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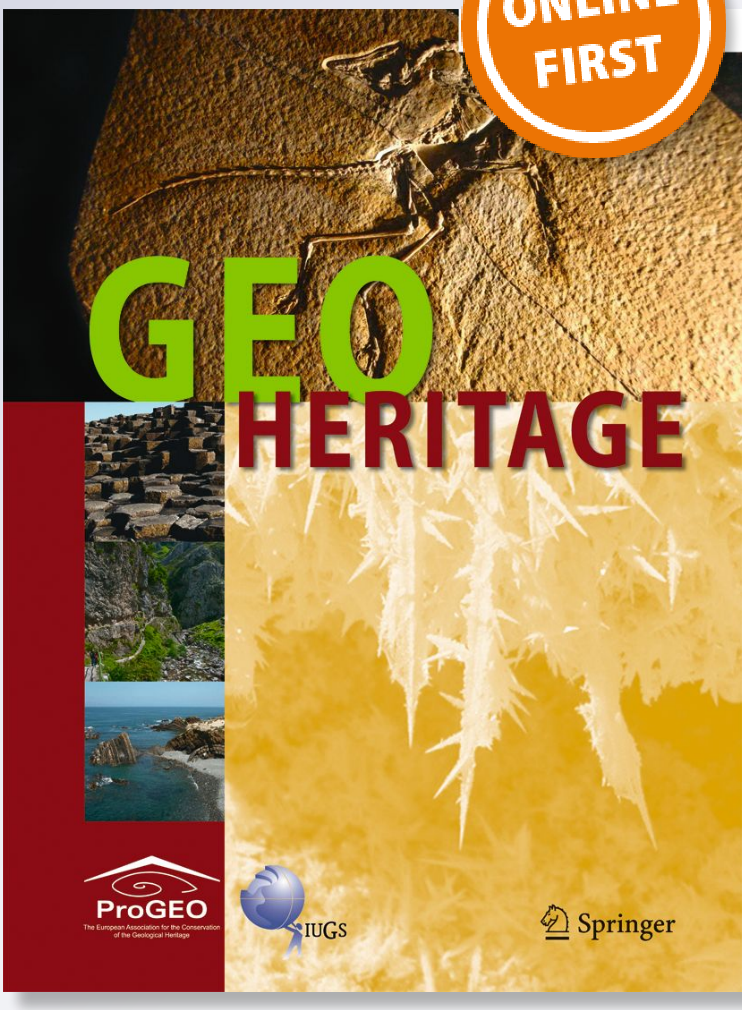

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ORIGINAL ARTICLE

Araripe Basin: A Major Geodiversity Hotspot in Brazil

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Abstract In addition to a Fossil-Lagerstätte of international significance for the Lower Cretaceous, the Araripe basin is one of the richest and most threatened reservoirs of geodiversity in Brazil. Far from being limited to its palaeontological heritage, the major importance of geodiversity in the Araripe region is also related to high levels of geomorphodiversity, pedodiversity, and hydrodiversity, as evidenced by recent research. However, numerous threats and severe damages were identified in the field, affecting all the components of the abiotic nature. As a major geodiversity hotspot, the Araripe basin requires greater attention along with an urgent need for conservation in areas without adapted protection tools. The creation of the Araripe UNESCO Global Geopark in 2006 was a crucial step toward geodiversity conservation, but its present borders are far from covering the Araripe basin as a whole. This implies the search for new solutions or alternatives, mainly in the field of geoeducation, to raise geodiversity awareness among the municipal authorities as well as the local population, in a predominantly rural region today affected by rapid and poorly planned urban growth.

Keywords Geodiversity · Geomorphodiversity · Pedodiversity · Hydrodiversity · Geopark · Araripe · Brazil

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Introduction

Situated at the border between the states of Ceará, Pernambuco, and Piauí (northeastern Brazil), the Araripe basin is world famous for its palaeontological heritage that exhibits abundant and diverse fossil records of Early Cretaceous age (Martill et al. 2007), promoting a part of the basin as the first UNESCO Geopark of the Americas and the Southern Hemisphere (Araripe Geopark; Herzog et al. 2008). Its worldwide recognition is mainly due to the exceptional state of preservation of faunal and floral fossil assemblages occurring in the Crato and Romualdo members of the Santana Formation (108–92 Myr), a stratigraphic unit internationally designated as a Conservation Lagerstätte of high significance for the Lower Cretaceous (Martill 1993, 2007). Such a rich palaeontological heritage and associated palaeobiodiversity makes the Araripe basin a high place of Brazilian geodiversity (Silva 2008). However, recent studies on landforms, soils, and landscape evolution of the Araripe basin and surroundings (Bétard et al. 2005; Magalhães et al. 2010; Peulvast et al. 2011; Peulvast and Bétard 2015a, 2015b) have revealed that the regional geodiversity is far from being limited to its palaeontological portion. According to the commonly used definition by Gray (2013), geodiversity

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encompasses "*the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features*," thus extending the geodiversity concept to the whole abiotic nature. In fact, the great diversity of landforms (morphostructural patterns, palaeolandforms, landslide deposits and processes…), soils (diversity of pedotaxa, palaeosoils, and pedogenic processes), and hydrological features (karstic springs, waterfalls, etc.) contribute to the high geodiversity of the Araripe region, both intrinsically and extrinsically.

Considering the numerous threats that today affect geodiversity in this developing region, and as a parallel to biodiversity hotspots (Myers et al. 2000), we consider in this paper the Araripe basin as a major "geodiversity hotspot" at a global scale—i.e., a geographic area that harbors very high levels of geodiversity while being threatened by human activities (Bétard 2016). The different threats identified in the area do not only affect the palaeontological heritage (Vilas-Boas et al. 2012), but all the elements of geodiversity (e.g., landforms, soils, and waters), and makes necessary to carry out an integrated assessment of geodiversity and a precise identification of the threats that endanger it, for a further integration into geoconservation strategies. With these issues and challenges in mind, the aims of this paper are (1) to reevaluate the geodiversity in the Araripe basin beyond the perimeter of the Geopark by taking into account all the components of abiotic nature, in the light of recent geomorphological, pedological, and hydrological data; and (2) to identify the current and potential threats to regional geodiversity and to propose sustainable solutions adapted to the economic and socio-educational context of interior northeast Brazil.

The Araripe Basin: A World Geoheritage Area

Geographical and Geological Setting

Together with other basins of northeast Brazil (Potiguar, Tucano–Jatobá–Reconcavo), the Araripe sedimentary basin belongs to a system of intracratonic rift structures formed during the Early Cretaceous as a result of the separation process between Africa and South America (Matos 1992; Valença et al. 2003; Fig. 1a). More precisely, the Araripe basin lies at the SW end of the Cariri–Potiguar rift zone which forms a wide and discontinuous series of NE–SW basins and half-grabens locally buried by remains of a post-rift sedimentary cover and intersected to the NE by the Equatorial Atlantic transform margin (Matos 2000; Nemčok 2016). Situated at the boundary between the Jaguaribe, Parnaíba, and São Francisco watersheds, the Araripe basin topographically straddles a high plateau (900–1000 m a.s.l.)—the Chapada do Araripe—overlooking the peripheral depressions of the Cariri Valley and the wider Sertão plain via a scalloped pattern of high cuesta-like scarps and glints (Peulvast and Bétard 2015a; Fig. 1b). Drawing a flat topographic surface gently inclined westward, the Chapada is capped by a slab of massive red sandstones of Albian/Cenomanian age (Exu Formation) which represent the final post-rift depositional stages of the basin (Baudin and Berthou 1996).

Fig. 1 Location of the Araripe basin geodiversity hotspot in northeastern Brazil. **a** Structural map of the Borborema province, showing the pre-, syn-, and post-rift structures along the Cariri–Potiguar rift zone. Compiled from Matos (1992, 2000) and Valença et al. (2003). *Rectangle* locates (**b**). **b** SRTM-derived relief map of the Araripe basin, showing the main perimeters of protection areas. *1* Araripe UNESCO Global Geopark, *2* APA (*Área de Proteção Ambiental da Chapada do Araripe*), *3* FLONA (*Floresta Nacional do Araripe*)

At the base of the sedimentary basin, the Araripe rift is divided into two sub-basins separated by a large crystalline horst. Inside, numerous NE–SW grabens filled by rift sediments are separated by minor horsts, transfer faults, and/or accommodation zones formed along preexisting Neoproterozoic shear zones (Corsini et al. 1991; Matos 1992). Initiated during the Late Jurassic–Early Cretaceous rifting stage, these faulted units are overlain by unconformable series which were deposited in the whole basin and beyond its present outlines during a post-rift phase of regional subsidence. Called the Araripe Group (Ponte and Ponte-Filho 1996), this series corresponds to fluvial, lacustrine, lagoonal, and marine sediments of Late Aptian to Albian/Cenomanian age, forming the Rio da Batateira, Santana (including the fossiliferous Crato, Ipubi, and Romualdo members), Arajara, and Exu formations (Fig. 2). Recently (Assine 2014), the post-rift series were re-defined as divided in a Late-Aptian to early-Albian Santana group (Barbalha Formation, the equivalent of the Rio da Batateira Formation, Crato, Ipubi, and Romualdo formations), and a mid-Cretaceous Araripe Group (Araripina and Exu formations).

