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A history of basin inversion, scarp retreat and shallow denudation: The Araripe basin as a keystone for understanding long-term landscape evolution in NE Brazil

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ABSTRACT

At the border between the states of Ceará and Pernambuco (northeast Brazil), the Chapada do Araripe is a high plateau (800–1000 m a.s.l.) formed by a slab of Cenomanian fluvial sandstone. This caprock is underlain by lacustrine or marine Albian layers and older rift deposits. During the Cretaceous, the Araripe basin lay at a palaeoelevation close to sea-level. Through a presentation and discussion of original field and cartographic data we analyse the mechanisms of topographic inversion in this sedimentary basin in relation to local or regional crustal upwarp. The contrast between the plateau — a weakly dissected structural surface — and the surrounding lowlands is explained through a study of the erosional scarps — cuesta-like landforms and their outliers — that fringe the Chapada. No evidence of local tectonic inversion is found. River incision, spring sapping, landslides and other forms of mass movement are listed as efficient processes of topographic inversion and scarp retreat, the rates and patterns of which appear to be controlled by lithological contrasts and conditions of exhumation of the basement. Geometric relationships with regional stepped surfaces (e.g., the low-elevation Sertaneja Surface), exhumed palaeosurfaces and regional drainage systems are analysed. Our estimation of the amplitude of denudation and topographic inversion (0.6–0.7 km) differs significantly from apatite fission-track-derived estimates reported in recent literature, which would imply burial by considerable thicknesses of younger sediments followed by 1.5 km or more of post-rift denudation — not just in the study area, but also in the Tucano–Jatoba basin to the south. The exhumation and reworking of surrounding basement surfaces probably began during the early Cenozoic, as shown to the northwest of the Chapada by the presence of widespread laterites of probable Palaeogene age. A second stage of topographic inversion occurred during the Oligocene or later. This would correspond to the major stages of river incision, partial planation and basin inversion.

1. Introduction

Together with other basins of northeast Brazil (Potiguar, Tucano–Jatobá–Reconcavo: Matos, 1992; Magnavita et al., 1994), the Araripe sedimentary basin is a fundamental landmark for reconstructing the regional morphotectonic evolution (Peulvast et al., 2008). At the border between the states of Ceará, Pernambuco and Piauí, which is also the boundary between the Jaguaribe and São Francisco drainage basins, its uppermost layers form the Chapada do Araripe, one of the high plateaus that overlook the semi-arid depressions of the "sertão" (Fig. 1). This plateau is gently inclined westward and underlain by fossiliferous lacustrine or marine Albian layers whose palaeontological diversity has recently promoted the area to the rank of first Geopark of South America (Herzog et al., 2008). The plateau is capped by Albian to Cenomanian fluvial conglomerate and sandstone, and the corresponding depocentre in middle Cretaceous time lay at an elevation close to palaeo-sea level. Previous work has argued that the Chapada has stood as a deeply weathered but weakly eroded topographic surface for the last 90 Ma (Peulvast and Claudino Sales, 2004; Peulvast et al., 2008). The lower land surfaces and landforms, therefore, would have mainly been shaped or exhumed in post-Cenomanian times by partial erosion of a local or a regional crustal upwarp that inverted the Araripe and other Cretaceous basins.

The term "inversion" often refers to any form of compressional tectonics consecutive to basin formation (Buchanan and Buchanan, 1995). In this restrictive sense, horizontal, rather than vertical crustal stresses are required because many deep sediment-filled basins around the world have never been inverted (Lowell, 1995). However, inversion may also be understood as a process of regional epeirogenic uplift and exhumation (Brodie and White, 1995) that finally makes the basin, or parts of it, stand above its surroundings. This is topographic inversion. Such a result can also occur on a more local scale (for example, inversion

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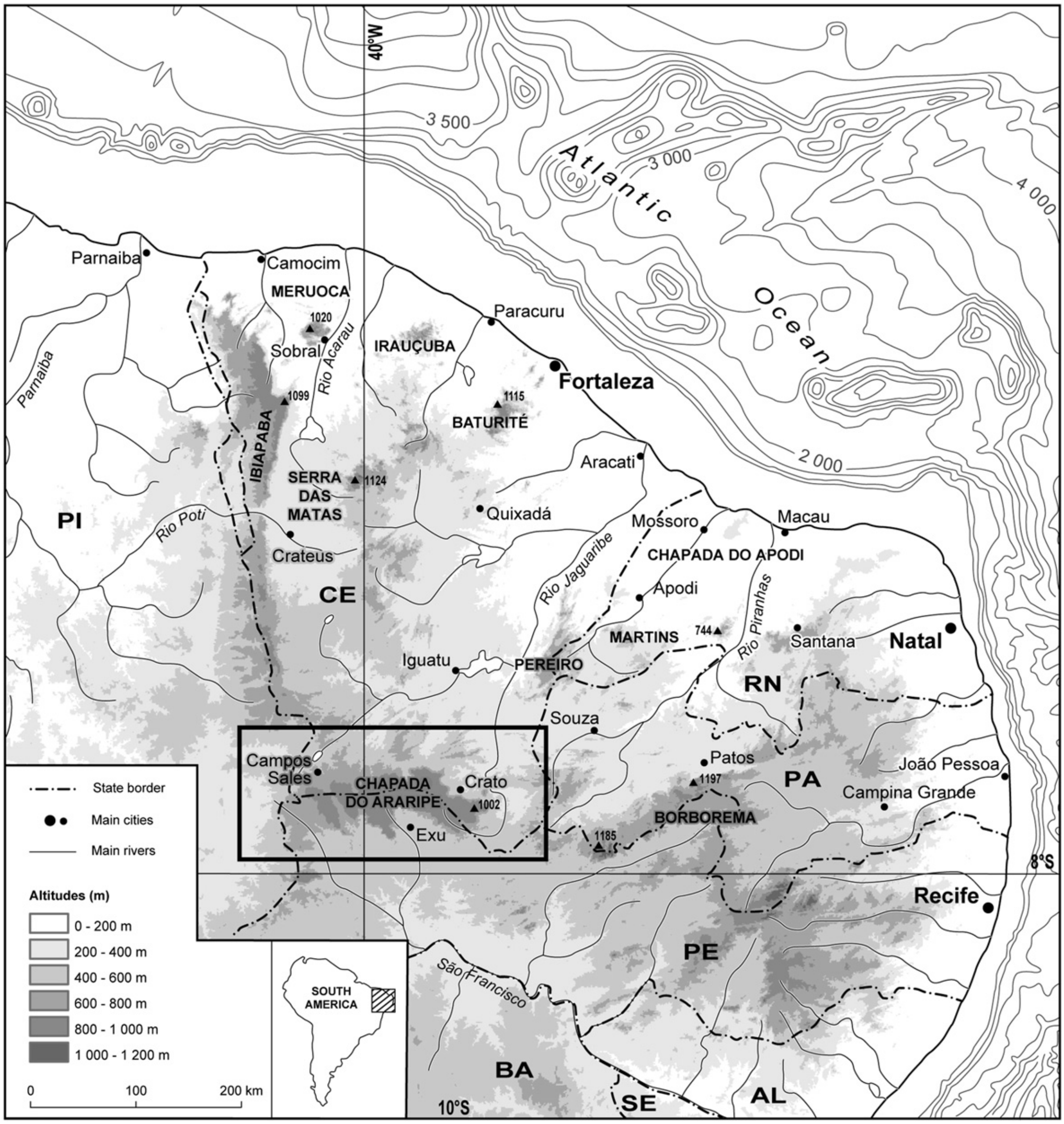

