3

Quantification of scientific, educational and touristic values and vulnerability of geosites	Safety	Logistic infrastructure	Association with other values	Scenic beauty	Outreach potential	Proximity to recreational areas	Deterioration by natural and anthropic action	Proximity to potentially degrading zones	Protection regime	Accessibility for vulnerability analysis
P. das Pedras	3	4	3	2	4	3	4	4	1	2
Lagoa dos Patos	2	4	4	0	1	4	4	4	4	2
Piau–Caiçara	2	3	1	0	3	1	4	2	4	1
Pedregulho	2	3	1	0	0	1	4	4	4	4
Piedade	2	3	1	0	1	1	4	2	3	1
S. do Pimenta	2	4	3	0	4	3	2	1	3	1
Matadouro	2	4	4	0	0	4	4	4	4	2
Riacho do Cazé	2	3	1	0	0	2	4	2	4	2

Table 5 (continued)

Quantification of scientific, educational and touristic values and vulnerability of geosites	Safety	Logistic infrastructure	Association with other values	Scenic beauty	Outreach potential	Proximity to recreational areas	Deterioration by natural and anthropic action	Proximity to potentially degrading zones	Protection regime	Accessibility for vulnerability analysis
Bênção de Deus	3	4	3	1	0	4	4	1	3	4
F. dos Borbas	2	2	1	0	3	0	4	4	3	4
Saguim	2	3	1	0	4	1	3	1	3	2
V. dos Ramos	2	3	1	0	4	1	4	3	3	0
Lagoa do Forno	2	3	1	0	0	2	4	2	4	4
Fazenda Paraíso	2	3	1	0	4	2	4	3	4	2
Mãe D'água	2	4	3	0	2	3	4	3	4	2
Curral Velho	2	4	3	0	0	3	4	2	3	2
Rio Novo	2	2	1	0	0	0	4	3	3	2
Riacho Novo	2	2	1	0	3	0	4	4	3	1
Juazeirinho	2	2	1	0	2	0	4	4	3	2
B. do Domício	2	2	1	0	3	0	4	4	3	2
Engenho Novo	2	2	1	0	4	0	3	3	3	2
Pereiros	2	1	1	0	3	0	4	4	3	4
Poço do Motor	2	4	3	0	0	3	4	3	3	2
S. do Letreiro	2	3	2	1	4	1	3	3	3	2
Cabra-Assada	2	2	2	0	0	3	4	1	3	3