The pre-Mesozoic basement, which underlies the basin and crops out on its margins, also protrudes as isolated hills within the eastern part of the basin (Serra de Juá, Horto). It is composed of sequences of schist, phyllite, gneiss, and migmatite intruded by calc-alkaline granites and granitoids with trondhjemitic affinities (Ferreira et al. 1998). Before and during rifting, fluvial and lacustrine deposits of Jurassic and early Cretaceous age (Vale do Cariri Group) were deposited over the Palaeozoic sandstone cover of the basement (Mauriti Formation; Da Rosa and Garcia 2000; Assine 2007; Martill et al. 2007). Unconformably covering the crystalline basement and/or the pre- and syn-rift layers, the post-rift sediment pile reaches its maximum thickness in the Cariri Valley where it comprises 250–280 m of mainly soft rocks (e.g., marls, shales, evaporites) overlain by the 150–250-m-thick Exu sandstone caprock. Because of the topographic inversion that has taken

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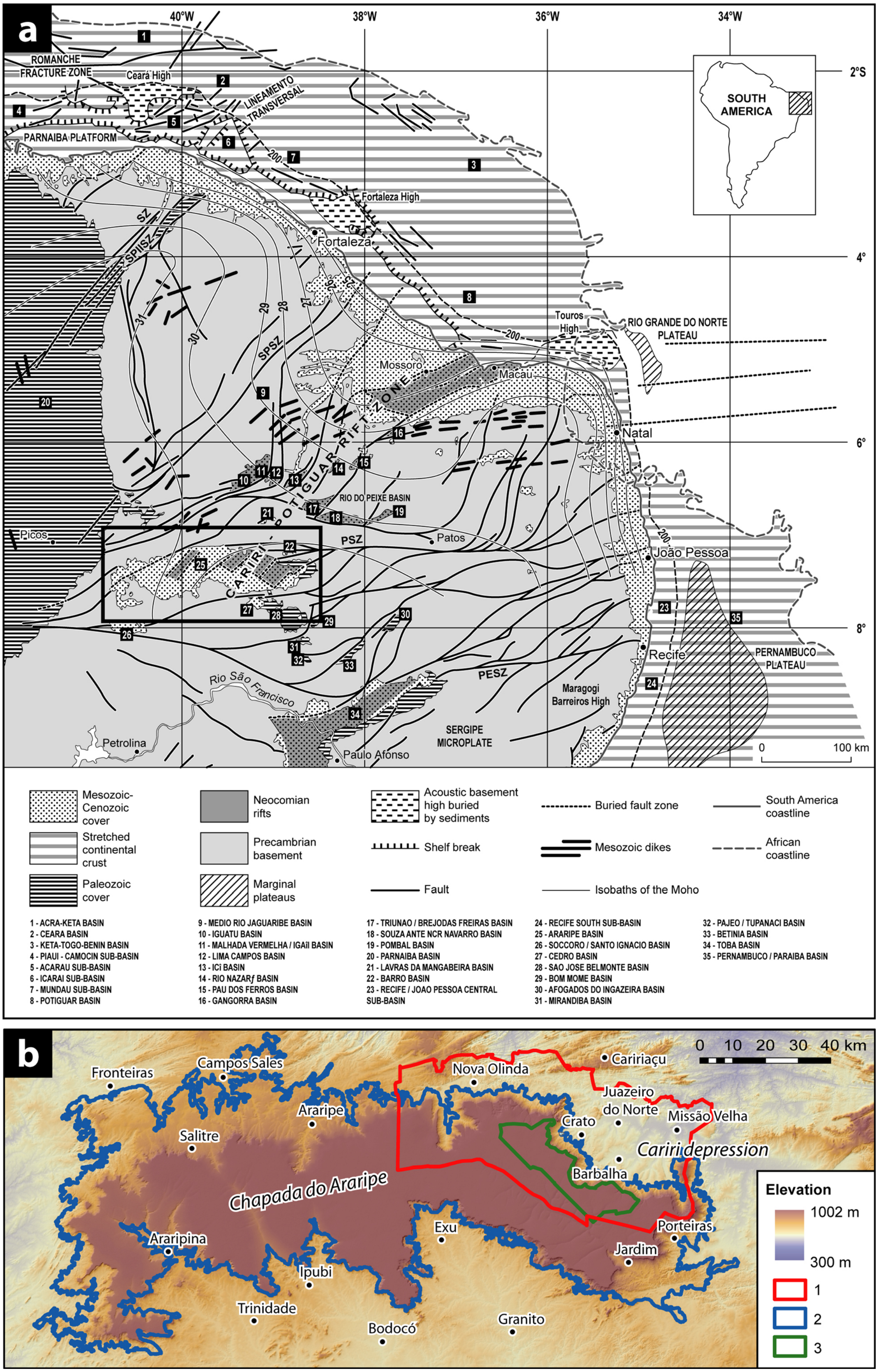

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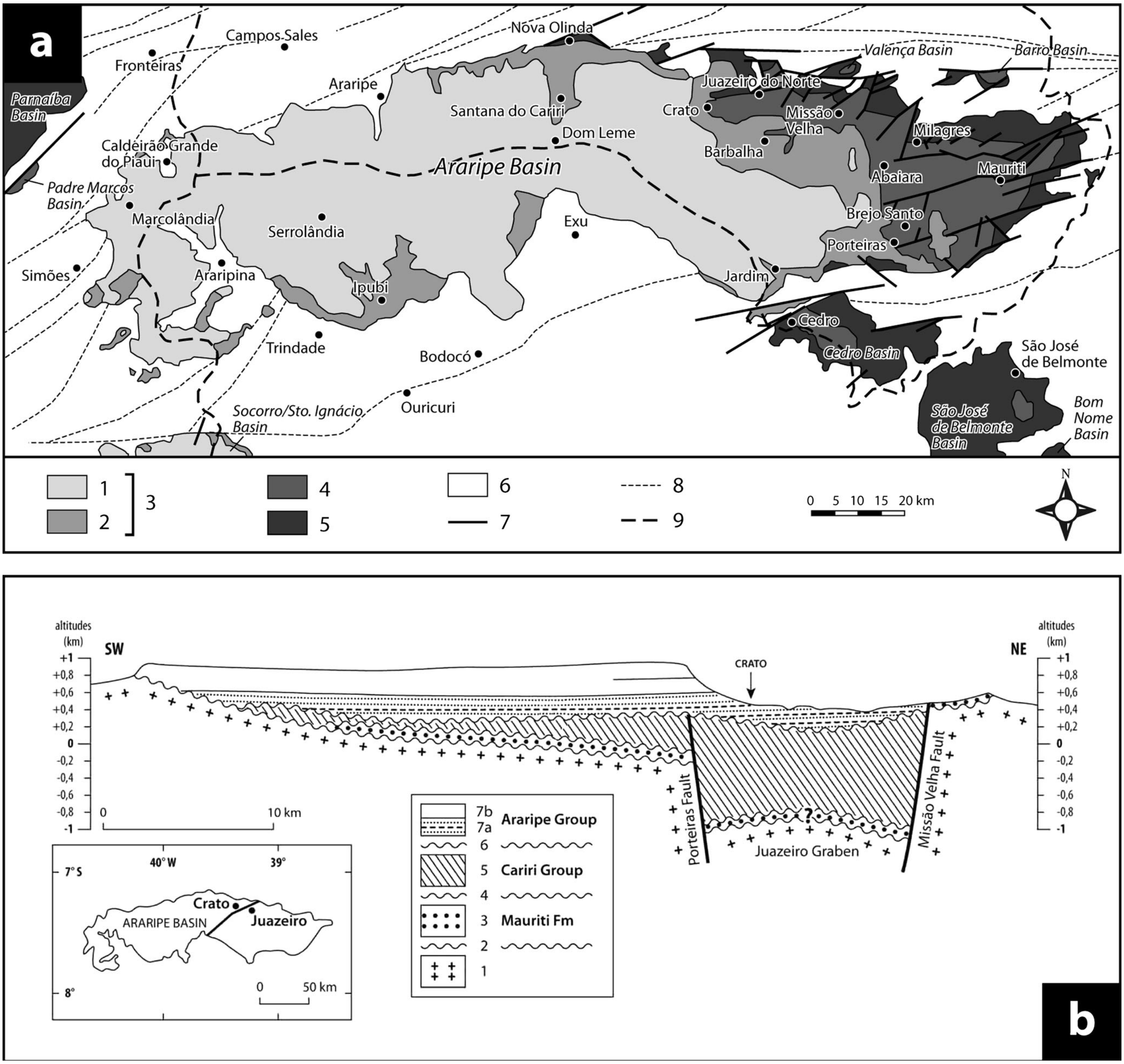

Fig. 2 Simplified geological map and cross-section of the Araripe basin. **a** Map modified from Ponte and Ponte-Filho (1996) and Assine (1994). *1* Exu Formation; *2* Arajara, Santana, Rio da Batateira formations; *3* Araripe Group; *4* Cariri Group; *5* Mauriti Formation; *6* basement complex; *7* fault; *8* lineament; *9* state border. **b** Geological profile through the Crato area, modified from Ponte and Ponte-Filho (1996). *1* Precambrian basement; *2* pre-Phanerozoic unconformity; *3* Silurian/Devonian: post-orogenic tectono-sequence; *4* pre-Mesozoic unconformity; *5* Late-Jurassic-Early Cretaceous: pre- and syn-rift tectono-sequence (undivided); *6* Pre-Aptian unconformity; *7* post-rift tectono-sequence (**a** Rio da Batateira Formation; **b** Santana, Arajara, and Exu formations)

place since the Late Cretaceous in response to large-scale flexural uplift (Peulvast et al. 2008; Peulvast and Bétard 2015a), the former basin floor now forms the plateau surface (or Chapada) as a direct result of differential erosion owing to the mechanical resistance of the Exu sandstones and to their high permeability which prevents them from deep erosion and dissection. Such a complex geological setting is particularly prone to high geodiversity, with some elements of high conservation or heritage values.