Fig. 1. Location of the Chapada do Araripe, northeast Brazil. Topography derived from the SRTM DEM v.4 (Shuttle Radar Topography Mission). Rectangle locates Fig. 2.

of lava flows channelled by a palaeovalley). It involves some post-depositional uplift mechanism but need not necessarily involve compressional tectonics. The process also requires differential erosion between the harder layers of the basin and softer rocks belonging either to the basin or the underlying basement.

In this paper, we analyse the modes and rates of topographic inversion and scarp retreat in the Araripe sedimentary basin in relation to regional uplift through a presentation and discussion of relevant topographic, geological, morphostructural and morphopedological data. Differential erosion is considered as one of the main driving processes of topographic inversion, but our analysis also provides scope for discussing the possible occurrence of differential vertical movements (tectonic inversion). A reconstruction of the conditions and chronology of inversion is proposed based on the principles and methods of morphostratigraphy (Peulvast et al., 2009). This approach challenges interpretations of episodic burial and exhumation of palaeosurfaces that have been predicated on thermochronological data models in this part of northeast Brazil (e.g., Japsen et al., 2012). This discussion bears strong implications about long-term landform evolution in northeast Brazil and other intracratonic areas. From a more general point of view, the present work is also a case study of processes and rates of vertical erosion and scarp retreat in sandstone tablelands of the tropics.

2. Materials and methods

2.1. The study area

2.1.1. Outlines and bioclimatic conditions

The Chapada do Araripe (9000 km^2) extends 190 km from E to W between 39°00′ and 40°50′W, and 7°05′ and 7°39′S, at the border between the states of Ceará, Pernambuco and Piauí (Figs. 1 and 2). The altitudes of this narrow plateau gently decrease from east (1002 m) to west (800 m), whereas its mean width remains fairly constant (~30–40 km, but up to 50–60 km in the central and westernmost parts). At the regional scale, the tread of this plateau belongs to the higher level of the two tiered topography defined in previous studies of the northern Borborema region (Peulvast and Claudino Sales, 2004; Peulvast et al., 2008). These levels are a low plain between 0 and 300 m a.s.l., gently sloping seaward (the so-called Sertaneja Surface), and the discontinuous remains of a high plain between 750 and

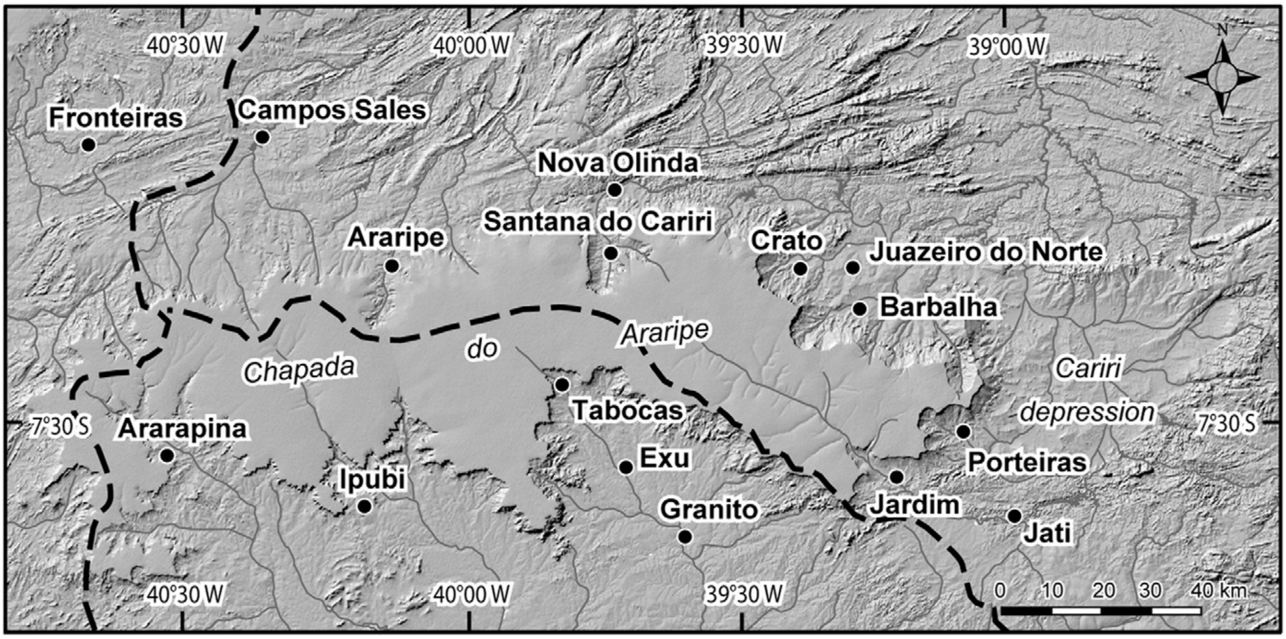

Fig. 2. SRTM-derived shaded relief and drainage map of the study area. Dotted lines: main drainage divides.