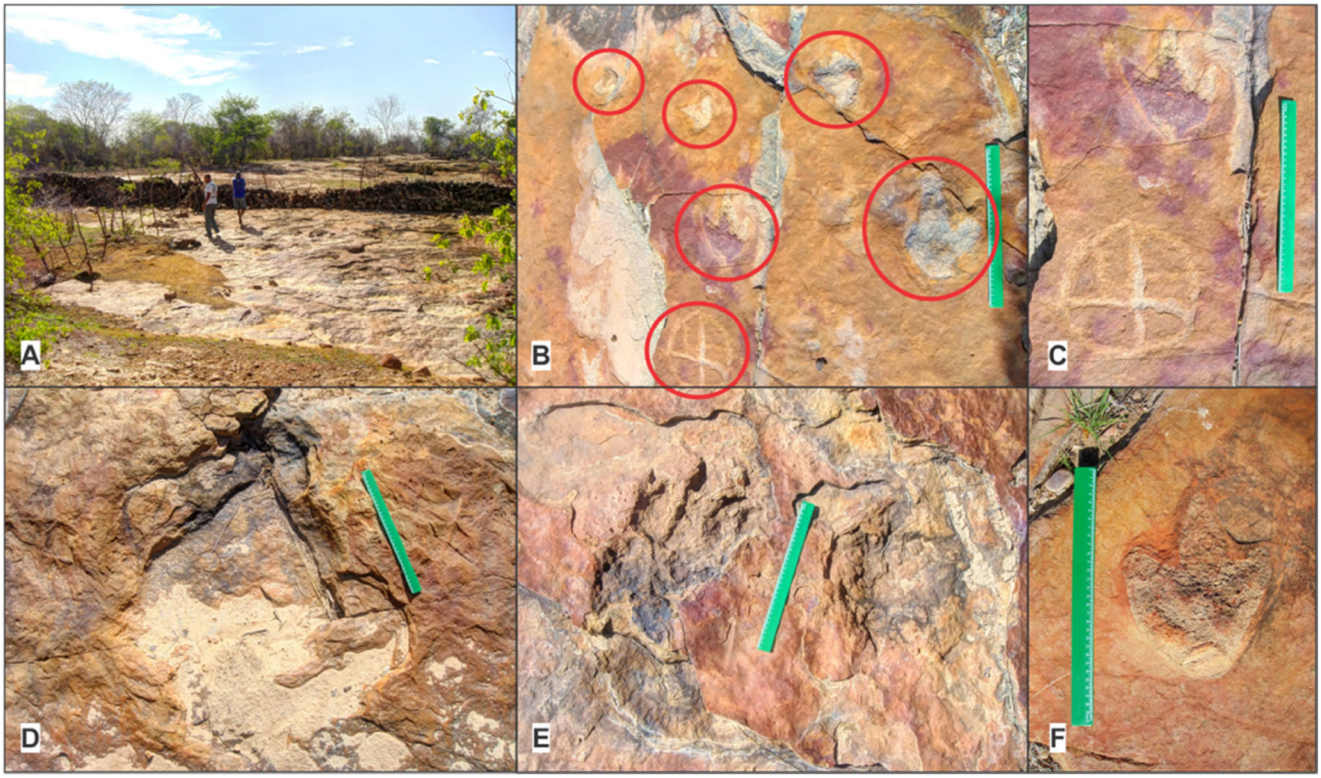

Fig. 16 Serrote do Letreiro geosite (March 2013). **a** Overview of geosite. **b**, **c** Theropod dinosaur footprints associated with petroglyphs. Note the rock fracturing. **d** Track of a large theropod dinosaur discovered during fieldwork. **e** Theropod dinosaur footprint. **f** Theropod dinosaur footprint in high relief

Conclusions

The results of the inventory and assessment of 25 geosites in the Sousa basin provide support for the establishment of a strategy to protect the palaeontological heritage of the region. Concerning the results of the quantification, conclusions are that, in general, Sousa basin geosites have a low scientific and touristic values, moderate educational value and high vulnerability. Only in the Passagem das Pedras geosite have conservation and dissemination measures been implemented, but they are not yet effective for protecting the fossils.

Regarding the management of the Sousa geosites, five categories can be established. In the first category is Passagem das Pedras geosite, which is the only one where geoconservation strategies are already implemented. In the second category, there are six geosites which are still intact and therefore with the possibility of being conserved in situ: Serrote do Pimenta-Estreito, Várzea dos Ramos-Tapera, Fazenda Paraíso, Engenho Novo, Serrote do Letreiro and Saguim.

The third category includes two fossiliferous areas that already show considerable deterioration, thus making it necessary to rapidly decide whether to conserve the fossils in situ or ex situ: Piau-Caiçara e Floresta dos Borbas. In the fourth category, there are eight geosites which the fossils should be conserved ex situ: Riacho Novo-Araçá, Barragem do Domício and Pereiros (these three have a low number of fossil occurrences) and Lagoa dos Patos, Piedade, Mãe D'água, Juazeirinho-Zoador and Poço do Motor (the last five are being rapidly destroyed).

Finally, in the fifth category, there are four geosites where fossils have a very high degree of deterioration (Pedregulho, Lagoa do Forno, Cabra-Assada and Matadouro), together with another four geosites where no fossils were found during the present fieldwork, which justifies a need to carry out more fieldwork (Riacho do Cazé, Serrote da Bênção de Deus, Curral Velho and Rio Novo)—we should not assume that sites where no fossils were found have lost their scientific value because ongoing process of erosion that may have caused the disappearance of dinosaur footprints can also reveal new tracks elsewhere in the same formation in the area. For this reason, *all* 25 identified palaeontological sites were still inventoried and quantified.

Two of the 25 geosites have another type of geological relevance besides palaeontological: the Serrote da Bênção de Deus geosite provides a panoramic perspective of Sousa city and of the surrounding sedimentary basin and the Saguim geosite where an oil seep (rare in the region) can be easily observed.

The Sousa basin is included in the Brazilian Geoparks Programme. However, only taking into account the status of the palaeontological sites of the region, it is clear that, currently, the area has a low potential to become a geopark, mainly