From Geodiversity to Geoheritage: The Araripe UNESCO Global Geopark

Whereas geodiversity refers to the variety of abiotic nature (Gray 2013), geoheritage is the set of the most relevant geodiversity elements with particular importance for science, education, or tourism (Pereira et al. 2012). In the study area, the societal recognition of geodiversity elements as geoheritage was favored inside the perimeter of the Araripe

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Table 1 List of geosites in the Araripe UNESCO Global Geopark

Number	Geosite	Municipality	Scientific value	Additional values
1	Colina do Horto	Juazeiro do Norte	*Petrography* (granites, diorites) and *geomorphology* (exhumed palaeorelief with panoramic view above the Cariri Valley)	*Cultural* value of religious concerns (Christian pilgrimage site, with the Cícero Priest statue and museum)
2	Cachoeira de Missão Velha	Missão Velha	*Hydrology* (spectacular waterfall of 12 m high) and *stratigraphy* (Silurian/Devonian sandstones of the Mauriti Formation)	*Cultural* value associated with an important archaeological site exhibiting prehistorical paintings ("Letreiro Stone")
3	Floresta Petrificada do Cariri	Missão Velha	*Palaeontology* (petrified forest—silicified trunks of conifers from the Missão Velha Formation) and *geomorphology* (badlands)	*Educational* value (school visits for environmental education with outdoor activities)
4	Batateiras	Crato	*Palaeontology* (bituminous clays rich in fossils—ostracods, plants, algae, fishes…) and *hydrology* (waterfalls)	*Cultural* (Kariri Indian legends) and *ecological* values ("Parque Estadual Sítio Fundão")
5	Pedra do Cariri	Nova Olinda	*Palaeontology* (fossiliferous laminated limestone from the Crato Member of the Santana Formation—insects, fishes…)	*Educational* value (school visits for environmental education with outdoor activities)
6	Parque dos Pterossauros	Nova Olinda	*Palaeontology* (fossiliferous carbonate concretions from the Romualdo Member of the Santana Formation—fishes, pterosaurs…)	*Educational* value (school visits for environmental education with outdoor activities)
7	Riacho do Meio	Barbalha	*Hydrology* (karstic springs) and *stratigraphy* (contact between the Exu and Arajara formations)	*Ecological* value ("Parque Ecológico"—remnants of Atlantic rainforest with some endemic species)
8	Ponte de Pedra	Nova Olinda	*Geomorphology* (sandstone arch above a narrow canyon carved by fluvial processes into the Exu Formation)	*Cultural* value (Kariri Indian legends, prehistorical paintings—Olho d'Agua archaeological site)
9	Pontal da Santa Cruz	Santana do Cariri	*Geomorphology* (natural belvedere on the Exu sandstone cornice above the Santana do Cariri box canyon)	*Cultural* (chapel São Bom Jesus das Oliveiras) and *ecological* values (botanical trail)

UNESCO Global Geopark, in the Ceará State, where the fossiliferous Santana Formation largely outcrops in the scarps and associated box canyons surrounding the Cariri Valley (Fig. 1b). The Geopark territory (3441 km^2) covers the municipalities of Barbalha, Crato, Juazeiro do Norte, Missão Velha, Nova Olinda, and Santana do Cariri, and encompasses a fast-growing conurbation of ~450,000 inhabitants (the Crato-Juazeiro do Norte-Barbalha urban area, or CRAJUBAR triangle). The Geopark project was politically initiated by the Government of Ceará State and scientifically coordinated by the Regional University of Cariri (URCA) in order to become a member of the Global Geoparks Network (GGN), officially claimed in 2006. Therefore, the Araripe Geopark was the first UNESCO Geopark of the American continent to be included in the GGN. The significance of the natural heritage of the area and hence its protection is also demonstrated by the National Araripe Forest (FLONA), already established in 1946, which protects an isolated area of Atlantic rainforest (Bétard et al. 2017).

In the Araripe Geopark, geoheritage includes both in situ elements (i.e., geosites) and ex situ objects (i.e., museum collections). In situ geoheritage is currently represented by a selection of 9 geosites—extracted from a first inventory of 59 geosites—which were effectively conserved and managed in order to support geotourism and educational uses (Table 1, Fig. 3). The selection of geosites was primarily made to encompass the geological diversity of the area and was based both on scientific and additional values (e.g., cultural, aesthetic, historical, ecological, etc.; see Mochiutti et al. 2012 for a complete analysis of geodiversity values of each geosite). Besides the existence of this network of geosites forming the in situ geoheritage, ex situ objects are mainly represented by specimens and fossil collections of the Palaeontological Museum of Santana do Cariri (PMSC) and smaller public or private museums (Crato, Jardim). With more than 6000 exhibited specimens, the PMSC houses various collections of minerals and fossils (silicified trunks, angiosperms, ferns, arthropods, fishes, reptiles including pterosaurs and dinosaurs…) mainly from the Santana and Missão Velha formations of the Araripe basin (Fig. 4).

Superimposed Patterns of Geodiversity in the Araripe Basin

Although geodiversity is often equated to geological diversity and thus mainly associated with solid rocks and fossils, it can comprise all the abiotic forms, materials, and processes that constitute the range of non-living nature (sensu Gray 2013). In that sense, we propose a qualitative reappraisal of geodiversity in the Araripe basin, well beyond the present boundaries of the Geopark, by examining successively the diversity of (1) rocks, minerals, and fossils

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Fig. 3 In situ geoheritage: managed geosites in the Araripe UNESCO Global Geopark. **a** Panoramic view on the Chapada do Araripe and the sandstone scarp overlooking the Cariri depression, as seen from the belvedere of the Horto granitic hill geosite. **b** The Missão Velha waterfall geosite: Palaeozoic sandstone (Mauriti Formation), constituting a resistant threshold to regressive erosion (background—Serra da Mãozinha outlier). **c** The Pedra do Cariri geosite: rehabilitated quarry in Albian laminated limestone (Crato Member of the Santana Formation) exhibiting abundant and well-preserved fossils (insects, fishes, algae, plants…). **d** The Ponte de Pedra geosite: natural arch shaped by fluvial processes into the Cenomanian Exu sandstone. **e** The Pontal de Santa Cruz geosite: natural belvedere on the Exu sandstone cornice above the Santana do Cariri box canyon. *Photographs*: F. Bétard and J.P. Peulvast

(i.e., geological diversity); (2) landforms and processes (i.e., geomorphodiversity); (3) soils and processes (i.e., pedodiversity); and (4) surface and groundwaters (i.e., hydrodiversity). Both components are regarded in intrinsic (i.e., complexity inside the study area) and extrinsic ways (i.e., compared with other areas). Figure 5 provides a synoptic view of the Araripe basin according to the four main components of geodiversity.

Geological Diversity

Geological diversity (sensu stricto) addresses the variation of rocks, minerals, and fossils, including their complex assemblages and the geological processes that shape them (Gray 2013). Petrographically, the three rock categories of the Earth's crust are represented in the Araripe region: igneous, metamorphic, and sedimentary. Plutonic and metamorphic rocks form the crystalline basement at the base and periphery of the sedimentary basin (GU1—Fig. 5). When exposed, this basement of Proterozoic–Paleozoic age appears as a complex assemblage of metasedimentary (schists, phyllites, quartzites, paragneisses…), metaplutonic (orthogneisses, amphibolites), and metavolcanic rocks (metabasalts, "green belt" rocks) intruded by syn- and post-tectonic granitoids of varied compositions (granitic, dioritic, tonalitic, trondhjemitic…; CPRM 2001, 2003). All these rocks are affected by intense deformations (folding and/or faulting) with mylonitic and migmatitic facies along major Neoproterozoic shear zones as, for example, along the EW trending Patos dextral shear zone that fringes the basin to the North (Santos et al. 2008; Neves 2015). Inside the Araripe basin, a wide range of sedimentary rocks form the successive, mainly horizontal strata of the pre-, syn-, and post-rift units, ranging from the Silurian/Devonian (Mauriti Formation) to the Albian/Cenomanian (Exu Formation), with several hiatus and unconformities (Ponte and Ponte-Filho 1996; Assine 2007; Fig. 2). Sandstones and conglomerates (silificied or not) are the dominant rock types of the basin, with numerous intercalations of limestones, marls, evaporites, shales, and siltstones (e.g., GU6—Fig. 5). Such a lithological complexity contributes to high intrinsic geodiversity.