1100 m a.s.l., without a well defined regional slope. Both the high and low plains are complex mosaics of structural and erosional surfaces of different ages, some of which coincide with exhumed stratigraphic unconformities (Peulvast and Claudino Sales, 2004).

The flat-lying and monotonous topography conveyed by the term “Chapada” is only interrupted by a few dendritic systems of shallow valleys mainly striking south or southeast. A sharp morphological contrast is observed between the plateau and the surrounding regions at an elevation band between 400 and 750 m a.s.l. These lower areas consist of plateaus, ridges, valleys and depressions. Altitudes gently decrease to the northeast on the north side (south Ceará uplands). On the south side, a large and weakly dissected plateau strewn with narrow ridges, slopes to the southeast from 520 to 400 m, towards the São Francisco River.

The outer scarp of the Chapada displays an irregular outline, with strong local variations in aspect and height. The eastern part is the most spectacular, with a high rock face emphasizing the scalloped contour of the plateau (Fig. 3a). Reaching 300 to 600 m in height from the Serra da Boa Vista (Crato) to Jardim, on the SE side, the scarp overlooks a crescent-shaped lowland where hills and dissected piedmonts alternate with wide fluvial plains. Reaching up to 50 km wide, this “Cariri depression” separates the Chapada from the tight systems of E–W ridges and furrows of the western slopes of the Borborema plateau and southern Ceará uplands. In its central part, the Chapada overlooks the surrounding plateaus without any wide intervening depression, except for a narrow corridor around Nova Olinda (north side). In the southern scarp, from Jardim to Bodocó, the upper rock face is separated from the underlying plateau by a narrow bench dissected into rocky hills (Fig. 3b), except where high concave slopes overlook small depressions (Exu–Tabocas, Ipubi: Fig. 3c). More generally, the southern side is cut by large triangular embayments between elongated NW–SE salients (Ipubi, Araripina).

Scarp height gently decreases westward, to 200–300 m. To the north, it overlooks smooth tabular surfaces forming a 10–30 km wide step along the Chapada rim, from Nova Olinda to Salitre, at about 650–700 m a.s.l., between the high plateau and the south Ceará ridge-and-valley system (Fig. 2). It is more spectacular at the west and southwest tips of the plateau, where several outliers, simple buttes (region of Simões) or large mesas (south of Araripina) protrude at a small distance from the scalloped rim of the Chapada over a more rugged surface draining towards the Parnaiba River. Among them, the E–W Serra Vermelha (40×15 km) occurs 15 km south of the southernmost promontory, which is also elongated in an E–W direction.

Asymmetric features between the north and south sides of the Chapada also apply to the plateau, with systems of shallow valleys mainly striking SE or ESE. The valley heads are located close to the northern plateau rim. Most of these valleys hang over the embayments that dissect the south rim (Jardim, Exu, Ipubi) but the westernmost (Araripina) is deeply entrenched, almost cutting the Chapada in two. However, the position of the drainage divide between the Jaguaribe (north), São Francisco (south) and Parnaiba (west) rivers does not fully reflect this asymmetry, since the easternmost valley (Jardim), first striking southeast, continues off the plateau to the east and then to the north as a tributary of the Salgado–Jaguaribe drainage (Fig. 2).

From a bioclimatic point of view, the humid east and northeast sides which are exposed to the trade winds, differ from the drier central and western parts. Whereas humid to sub-humid forests (including the National Araripe Forest — FLONA) cover the plateau and the scarp above the Cariri depression, forming one of the “brejos de altitude” enclaves in the semi-arid “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.

2.1.2. Structure and lithostratigraphic units

The Araripe basin lies at the SW end of a wide and discontinuous series of NE–SW basins, half-grabens and horsts known as the Cariri–Potiguar intracratonic rift zone (Matos, 1992; Fig. 4). This 500 km-long rift zone consists of aborted Mesozoic rift structures locally buried by remains of a post-rift sedimentary cover (Araripe and Potiguar basins), and is intersected to the NE by the Atlantic margin. The Araripe rift is divided into two sub-basins (W: Feitoria or Feira Nova sub-basin; E: Eastern or Cariri sub-basin; Ponte and Ponte-Filho, 1996; Castro and Castelo Branco, 1999; Assine, 2007; Martill et al., 2007) separated by the Dom Leme 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 sigmoid shear zones that connect to the north and south with the major E–W-trending Patos and Pernambuco shear zones (Corsini et al., 1991; Matos, 1992).