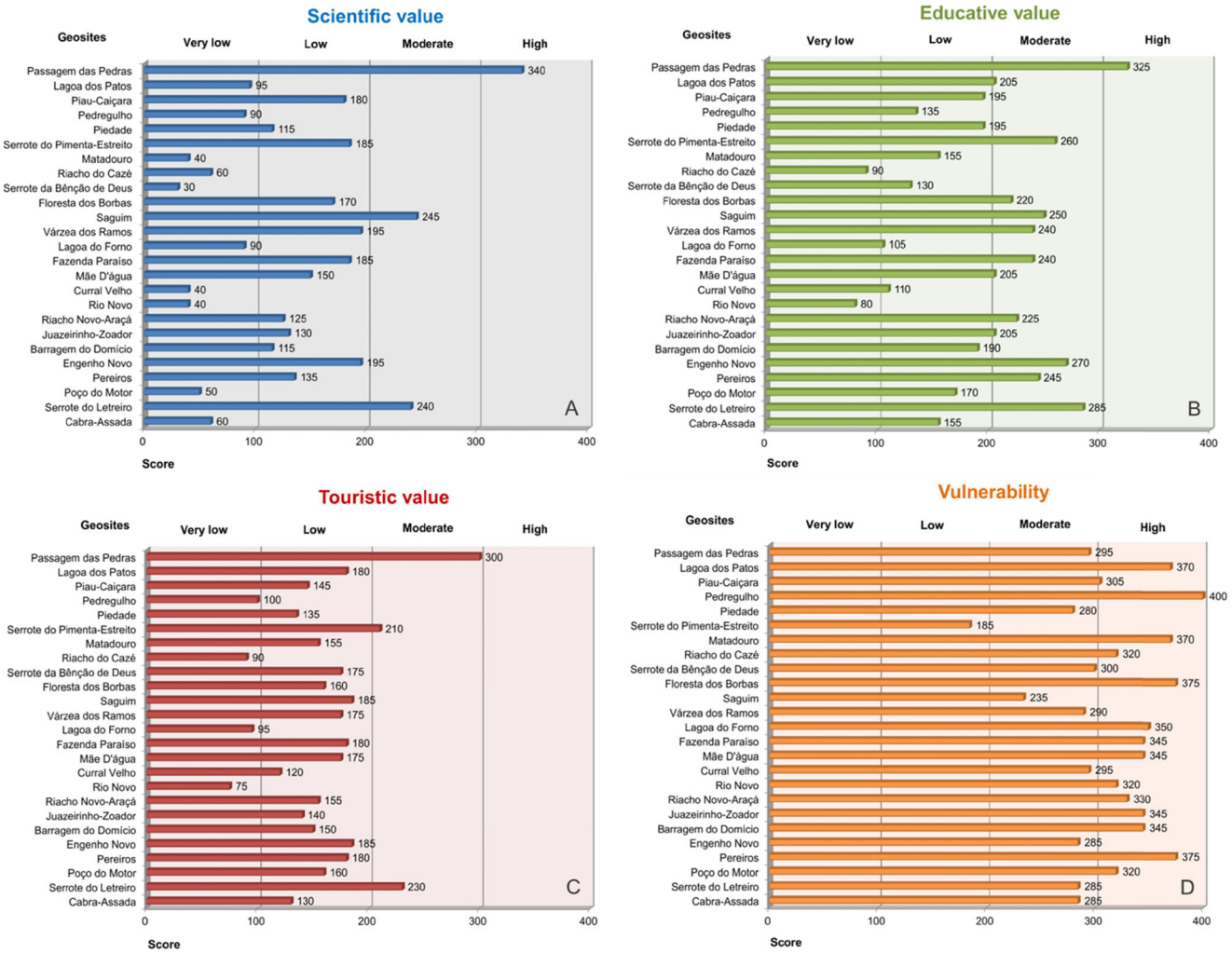

Fig. 17 Final scores of palaeontological sites and suitability in each of the classes: very low, low, moderate and high. **a** Scientific value. **b** Educational value. **c** Touristic value. **d** Vulnerability

due to a low scientific and touristic values and to a high vulnerability of the majority of the geosites (some geosites no longer exhibit any palaeontological record or have significantly deteriorated geological elements).

However, sites that still have conditions to be conserved in situ could support a future geopark application if complementary features are included in the geopark strategy, such as elements with ecological and cultural values. Additionally, partnerships between local administration, private companies and scientific institutions should be implemented, which can seek to raise financial support for the conservation of the Sousa fossils. As many geosites of the Sousa basin are located on private land, it is very important to establish agreements with the owners to guarantee the future implementation of scientific, educational and touristic uses of these areas. It is also necessary to develop educational and touristic programmes and a management structure with capacity to operate in the territory and establish community involvement with the project.

The ex situ conservation of Sousa fossils should be carried out in an appropriate institution within the 'Dinosaur Valley' area, in order to retain the fossils in the region where they were found and to make the more representative examples available to students and the general public.

Table 6 Number of palaeontological sites that have scientific, educational and touristic values and vulnerability in each of the classes: very low, low, moderate and high

Topic	Very low 0–100	Low 101–200	Moderate 201–300	High 301–400
Scientific value	10	12	2	1
Educational value	2	10	12	1
Touristic value	4	18	3	0
Vulnerability	0	1	9	15

We can conclude that the Sousa basin is an excellent example of an area that is losing its potential to become a geopark because geoconservation strategies have not been implemented at the geosites, which makes the palaeontological heritage very vulnerable. The trend is that all the geosites could be destroyed in a human timescale if no urgent conservation actions are established. A management plan for the fossiliferous areas that still have potential to be conserved in situ needs to be prepared and implemented by the authorities.

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