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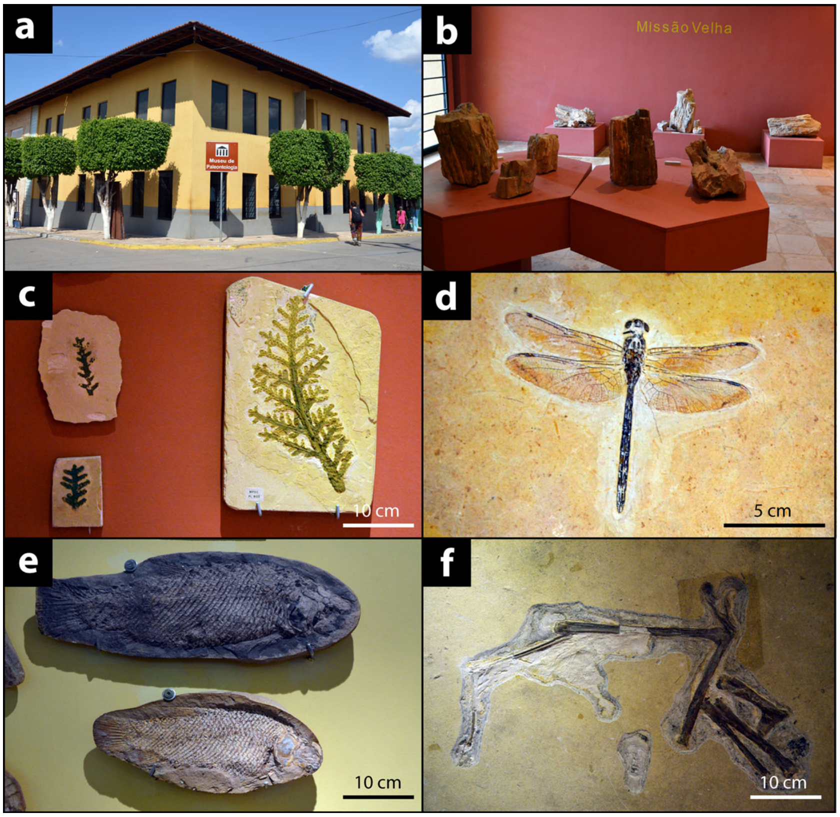

Fig. 4 Ex situ geoheritage: fossil collections from the Palaeontological Museum of Santana do Cariri (PMSC). **a** The PMSC (outdoor), one of the most comprehensive collections of Lower Cretaceous fossils in the world. **b** Silicified trunks of conifers from the Missão Velha Formation, collection PMSC. **c** Fossil plants (*Brachyphyllum obesum* Heer, 1881) from the Crato Member of the Santana Formation, collection PMSC. **d** Fossil dragonfly (*Cordulagomphus fenestratus* Carle & Wighton, 1990) from the Crato Member of the Santana Formation, collection PMSC. **e** Fossil fish (*Araripelepidotes temnurus* (Agassiz, 1841)) from the Romualdo Member of the Santana Formation, collection PMSC. **f** Pterosaur skeleton (Family: *Anhanguaridae*) from the Romualdo Member of the Santana Formation, collection PMSC. *Photographs*: F. Bétard

A huge diversity of minerals characterizes the complex geological environment of the Araripe region, corresponding to various contexts of formation by a wide variety of mineralization processes: magma cooling, low- to high-grade metamorphism, hydrothermal precipitation, supergene weathering, evaporation of saline water, transport sorting by erosional agents, chemical precipitation in oxic and anoxic waters, etc. The crystalline basement exhibits the highest richness of gemstones due to its great petrological heterogeneity which also participates in the high intrinsic geodiversity of the Araripe region: amethyst, baryte, beryl, rock crystal, garnet, gold, pyrite, rutile, tourmaline… (GU1—Fig. 5). A range of mineral occurrences is also referenced on geological maps (CPRM 2001, 2003) in the sedimentary units of the basin because of their economic exploitation for artisanal or industrial uses (iron ores, kaolinite, montmorillonite, calcite, gypsum…).

Last but not least, many rocks of the Araripe sedimentary basin include fossils that provide direct evidence of ancient life and past environments of high significance for the history of the Earth. These have led to the worldwide recognition of this region of interior Northeast Brazil among geologists and palaeontologists (Martill 1993, 2007). In the Araripe basin, the high palaeontological diversity (or palaeobiodiversity) is well illustrated by the ~6000 specimens exposed in the Palaeontological Museum of Santana do Cariri (Fig. 4) as well as in smaller public or private museums inside and outside the UNESCO Geopark. Many fossil species are unique or "endemic" to the Araripe basin with no equivalent elsewhere (Carvalho et al. 2015), contributing to its high extrinsic geodiversity. Most of the fossil record comes from the Crato and Romualdo members of the Santana Formation Konservat Lagerstätte (GU6—Fig. 5). The limestone fossil beds of the Crato Member show exceptional states of preservation for entomofauna (>200 species of insects) and flora (>50 species of plants) of high significance for the development of angiosperm in the Lower Cretaceous, whereas the Romualdo Member contains carbonate concretions with very diverse and well-preserved fossils of fishes (22 species), reptiles (including dinosaurs and 23 species of pterosaurs), invertebrates, and plants (Schobbenhaus et al. 2002; Martill et al. 2007). The

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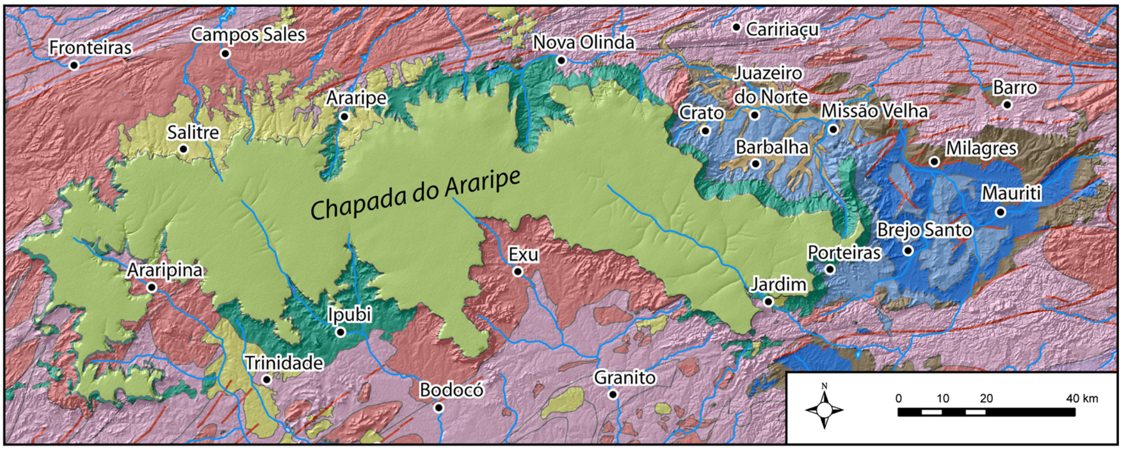