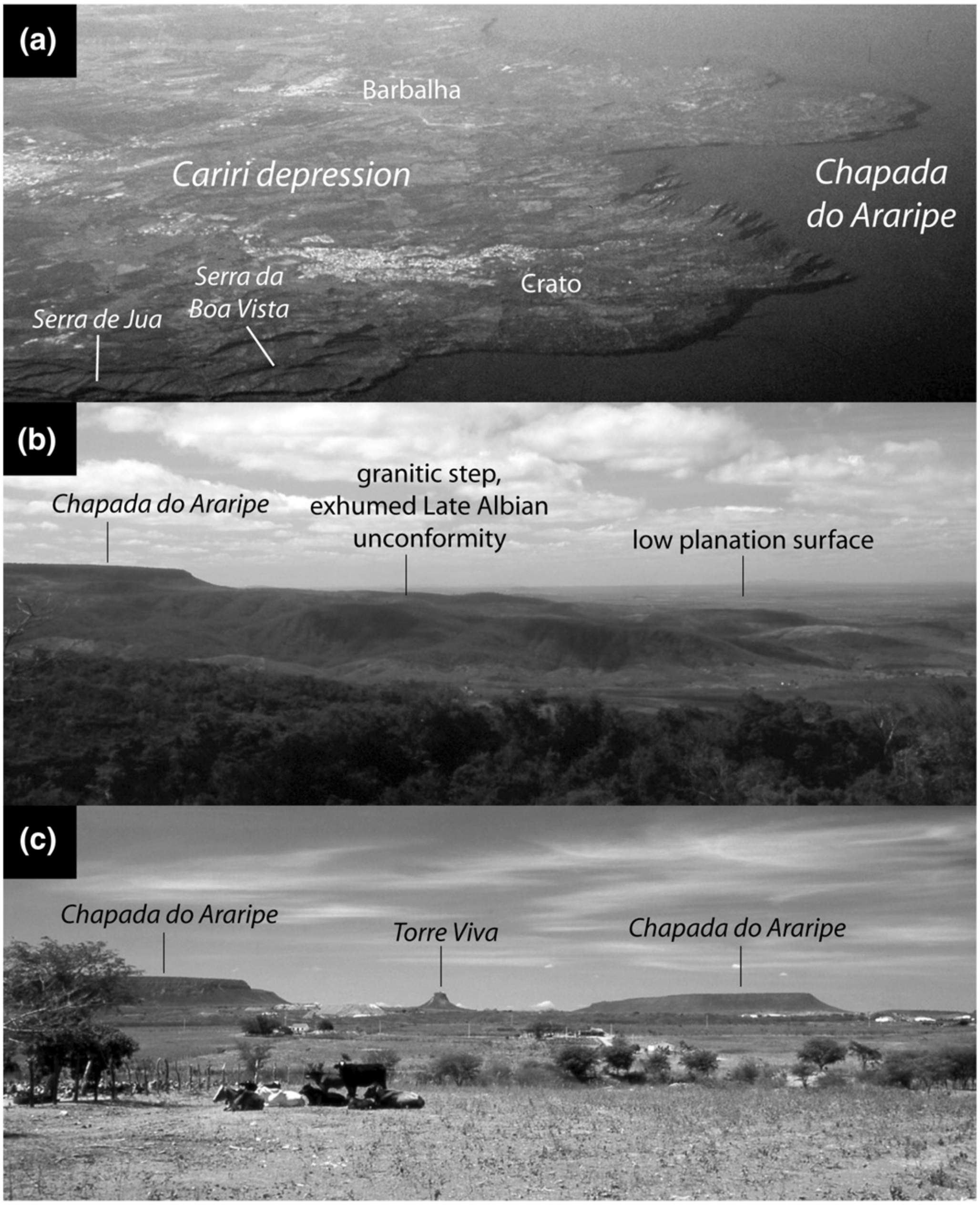

Fig. 3. Contrasting outlines along the rim of the Chapada do Araripe. (a) The Chapada do Araripe and the Crato and Barbalha re-entrants, viewed towards the SE; (b) South rim of the Chapada, east of Exu, looking west. Short sandstone crag overlooking a narrow and dissected granite step; (c) Scarp with sandstone outliers overlooking the sedimentary depression of Ipubi. In the centre: Torre Viva. Credits: J.P. Peulvast.

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 (Sial, 1986). In Jurassic and Cretaceous times, reactivation of the late Precambrian shear zones resulted in the formation of the Araripe basin during the intracratonic rifting phase that preceded ocean spreading in the Atlantic (Matos, 1992, 2000).

Before and during rifting, fluvial and lacustrine deposits of Jurassic and early Cretaceous age (Vale do Cariri Group) were deposited on the sandstone cover of the basement (Mauriti or Cariri Formation, Palaeozoic or Jurassic) (Da Rosa and Garcia, 2000; Assine, 2007; Martill et al., 2007; Fig. 5). Following a late Jurassic–early Cretaceous phase of regional subsidence and continental sedimentation (Brejo Santo and Missão Velha Formations: clay, siltites, sandstones, up to 600 m thick) (Coimbra et al., 2002; Valença et al., 2003), the main rifting stage (Berriasian–Lower Barremian) involved graben infilling by thick fluvial, deltaic and lacustrine sediments transported from the NNE (Abaiara Formation: siltite, sandstone and conglomerate). At the same time, the intervening basement areas and the overlying sediments were eroded and partially bevelled during the transitional post-rift stage (early Aptian), except for some residuals ultimately buried and later exhumed (Horto, Serra do Juá). Along the faults limiting the Crato–Juazeiro do Norte graben, throws and sediment thicknesses reach up to 1000 m (Assine, 2007).