Geodiversity units	Geological diversity	Geomorphodiversity	Pedodiversity	Hydrodiversity
Alluvium geodiversity unit GU8	*Rocks*: alluvial sediments of Quaternary age, including sands, gravels, clay sands and clayey beds in large valleys. *Minerals*: clay minerals (smectite, kaolinite) for artisanal brickyard/tilery.	*Structural landforms:* water gaps in appalachian-type landforms. *Erosional landforms and processes*: alluvial plains and terraces, braided systems, fluvial fans at confluence.	*Soil types:* Fluvisols, Planosols, Vertisols. *Soil processes*: incipient pedogenesis in recent alluvium; planosolization in large valleys and vertisolization in some confined hollow systems.	*Surficial waters:* intermittent or semiperennial streams, with single or multiple channels. *Subterranean waters*: alluvial aquifer with a water table dependant to the stream level.
Exu geodiversity unit GU7	*Rocks*: sandstones and conglomerates of Albian/Cenomanian age (Exu Fm), locally silicified and cross-bedded. *Fossils*: pterosaur remains, branched trace fossils of plants.	*Structural landforms:* near-structural surface (Chapada). *Erosional landforms and processes*: shallow fluvial and dry valley systems above deeper box canyons at the periphery of the Chapada.	*Soil types:* Ferralsols. *Soil processes*: ferrallitization and kaolinitic weathering, mainly inherited from more humid climates than the present-day conditions of the Chapada.	*Surficial waters:* ephemeral flows at the top of the sandstone Chapada. *Subterranean waters*: granular aquifer system with a true karstic network (e.g., cave systems and exsurgences)
Santana geodiversity unit GU6	*Rocks*: laminated limestone, gypsum, marls, clays of Aptian /Abian age (Santana Fm). *Minerals:* gypsum. *Fossils*: diverse and abundant faunal and floral fossil assemblages (K-Lagerstätte).	*Structural landforms:* cuesta-like scarps and box canyons. *Erosional landforms and processes*: spring sapping, landslides, debris flows, debris avalanche, pediment remnants with colluvial cover.	*Soil types:* Vertisols, Leptosols. *Soil processes*: vertisolization on marls and clays (lithovertisols); leptosolization on steep slopes due to intense erosional processes (sapping, sheet/rill erosion, landslides).	*Surficial waters:* karstic springs and perennial streams in wide box canyons and funnels. *Subterranean waters*: confining unit (Romualdo/Ipubi aquiclude) above a karstic aquifer (Crato limestone aquifer).
Missão Velha geodiversity unit GU5	*Rocks*: clays, siltites and sandstones of Tithonian to Barremian age (Missão Velha and Abaiara Fm) *Fossils*: silicified trunks of conifers (petrified forest), vertebrate fossil assemblages.	*Structural landforms:* peripheral depression shaped by differential erosion. *Erosional landforms and processes*: pediment remnants with colluvial cover, gullying in the softer sandstones.	*Soil types:* Lixisols. *Soil processes*: ferrallitization with moderate desaturation (lixiviation) and intense leaching conducive to the accumulation of low-activity clays in a B (argic) horizon.	*Surficial waters:* dense network of perennial streams of the Salgado river watershed. *Subterranean waters*: the most voluminous and productive aquifer of the Araripe basin (Missão Velha aquifer).
Brejo Santo geodiversity unit GU4	*Rocks*: calciferous shales, siltstones and sandstones of Oxfordian/Kimmeridgian age (Brejo Santo Fm). *Minerals:* aragonite. *Fossils*: non-marine ostracods, conchostracheans.	*Structural landforms:* peripheral depression shaped by differential erosion. *Erosional landforms and processes*: pediment remnants with colluvial cover, fluvial dissection.	*Soil types:* Vertisols, Lixisols. *Soil processes*: vertisolization on shales (lithovertisols) and valley bottoms (topovertisols); ferrallitization with moderate desaturation (lixiviation) on siltstones and sandstones.	*Surficial waters:* dense network of perennial streams of the Salgado river watershed. *Subterranean waters*: granular aquifer with poor productivity below an upper confining unit (Brejo Santo aquiclude).
Mauriti geodiversity unit GU3	*Rocks*: massive and partly silicified sandstones (coarse to conglomeratic, with cross-bedding features) of Silurian/ Devonian age (Mauriti Fm). *Fossils*: a few ichnofossils (traces of bioturbation).	*Structural landforms:* near-structural surface (on resistant sandstones) and depression shaped into softer sandstones. *Erosional landforms and processes*: fluvial dissection with knickpoint retreat.	*Soil types:* Leptosols, Lixisols. *Soil processes*: leptosolization on structural surfaces of resistant sandstones; incipient ferrallitization with moderate desaturation in topographic depressions with softer rocks.	*Surficial waters:* waterfall and rapids of the Salgado river (Missão Velha waterfall). *Subterranean waters*: granular and/or fractured aquifer with moderate productivity (Mauriti sandstone aquifer).
Campos Sales geodiversity unit GU2	*Rocks*: granites and gneisses of Proterozoic age, locally covered by thin sandstones and conglomerates of Paleogene age or older. *Minerals:* goethite, haematite, kaolinite.	*Structural landforms:* lateritic mesas and buttes, above etch surfaces strewn with rocky knobs and tors at periphery. *Erosional landforms and processes*: gullying on the slopes of lateritic mesas.	*Soil types:* Plinthosols. *Soil processes*: lateritization involving the formation of Fe-rich duricrusted horizons of carapace- or cuirasse-type above a kaolinitic saprolite formed during the Paleogene.	*Surficial waters:* dense network of intermittent streams dissecting the lateritic paleosurface. *Subterranean waters*: weathered mantle aquifer and fractured aquifer of the parent crystalline rocks.
Basement geodiversity unit GU1 (a / b)	*Rocks*: granitoids (a) and metasedimentary rocks (b) of Proterozoic age with a wide diversity of lithotypes (schists, quartzites, marbles...). *Minerals:* amethyst, baryte, rock crystal, garnet, pyrite...	*Structural landforms:* inselbergs (in granitoids), crests and hogbacks (in metasedimentary rocks). *Erosional landforms and processes*: fluvial dissection, shallow landslides on slopes.	*Soil types:* Luvisols, Cambisols. *Soil processes*: fersiallitization (chromic Luvisols), involving high contents of free iron and the neoformation of 2:1 clays; brunification (Cambisols) on eroding steep slopes.	*Surficial waters:* dense network of intermittent streams; constellation of hill lakes/ reservoirs ("açudes"). *Subterranean waters*: fractured aquifer in the crystalline rocks and related grus mantle.

Fig. 5 Geodiversity map of the Araripe basin

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fossiliferous Santana Formation largely outcrops in the Ceará State, inside the Geopark (to the northeast), as well as in the Pernambuco and Piauí States, outside the Geopark (to the south and west—Fig. 5; Barreto et al. 2012). Other geological formations also participate in the high levels of palaeontological diversity of the Araripe basin, particularly the Missão Velha Formation with its petrified forest (Herzog et al. 2008; GU5—Fig. 5).

Geomorphodiversity

According to the definition by Panizza (2009), geomorphodiversity (or geomorphological diversity) is "*a critical and specific assessment of the geomorphological features of a territory, by comparing them in an extrinsic and in intrinsic way, taking into account the scale of investigation, the purpose of the research and the level of scientific quality.*" As a subset of the wider concept of geodiversity, geomorphic features contribute to the high levels of geodiversity of the Araripe basin at various scales, as highlighted by recent geomorphological works (Magalhães et al. 2010; Peulvast et al. 2011; Peulvast and Bétard 2015a, b).

On a regional scale and in relation to morphostructural patterns, those studies revealed the great variety of structural landforms in different geological contexts (sedimentary, metamorphic, granitic…) that points out a high degree of extrinsic geomorphodiversity compared to nearby platform regions (e.g., the monotonous flat landforms and landscapes of the inner Parnaiba basin, in the Piauí State). A weakly dissected structural surface of Cenomanian age characterizes the top of the Chapada (GU7—Fig. 5) and is separated from the peripheral depressions by a complex set of cuesta-like landforms, glints, and outliers (Peulvast and Bétard 2015a). Moreover, the coexistence of typical granitic landforms (inselbergs, bornhardts, tors, and microforms of the southern border of the Chapada of glint type—Fig. 6a), karstic landforms on limestone and sandstone caprocks (canyons, caves, karren, etc.—Fig. 6b), and Appalachian-type landforms on metamorphic rocks (schist, marble and quartzite crests and hogbacks) make this region an open-air museum of lithology-dependent landforms. The identification of a stepped pattern of palaeolandforms of various ages (e.g., the exhumed infra-Paleozoic and Albian palaeosurfaces that fringe the Araripe basin to the northwest and to the south, respectively) greatly accentuates extrinsic geomorphodiversity. Indeed, the present relief of the Chapada reflects a juxtaposition of highly contrasted elements of varied ages, partly exhumed or still buried by the sedimentary cover, in a context of basin inversion initiated in the Late Cretaceous (Peulvast et al. 2008; Peulvast and Bétard 2015a).

From the morphoclimatic viewpoint, the present-day climatic conditions, highly contrasted in the Araripe region, are factors of intrinsic geomorphodiversity: the humid east and northeast sides, which are exposed to the trade winds, strongly differ from the drier central and western parts. Whereas humid to subhumid forests cover the plateau and the scarp above the Cariri depression, forming one of the "brejos de altitude" enclaves in the semiarid "sertão" (Cavalcante 2005; Bétard 2007), less dense "cerradão," "cerrado," and "caatinga" vegetation covers, often degraded by agro-pastoral activity, are found to the west and on the lower plateaus and depressions that necessarily influence the morphodynamics. This bioclimatic pattern typically opposes two types of climatic landforms in the regional setting: a multiconvex topography in humid and subhumid areas (e.g., north of the Cariri depression, where a tread of convex hills is shaped into weathered micaschists) and a multiconcave topography formed by mantled pediments and inselbergs in the semiarid areas of the "Sertão" (e.g., the monumented semiarid landscapes of sandstone buttes and pediments at Ipubi; Fig. 6c).

At a smaller scale (i.e., local scale), many geomorphological features contribute to increase the intrinsic geomorphodiversity of the area as, for example, the great variety of landslides and other mass movements recently discovered in the rims of the Chapada do Araripe (Peulvast et al. 2011). Various types of mass movements were recognized and measured, ranging from slumps to composite types of landslides and debris flows of pluri-kilometric scale, including one avalanche debris or sturzstrom with a volume >10^8 m^3 of debris (Carretão, south of Crato). Some of the most spectacular sets of gravitational landforms occur along the western rim of the Chapada, near Araripina (Piauí), where wide tilted sandstone blocks have slid along listric faults parallel to the plateau rim (Fig. 6d). Degraded landslide scars and pediment covers with weathered block deposits also indicate the involvement of large-scale mass movements in older stages of scarp evolution and retreat of the sandstone plateau (Peulvast and Bétard 2015a). Between the smooth and concave segments of the scarp interpreted as landslide scars, highly scalloped segments display "spur-and-funnel" topography (Peulvast et al. 2011). Each funnel contains one or more springs and corresponds to a valley head incised in the lower pediments. This sapping process, related to the numerous springs distributed at the base of the sandstone cap, is one of the most spectacular processes involved in scarp retreat and dismantling of the upper plateau, together with the large-scale mass movements. It has also produced the large box canyons that indent the rim of the Chapada on its north side. The largest of them—10 km long, up to 6 km wide—is that of Santana do Cariri, in the bottom of which the fossiliferous sediments of the Santana Formation largely outcrop (GU6—Fig. 5).

Pedodiversity

Like the concept of geomorphodiversity, pedodiversity (or soil diversity) may be considered as a subset of geodiversity. It is

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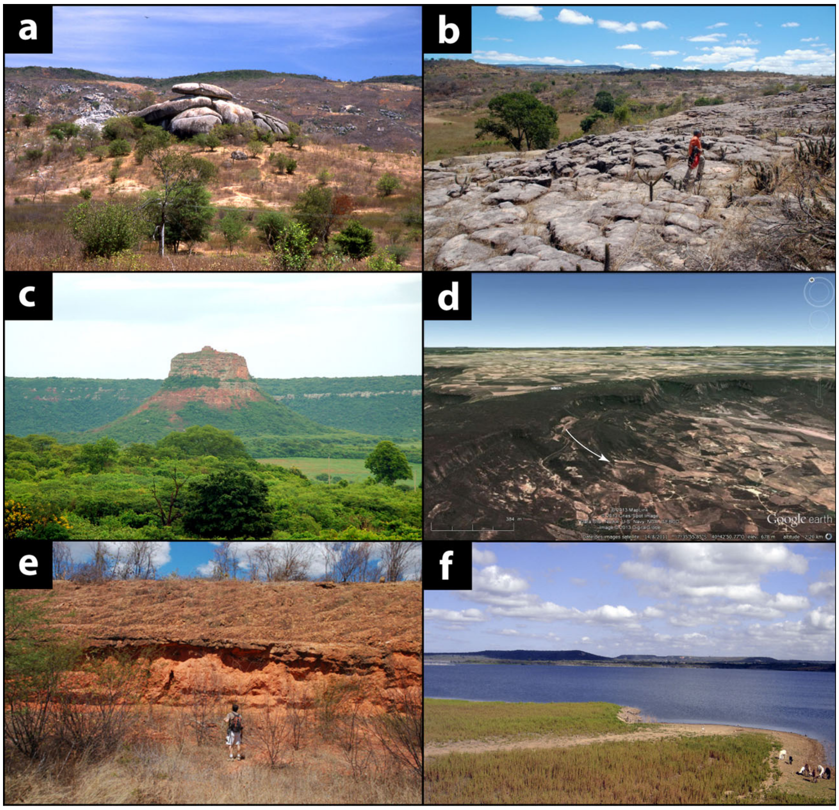

Fig. 6 Relevant geodiversity features of the Araripe basin outside the perimeter of the UNESCO Geopark. **a** Granitic tor and ruinform features in front of a glint segment of the Chapada do Araripe, Timorante (Bodocó, Pernambuco). **b** Sandstone karren near Abaiara (Ceará): exokarst features developed on the resistant sandstones of the Missão Velha Formation. **c** Torre Viva (Ipubi, Pernambuco): narrow and spectacular sandstone butte in front of the cuesta-like scarp of the Chapada do Araripe. **d** Rotational landslide (slump) near Araripina (Piauí), as seen by Google Earth. **e** Thick laterite profile west of Campos Sales (Ceará): duricrusted horizons of *cuirasse*-type over a kaolinitic saprolite developed from granite parent rock. **f** Hill dam ("açude") in a landscape of etch topography near Campos Sales (background—lateritic mesas). *Photographs*: J.P. Peulvast and F. Bétard

conceptually defined as "*an inventory of the various discrete pedological entities (e.g. soil taxa) and the analysis of their spatial and temporal patterns*" (Ibáñez et al. 2012). The temporal dimension means that it implicitly includes the inventory of pedological legacies (i.e., palaeosoils) of past climates and the pedogenic processes that originate them.

Soil diversity estimates can be based on existing soil maps and surveys over the region (Guichard 1970; Projeto Radambrasil 1981; IPECE 2007). According to the World Reference Base soil classification system (IUSS Working Group WRB 2015), 14 pedotaxa at the Reference Soil Group level are represented in the Araripe region: Arenosols, Anthrosols, Cambisols, Ferralsols, Fluvisols, Leptosols, Lixisols, Luvisols, Nitisols, Planosols, Plinthosols, Regosols, Technosols, and Vertisols. Pedodiversity values are logically much higher if the hierarchical level used in the reference taxonomy integrates one or more "qualifiers" (e.g., Rhodic Lixisol). Such a huge diversity of soil properties reflects a wide variety of pedogenic processes acting in the different geological, geomorphological, and bioclimatic settings that characterize the Araripe basin and surroundings (see sections above). Whereas ferrallitic pedogenesis prevails on the highly weathered sandstone plateau under conditions of humid climates, an original pathway of fersiallitic pedogenesis, which involves high contents of "free iron" and the prevalence of 2:1 clays in the soil mineral assemblage, typifies the wash divides on the crystalline, semiarid piedmont (Bétard 2007). In the regional setting, the red fersiallitic soils (i.e., Chromic Luvisols) typically formed above shallow, grus-type weathering mantles developed from crystalline parent rocks, under pedoclimatic conditions of low, but irregular, deep drainage (Bétard 2012). They are very different from the ferrallitic and ferruginous soils (Ferralsols, Acrisols, and Lixisols) which cover large tracts of tropical America and Africa. In that sense, such soils, quite rare in tropical environments, are factors of high extrinsic pedodiversity.

On a local scale, other soil types appear as regionally sparse pedotaxa and greatly participate in the high intrinsic pedodiversity. This is particularly the case of Vertisols, which are surprisingly rare in semiarid Northeast Brazil, whereas they occupy large areas of the Araripe basin. Their existence

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is mainly associated with marls and shales of the Santana Formation (Guichard 1970), i.e., parent rocks that have high contents of smectitic clays capable to produce vertic properties (GU6—Fig. 5). Another rare soil type, given the pedogeography of Northeast Brazil, is found close to the north of the Araripe basin (NW of Nova Olinda), where large Nitisol areas cover the basement unit. Corresponding to the "Terra Roxa estructurada" of the former Brazilian soil classification system, Nitisols are deep red, strongly weathered and well-drained soils with high contents of halloysite, contrasting with the thin, brown, and lithic soils of nearby areas (Leptosols, Cambisols). Today situated in a semiarid region with precipitations <800 mm $year^{-1}$, their formation is probably inherited from more humid palaeoclimates.

Because of their high significance for reconstructing past climates and geomorphic evolution, palaeosoils of the Araripe region have been systemically mapped, inventoried, and interpreted (Bétard et al. 2005; Peulvast and Bétard 2015a, b). Special attention was paid to the distribution and properties of laterites (i.e., Plinthosols), which are commonly considered as reliable markers in the reconstruction of denudation histories and can be easily correlated with regional palaeoclimates (Tardy and Roquin 1998). Most of the laterites, of probable Palaeogene age, cover the northwestern fringe of the Araripe basin (GU2—Fig. 5) in the plane of the exhumed infra-Palaeozoic and Pre-Cenomanian palaeosurfaces. Many of them are true autochthonous laterites, directly developed from the Precambrian crystalline rocks of the basement, as indicated by the observation of preserved quartz veins through the duricrusted horizons. With thicknesses exceeding 20–30 m, the laterite profiles comprise an upper lateritized horizon of carapace- or cuirasse-type above a friable, kaolinitic saprolite (Fig. 6e). Delimiting a series of laterite-capped plateaus easily discerned on satellite Landsat and Radar imageries, the area of lateritization is now largely eroded and dissected by the present entrenched drainage system and the ancient weathering front is often exposed (i.e., exhumed etch surface, strewn with rocky knobs, tors, and bornhardts). This recent exhumation by mechanical erosion allows the initiation of a new, primary pedogenesis by brunification and fersiallitization under the present-day semiarid conditions that prevail in the northwestern Araripe region.