Sedimentation resumed after a 10 to 12 My gap following the deposition of the last syn-rift layers. Owing to a combination of thermal subsidence and global eustatic events, the post-rift series were deposited throughout the Araripe basin and beyond its present limits. The post-rift basin first formed in the northeast, where the Albian to Cenomanian series are more complete, and then extended to the south and west,

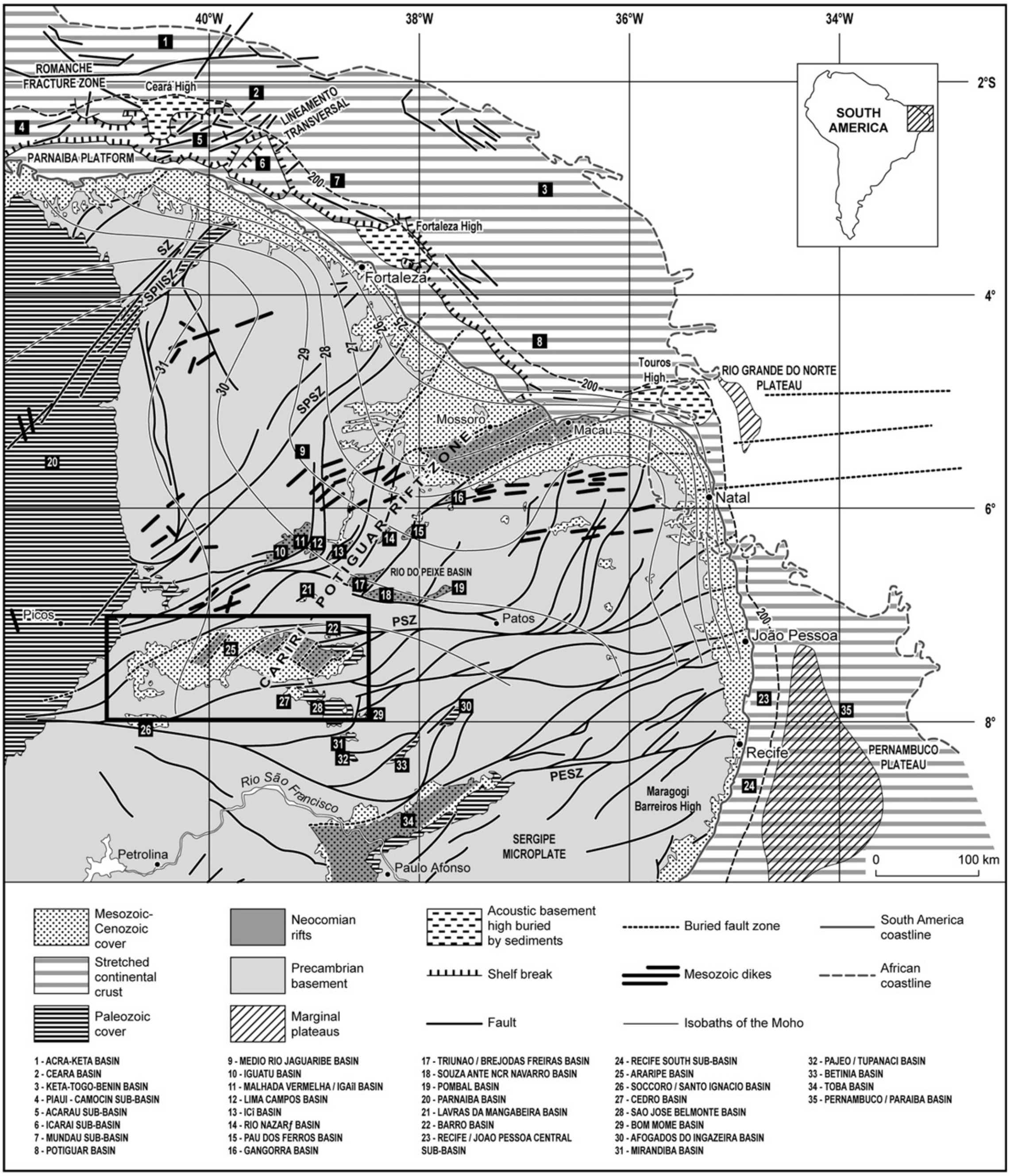

Fig. 4. Structural map of the Borborema province, showing the pre-, syn- and post-rift structures along the Cariri–Potiguar rift zone. Compiled from Matos (1992, 2000) and Valença et al., 2003. Rectangle locates Fig. 5.

progressively lapping onto the basement (Fig. 5). This stratigraphic transgressive–regressive sequence, known as the Araripe Group (Ponte and Ponte-Filho, 1996) is made of fluvial, lacustrine, lagoonal and marine sediments of Aptian to Cenomanian age. They divide into several formations: the Rio da Batateira (or Barbalha: Assine, 2007), Santana (Crato, Ipubi, Romualdo Members), Arajara and Exu Formations.

In the Cariri depression, the post-rift series comprises 250–280 m of mainly soft rocks overlain by thick massive sandstone (Exu Formation, 150–250 m). In this area, the resulting stratigraphy offers the best potential for differential erosion. The coarse to fine and clay-rich sandstone of the basal post-rift layers (Rio da Batateira or Barbalha Formation) corresponds to two upward-fining fluvial cycles with interlayers of lacustrine pelites and carbonates (Batateira layers: Assine, 2007). Reaching 60 to 200 m in thickness (Baudin and Berthou, 1996), these layers are overlain by the 80 to 180 m-thick Santana Formation. The Crato member of this formation corresponds to 20–70 m of discontinuous laminated limestone interlayered with mudstone, siltstone or shale (Martill et al., 2007). The overlying Ipubi Member, of late Aptian age, mainly consists of discontinuous and thick layers of gypsum (up to 20 m) alternating with black to brown or green foliated clays passing upwards to marls, clays and sandstones (Romualdo Member, early Albian) that were deposited after an unconformity indicating a short period of erosion (Assine, 2007). Although the total thickness of gypsum layers remains moderate, the role of this rock as a ductile level prone to shearing at relatively low temperatures (Barberini et al., 2005) is commonly recognized as a factor of slope destabilization when sufficiently thick. As shown in later sections, these gypsum layers have played a key role in Cenozoic landscape evolution.