Hydrodiversity

Hydrodiversity (or hydrological diversity), as a component of geodiversity, refers to the variety of both surface water and groundwater resources (Winter et al. 1998; Lazzerini 2015). As fundamental agents of geological and biological processes and evolution on Earth, water features are key elements of geodiversity and biodiversity and, in some cases, may be part of geoheritage when exhibiting a scientific, educational, and/or touristic value (Simić 2011; Cruz et al. 2014). The assessment of hydrodiversity—either qualitative or quantitative—is thus of major concern in the scope of a broader geodiversity assessment and may integrate an analysis of rainfall and runoff data, drainage density, stream ordering, aquifer productivity, and natural and artificial water reservoir occurrences (Pereira et al. 2015).

At the intersection between the Jaguaribe (north), São Francisco (south), and Parnaiba watersheds (west), the Araripe basin displays contrasted elements of surface waters owing to varied geological, geomorphological, and climatic conditions, contributing to its high intrinsic geodiversity. Whereas only ephemeral flows run through the sandstone plateau (Chapada), including its northeastern edge with more humid climate (>1000 mm $year^{-1}$), many rivers of the Cariri depression (Salgado subwatershed) are perennial or semiperennial streams fed by the numerous karstic springs located at the base of the sandstone cliff. This hydrographic pattern results in strong differences in terms of drainage densities between the porous sandstone cover and the less permeable rocks of the sedimentary basin and the crystalline basement, where a dense network of intermittent rivers characterizes all stream orders. Picturesque valleys locally exhibit impressive waterscapes, such as the waterfalls of Batateiras and Missão Velha (Fig. 3b), the natural bridge over an intermittent creek at Ponte de Pedra (Fig. 3d), or the active microcanyons of the upstream branches of the Salamanca river (southwest of Barbalha, Ceará). Because of the rarity of these hydrological features in northeast Brazil, they may be considered to be elements of extrinsic hydrodiversity.

Two aquifers with moderate productivity outcrop in the highest scarp zone of the Chapada (northeast), corresponding to the Arajara and Exu sandstones, and to the Crato limestone, respectively (Costa 1999). Below the first of them, the clays, marls, and gypsum of the Romualdo and Ipubi members form an aquiclude ("Santana aquiclude") as well as a thick plastic level prone to small- to large-scale mass movements (see "Geomorphodiversity" section). The most voluminous and productive aquifer of the Araripe basin is the "Missão Velha aquifer" (GU5—Fig. 5), which represents the main source of groundwater for the densely populated Cariri region. By contrast, the fractured aquifers of the crystalline basement have a very low productivity, locally completed by the alluvial zones acting as reservoirs with higher recharge potential. In this semiarid environment with low and irregular rainfall (400–800 mm $year^{-1}$), the multiplication of small artificial reservoirs, or "açudes" (Fig. 6f), is a human factor of increasing hydrodiversity in an intrinsic way. Designed as water harvesting strategies to mitigate the effects on agriculture of recurring droughts, this multi-thousand network of hill dams has been part of the traditional landscape scenery of interior Northeast Brazil for two centuries and is thus inseparable from its current geodiversity.

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Threats to, and Solutions for, Geodiversity Conservation in a Developing Region

The Araripe basin, viewed as a reservoir of high geodiversity in Brazil, is also an endangered place given the numerous threats and human disturbance that affect all the components of abiotic nature. In that sense, it may qualify as a "geodiversity hotspot" (Bétard 2016). Because many elements of geodiversity are nonrenewable and threatened with destruction, there is an urgent need for conservation with tools adapted to the regional and local contexts. The Araripe UNESCO Global Geopark is one of the tools well suited to geodiversity conservation and education, but its present perimeter is far from covering the entire Araripe basin (Fig. 1b), a situation which involves the search for new solutions or alternatives to the present one.

Main Threats to Geodiversity in the Araripe Basin Hotspot

The types of human activities that may degrade geodiversity depend on the component affected (geological, geomorphological, pedological, or hydrological) and on the types of objects impacted, with respect to their "sensitivity." As already stressed by several authors (Vilas-Boas et al. 2012; Barreto et al. 2012), the palaeontological diversity and heritage of the Araripe basin is primarily threatened by illegal collecting of fossils, both inside and outside the UNESCO Geopark. Despite the existence of a national legislation dedicated to fossil protection and the prevention made by the Geopark authorities, illegal collecting of specimens constitutes a major pressure on the paleontological component of geological diversity, particularly in those areas of the basin where the fossiliferous Santana Formation crops out (GU6—Fig. 5).

Another damaging activity of major importance in the local context is mineral extraction, with the Rio da Batateiras and Santana formations industrially exploited for clay (ceramic factories), gypsum (Ipubi Member; Fig. 7a), and laminated limestone (ornament rocks, pavement, cement making; Crato Member). Besides the removal of geological specimens and fossils (Vilas-Boas et al. 2012), quarrying or mining also results in partial or total degradation of landforms, with some visual impacts and geomorphic changes on the landscapes. In post-mining sites, infilling of excavation pits or technical reclamation, consisting of covering sites by topsoil or overburden, may also cause significant negative impacts, such as a loss of geological exposures and/or palaeoenvironmental information (Gray 2013). That is the case of many clay pits or gypsum quarries locally used for storage of inert waste after exploitation. However, in cases of restoration with the aim to conserve quarrying landforms and geological exposures, the quarry may be viewed as a factor of increasing geodiversity because of the new landforms and the geological window created by quarrying (Dávid 2008; Prikryl 2009; Bétard 2013). In the Araripe Geopark, for instance, the site locally known as "Mina Triunfo" is a former quarry of fossiliferous laminated limestone (Crato Member of the Santana Formation) which was suitably restored and now belongs to the network of geotouristic sites of the UNESCO Geopark (Pedra do Cariri geosite; Fig. 3c).

The threats to pedodiversity are of major concern as well. Several human activities (e.g., deforestation, intensive agriculture) are responsible for the degradation of soil profiles and structure, including compaction and loss of organic matter, and may result in soil acidification and accelerated erosion processes (see, for instance, the rapid formation of deep "voçorocas" in recently deforested hillslopes of the Chapada; Fig. 7b). More substantial threats are probably posed by the accelerated urban development of the CRAJUBAR (Crato–Juazeiro do Norte–Barbalha) conurbation in the Ceará part of the basin (Fig. 7c). With this fast-growing urban area of >450,000 inhabitants, deforestation and soil sealing are rapidly increasing in all geomorphological units, including the lower slopes of the escarpment highly prone to surface runoff, with the effect of accentuating hazards such as flash floods at the origin of more and more damages in the cities of Crato and Barbalha (Magalhães and Peulvast 2013). While rapid urbanization is taking place toward the Chapada around Crato, geodiversity features are progressively destroyed due to the absence of urban or environmental planning taking into account the values of geodiversity elements. These facts point out a certain inadequate legislation in terms of integrating geodiversity into protected area management.

In the study area, pollution remains one of the major problems with dramatic consequences on soil and water resources. Open refuse dumps are still frequent in the Cariri region—in spite of recent projects of confined, engineered landfill sites at a metropolitan scale—and often cause significant contamination of soil, surface water, and groundwater through leaching and percolation of waste pollutants at depth (Fig. 7d). Contamination of water bodies and rivers by domestic and industrial sewage is a general phenomenon in the absence of an efficient system of wastewater collection and treatment by the municipalities (Fig. 7e). Private appropriation of sites and water resources (illegal pumping and direct connection to springs; Fig. 7f) finally reveals a relative inefficiency of local authorities to enforce environmental regulation and to protect hydrodiversity. In this last case, the result is that originally semi-permanent creeks and rivers, including the Salgado river which collects all the water of the Cariri depression, are now completely dry during the major part of the year or replaced by small streams of polluted and stinking water.