Abundant fossils in the Romualdo layers indicate a shallow marine incursion from the SSE and reaching the western extremity of the

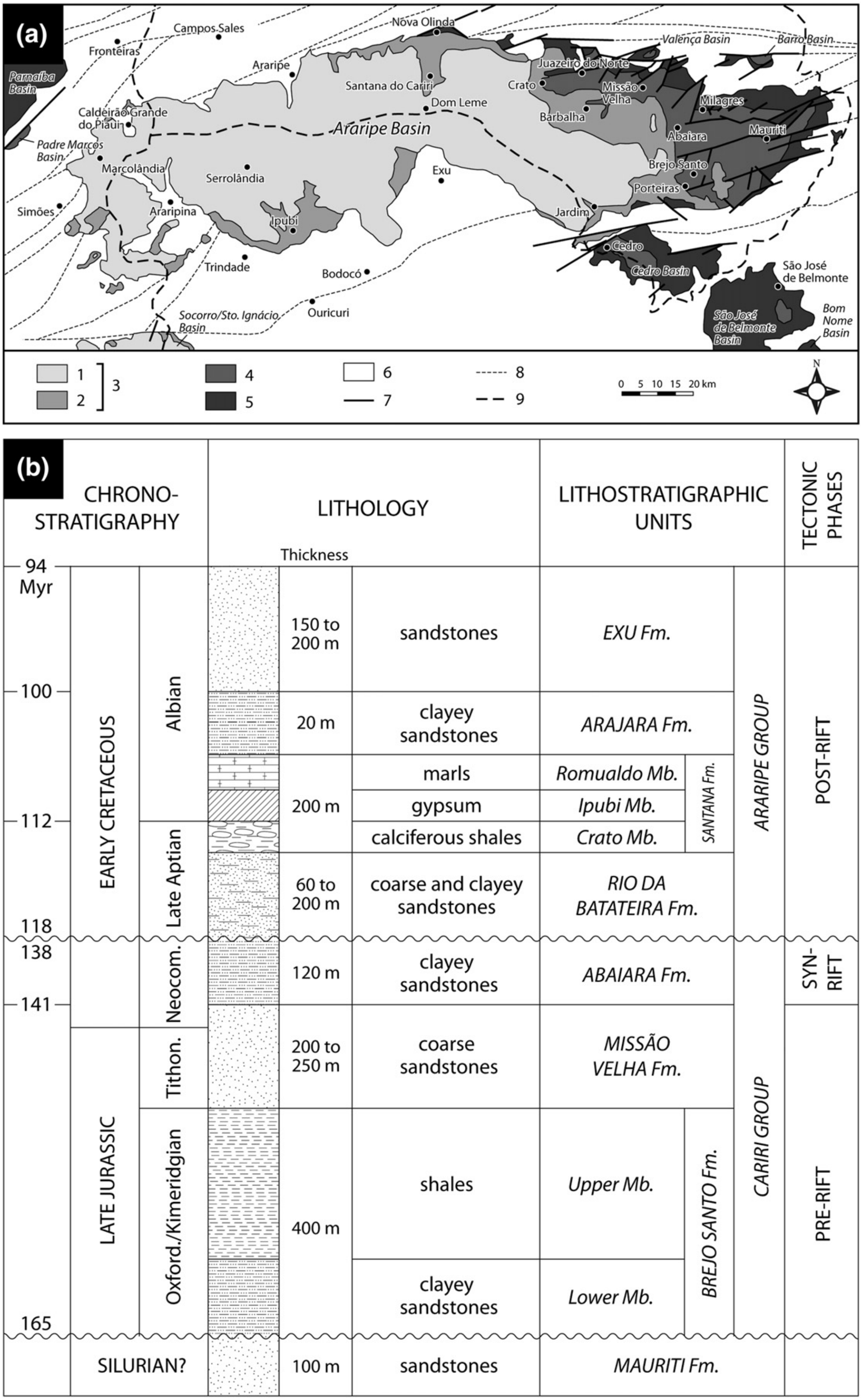

Fig. 5. Geological map and stratigraphic log of the Araripe–Cariri region. (a) Map modified from Ponte and Ponte-Filho (1996) and Assine (1994). 1: Exu Formation; 2: Arajara, Santana, Rio da Batateira Formations; 3: Araripe Group; 4: Cariri Group; 5: Mauriti Formation; 6: basement complex; 7: fault; 8: lineament; 9: state border. (b) Log compiled from Ponte and Ponte-Filho (1996) and Neumann (oral comm., 2008).

basin. The overlying clay-rich sandstone is the last deposit relevant to lacustrine to marine phases of sedimentation. It reaches 20 to 80 m in thickness and forms the Arajara Formation (Ponte and Appi, 1990) or the terminal sequence of the Santana Formation (Assine, 2007). Outliers of lacustrine limestone, similar to those of the Crato Member, exist in the Tucano basin, indicating a continuation of the lake systems to the south of the Pernambuco lineament. Other outliers containing the whole sequence are located in the Socorro basin (Serra Vermelha, Pernambuco–Piauí border) and the Serra Negra (Jatobá basin), at similar altitudes.

At a time when other basins of the eastern margin of northeast Brazil were still experiencing transgressive marine conditions until the late Cretaceous, the end of the sedimentary sequence in the Araripe basin was continental. The alluvial sediments of the so-called Exu Formation (150–250 m in thickness) unconformably cover the older layers and, to the south, west and north-west, the basement (Fig. 5). According to Assine (2007), they consist of two distinct lithological units separated by an erosional unconformity. The upper unit is the Exu Formation, whereas the lower unit, of middle Albian age, is the Araripina Formation. The latter is restricted to the western part of the basin and consists of rhythmites where fine-grained, reddish laminated sandstone contains plurimetric lenses of coarser sandstone with load structures and cross-bedding indicative of a floodplain environment. Where present, this basal layer ensures a strong contrast in mechanical resistance to erosion between the sedimentary cover and the crystalline rocks of the basement.

An erosional unconformity separates the Araripina series from the Exu sandstone, with a slight angle suggesting syn-sedimentary deformation. Conglomerates to fine-grained sandstones displaying graded bedding occur in the western (distal) part of the basin, where argillaceous layers also indicate a floodplain environment. In the eastern (proximal) part of the basin, the sandstones are coarser and more immature, with abundant conglomerate beds and cross-bedding. These indicate sedimentation in braided channels. The age is considered as Albian to Cenomanian, and palaeoflow directions suggest transport to the west (Assine, 2007).

2.2. Methods

Our study is based on fieldwork preceded and followed by the acquisition, processing and study of satellite images, Google Earth 3D visualizations, digital elevation models (mainly SRTM DEM) and aerial photographs. The large-scale landforms were analysed from topographic and geological maps. In the field, the landforms were documented at all scales by ground and aerial photographs and sketches. The present work is also based on morphostructural mapping of the medium- and large-scale landforms, in which field observations were combined with topographic data and geological maps at different scales (1:50,000, 1:100,000, 1:500,000), integrated into a geographical information system (ArcGIS 9) and supplemented by sets of geological profiles.

Establishing the conditions of basin inversion involves the detection of distinct generations of landforms at various topographic levels, and linking them to the geological structure while making inferences about present and past processes of denudation. The nature, origin and relative ages of stepped surfaces, scarps and depressions were inferred on the basis of morphostructural and morphostratigraphic analysis (Peulvast and Vanney, 2001; Peulvast et al., 2009). This approach is an effective tool for reconstructing the history of basin inversion and its links with the regional systems of palaeolandforms and with the conditions of regional uplift and erosion (Peulvast et al., 2008).

The search for chronological indicators was completed by a morphopedological approach (Bétard and Bourgeon, 2009), which focuses on the interactions between geomorphic evolution and soil development. Observational data on soils and weathered materials were collected in the field and from existing soil maps and previous inventories (Guichard, 1970; Projeto Radambrasil, 1981). Special attention was paid to the distribution of laterite (i.e. duricrusts), which is commonly considered as a reliable morphostratigraphic marker in the reconstruction of denudation histories and can be correlated with regional palaeoclimates (Tardy and Roquin, 1998). Laterite mapping was completed using a combination of field surveys and the processing of Landsat imagery and digital elevation models (SRTM DEM). Analysing the relationship between stepped surfaces, laterite distribution and soil development yielded a tentative correlation between the maturity of soil or weathering profiles and the different generations of landforms in the multi-storeyed landscape. These morphopedological criteria were used in support of the chronology of topographic inversion and the relative chronology of Chapada scarp retreat.

3. Results: evidence for shallow basin inversion and plateau evolution driven by scarp retreat

3.1. Morphostructural patterns and topographic inversion

3.1.1. The sandstone plateau: a weakly dissected structural surface

The surface of the Chapada do Araripe approximately coincides with the uppermost layers of the Exu sandstone, which are slightly tilted to the west. Its culminating position in the regional landscape reflects the differential erosion which has removed parts of the underlying series and exhumed the basement at the periphery of the plateau (Figs. 6 and 7). Although a rough parallelism is observed between the deeply weathered sandstone layers of the Exu Formation and the topographic surface, whether the plateau is an erosional or a structural surface is debatable. In places, a slight angle between the horizontal topographic surface and the dips locally observed in the scarp and its rock ledges (best observed along erosional re-entrants and box canyons, e.g. Crato, Santana do Cariri–Brejo Grande: Fig. 8a) suggests that slight bevelling may have occurred. However, part of the deformation is syn-sedimentary and is mainly observed in the deeper sandstone layers (Brejo Grande: Fig. 8b and c); the topmost layers are almost parallel to the surface. The Chapada, therefore, rather has the features of a structural surface, i.e. the topographic surface coincides with the bedding plane of resistant rock layers.

On shaded relief maps (Fig. 2), the topographic surface appears less flat than suggested in the field. Beyond the general westward inclination, gentle slopes are observed towards the axis of the shallow valley systems, and also around the heads of much shorter catchments that hang above a few scarp re-entrants and box canyons of the north side (Santa Fé, Santana do Cariri, Araripe). This hanging valley topography (absent in the east, over the Cariri depression, where the scarp directly cuts the highest parts of the plateau) suggests that shallow fluvial erosion has taken place on the sandstone cover, independently of (or earlier than) the inversion processes that have been restricted to the periphery of the plateau.

Except for the Araripina valleys, this drainage system is dry and disconnected from that of the surrounding depressions, although a few thalwegs continue beyond the plateau while conserving the same strike over short distances. No clear structural control can be identified, but the easternmost drainage system (Jardim) follows the SE-trending axis of the narrow eastern part of the Chapada (Fig. 6). The valley system does not appear to be controlled by the general westward dip of the sandstone cap or by the underlying NE–SW to E–W rift structures. Its configuration and gently sloping longitudinal profiles probably reflect the early coincidence between the E–W axis of the basin and a water divide located close to the northern rim of the plateau, at a time when the Chapada already existed as a low and weakly dissected ridge. The current absence of surface discharge in these valleys and the permeability of the sandstone caprock, confirmed by the presence of numerous springs all along the scarp, also imply an elevated watertable at the time of their formation. This suggests a situation