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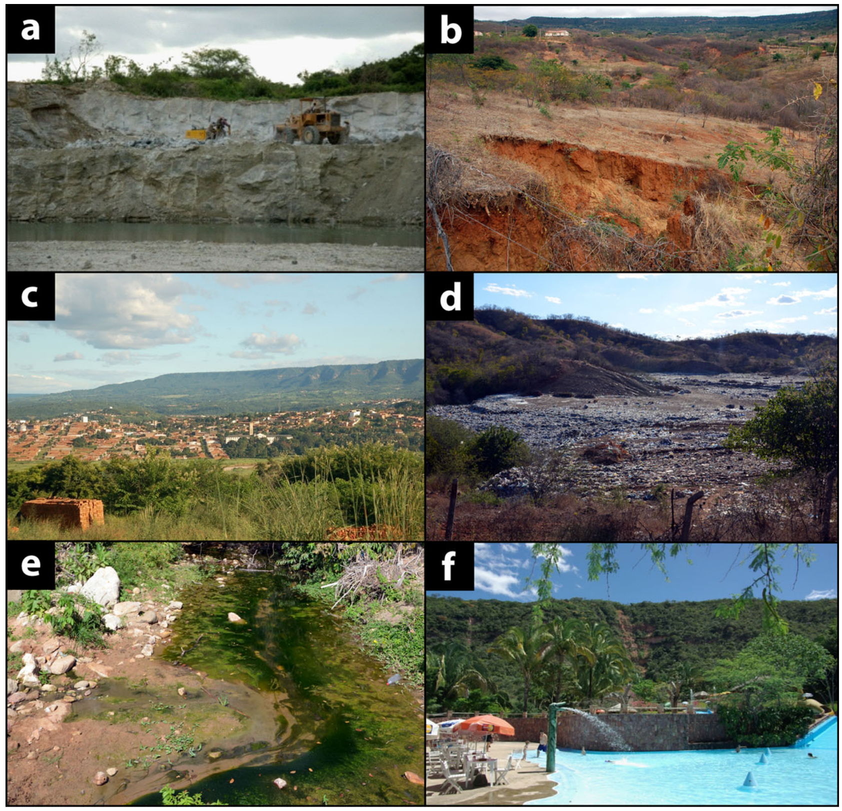

Fig. 7 Main threats to geodiversity in the Araripe basin hotspot. **a** Gypsum quarry excavated in the Ipubi layers of the Santana Formation (Nova Olinda, Ceará). **b** Recently deforested hillslope affected by deep gullies or "voçorocas" (Porteiras, Ceará). **c** Urban expansion (Crato, Ceará) and soil sealing prone to runoff at the foot of the Chapada do Araripe. **d** Open dump at Serra do Horto (Juazeiro do Norte, Ceará). **e** Water pollution and eutrophication caused by wastewater discharges from domestic and industrial sources at Crato (Ceará). **f** Recreational park in a scarp segment of the Chapada directly water-fed by karstic springs. *Photographs*: J.P. Peulvast and F. Bétard

Solutions to Address the Threats: Geoconservation or Geoeducation?

In the Araripe region, several remarkable elements of geodiversity (i.e., geoheritage) are currently protected and managed in different ways. Facing growing threats to the natural diversity of the Brazilian territory, successive federal and state governments of Brazil have multiplied, for a half century, the efforts of nature conservation by creating natural parks and reserves, and special "areas of environmental protection" (APA, Áreas de Proteção Ambiental; Fig. 1b; Conto 2004). These national initiatives have been locally relayed to private ones, with the creation of "special reserves of natural heritage" (Reservas Particulares do Patrimônio Natural) and other "ecological reserves" (Reservas Ecológicas) in several localities of the Cariri region. Historically, all the protection areas listed above were primarily employed to protect biodiversity and bioheritage (Bétard et al. 2017). The geodiversity and geoheritage value of Brazilian landscapes were recognized more recently (Nascimento et al. 2008; Silva 2008; Vieira et al. 2015), but the preexisting protection status indirectly allows the conservation of geodiversity elements. Among the types of protection areas available in the Brazilian legislation, the "natural monument" class of conservation unit (Monumento Natural) is currently the only legal tool adapted to the integral protection of local geodiversity features, or geosites. In the Araripe region, it was used in 2006 to protect four geological sites from human threats in the perimeter of the UNESCO Geopark (decree no 28.506 of 1st December 2006).

As a result, specific actions of geoconservation have been developed since 2006 (i.e., the year the label Global Geopark was obtained), both in situ (quarry rehabilitation; e.g., Pedra Cariri geosite; Fig. 3c) and ex situ (inventory of fossil collections and renovation of the palaeontological museum of Santana do Cariri, Fig. 4; inauguration of the "Casa de Pedra" geoscientific center at Santana do Cariri in June 2015). However, given that the current geographical boundaries of the Geopark are far from covering the entire Araripe basin (Fig. 1b), many geodiversity elements and potential geosites located in the Pernambuco and Piauí States are under threat and require urgent measures of geoconservation (Barreto et al. 2012). This implies the use and/or extension of protected areas to conserve those regions of the basin where high levels of geodiversity are particularly endangered (e.g., the Ipubi and Araripina areas, south of the basin, where the fossiliferous Santana Formation widely outcrops; Fig. 5).

However, geoconservation must stay compliant with the maintenance, in several parts of the Araripe region, of controlled and environmentally responsible mineral extraction since this traditional activity is also important for the local economy (extraction of clays for ceramic factories, quarrying

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of laminated limestone and gypsum for construction geomaterials). As a compromise between in situ conservation and socio-economic development, two strategies might be adopted according to the geographical scale of political intervention: (1) at the regional scale, we may recommend extending the perimeter of the APA Chapada do Araripe—a protected area based on sustainable use of natural resources (Conto 2004)—because its present borders are defined by elevation-based contour lines (>500 m a.s.l. in the Ceará, >640 m a.s.l. in the Pernambuco, >480 m a.s.l. in the Piauí) whereas a major part of threatened geodiversity is located below these altitudes (Fig. 1b); inside this perimeter, quarrying or mining would be tolerated and legally controlled; (2) at the local scale, another recommendation would be to create strictly protected areas (e.g., natural monuments and reserves) on the most sensible and threatened geosites located outside the Araripe Geopark; in this type of integral protection, quarrying or mining would be prohibited as would any human activity having impacts on local geodiversity. As a complementary method to in situ conservation, another strategy to preserve fossils from illegal collecting is the ex situ creation of palaeontological museums, as proposed by Barreto et al. (2016) in some of the Araripe municipalities within the Pernambuco state. Beyond their efficiency as geoconservation tools, these museums might also support sustainable local development through geotourism (Farsani et al. 2011) in a rural area with persistent socio-economic difficulties.

In such a context, the power of geoeducation for public awareness on the values of geodiversity appears as an alternative, promising way in this developing region. Because geoeducation is one of the objectives of UNESCO's Geopark strategies, many geoeducational activities are already organized in the Araripe Geopark for scholars and also for the general public (seminars, school class excursions, educational workshops…), mainly to raise local community awareness on the importance of protecting the environment and the palaeontological heritage (e.g., actions to prevent illegal collecting of fossils). Interpretative centers of the Crato office, the PMSC and the "Casa de Pedra" at Santana do Cariri provide logistic support to communicate geoscientific knowledge to the public. Given their potential for public awareness on the importance to preserve geodiversity, geoeducational purposes should be improved in the Geopark itself (for example on the Horto Geosite, where mainly cultural and religious information is given, whereas the geological and geomorphological explanations remain hardly evoked) and extended to areas outside the Geopark (e.g., south of the basin) and to other environmental problems that affect geodiversity as the pollution of soils and waters.

A major challenge in geoeducation in the Araripe region concerns the prevention of natural hazards and risks (e.g., floods, landslides). This new challenge is meaningful since the Shimabara Declaration (approved during the 5th International UNESCO Conference on Geoparks, 2012, Japan) has alerted Geoparks on the need to address these issues, particularly in high vulnerable and geohazard-prone areas. In the Cariri region, the notion of natural risk remains poorly pregnant in the mentalities and behaviors of the inhabitants as well as the local actors, and it does not feature in management and urban planning, except in the form of more or less isolated technical measures responding to successive crises (Magalhães et al. 2010; Magalhães and Peulvast 2013). Inside the Araripe Geopark, the catastrophic floods of the Grangeiro River, which regularly damaged the city of Crato, are a good example of the sudden events which threaten properties, infrastructures, and lives in the region. Being more frequent than the large-scale mass movements recently discovered in the rim of the Chapada do Araripe (Peulvast et al. 2011), the floods, particularly flash floods, remain poorly studied and treated, in spite of the numerous political announcements repeated after each flood. Because landslides and floods are natural hazards related to geomorphological and hydrological processes, a new mission of the Araripe Geopark should be to develop educational actions on georisks that directly threaten the local population. In our opinion, this is a powerful way of improving communications on geosciences and on the importance of taking into account geodiversity in land-use planning.

Conclusion

By focusing on the Araripe basin and immediate surroundings, this study refers to one of the most significant and most threatened reservoirs of geodiversity in Brazil. According to its varied geodiversity attributes and to the numerous threats we identified both inside and outside the UNESCO Geopark, the Araripe basin undoubtedly belongs to the category of "global geodiversity hotspots" (Bétard 2016), notably because of its high extrinsic geodiversity (e.g., fossil endemism) which, in particular, is threatened. Of particular relevance to the aim of this study, we have demonstrated that the regional geodiversity is far from being limited to its palaeontological component which gives a worldwide recognition and includes high levels of geomorphodiversity, pedodiversity, and hydrodiversity, which have been inventoried and identified both in intrinsic and extrinsic ways. By assessing all the components of geodiversity, this study provides qualitative support for the establishment of geoconservation strategies at the scale of the whole Araripe basin, going beyond administrative boundaries such as state borders or Geopark boundaries. Further works should apply complementary, numerical methods in order to quantify geodiversity and its loss in the Araripe region and, thus, guide novel geoconservation strategies with respect to the legal framework and local contexts.

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This study has already highlighted that geoeducation efforts are still needed both inside and outside the Araripe Geopark, in the field of geodiversity and geoheritage awareness as well as on the prevention of geohazards which directly threaten the vulnerable population of this interior area of northeastern Brazil.

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