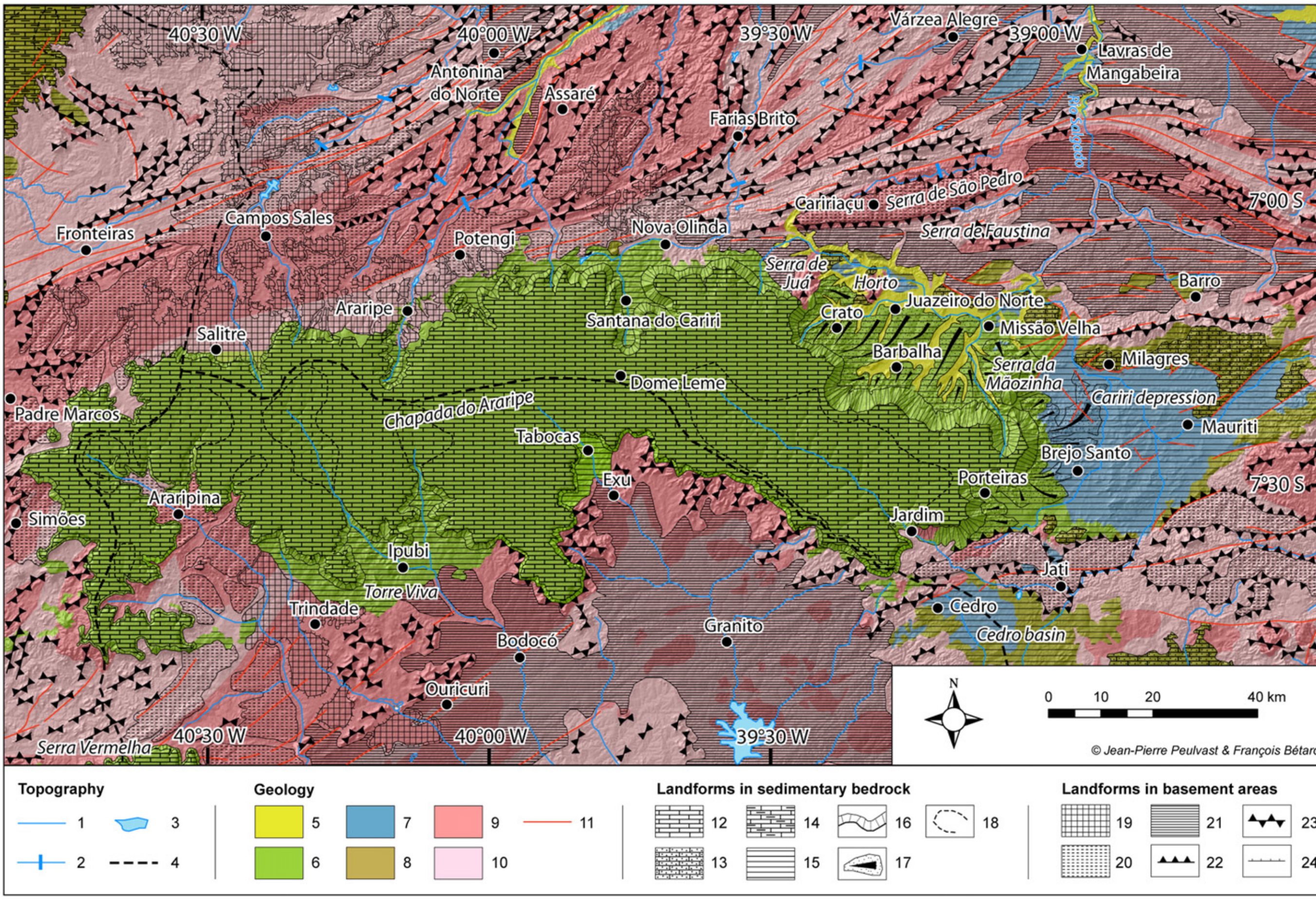

Fig. 6. Morphostructural map of the study area. 1: Main river; 2: knickzone; 3: lake ("açude"); 4: main drainage divide; 5: Quaternary alluvium; 6: post-rift series (Aptian to Cenomanian); 7: pre- and syn-rift series (Jurassic to Barremian); 8: Palaeozoic sedimentary cover, pre-rift sediments; 9: granitoids, migmatites; 10: Precambrian metamorphic rocks, undifferentiated; 11: major fault; 12: structural or near-structural surface, sandstones of the Exu Fm (Cenomanian); 13: structural or near-structural surface, sandstones of the Mauriti Fm (Silurian?); 14: structural or near-structural surface, sandstones of the Serra Grande Fm (Palaeozoic); 15; depression shaped by differential erosion into soft rocks of the rift and post-rift series; 16: escarpment shaped by differential erosion and sapping in tabular structures; 17: main remnants of pediments with colluvial cover, landslides and debris flows; 18: areas of shallow dissection in the structural surfaces; 19: high erosion surface (Step 1), with laterite; 20: elevated erosion surface, degraded or dissected; exhumed etch-surface at the periphery of vestigial duricrust mesas; 21: low erosion surface, often dissected by narrow and shallow valleys ("Sertaneja Surface"); 22: main escarpments; 23: main isolated ridges, crests and hogbacks; 24: edge of lateritic plateaus and mesas.

with low relief and shallow dissection of the surroundings, controlled by shallow regional base levels. As suggested by the lack of hanging valleys in the northeast, the drainage divide only migrated in this area during the later and deeper dissection stages. This was driven by substantial retreat of the NE scarp and by headward retreat of the Salgado river system into the plateau. In other cases, the earlier shallow dissection prepared the deepening stage and promoted the formation of dendritic canyon systems on the plateau (Araripina: Fig. 6).

3.1.2. The Chapada rim: a typology of erosional scarps

Depending on local variations in dip and stratigraphic succession, the morphology of the dissected plateau rims varies from place to place. Features vary from a cuesta-like escarpment (so called because of faint dips) (A type: Fig. 9) to a glint (i.e. a scarp shaped out of hard sedimentary rocks resting unconformably on a basement surface: Peulvast and Vanney, 2001). The glint configuration can be observed on both sides of the central and western parts of the Chapada (B type: Araripe, Exu–Bodocó, Araripina), where the basement forms highs and elevated platforms (Dom Leme horst, Araripina platform; Fig. 9). In all cases, this scarp owes its existence to differential erosion (Fig. 7). It is dissected on both sides by wide box canyons (Araripe, Santana do Cariri, Porteiras, Ipubi NE) or by embayments that form the continuation of canyons in the sandstone (Jardim, Exu–Tabocas, Ipubi NW, Araripina) (Fig. 6). The initial extent of the sandstone cap is not known, but several outliers reflect a substantial areal reduction and a breaking up of the sedimentary plateau around the tributaries of the Jaguaribe, São Francisco and Parnaiba rivers. Lateral erosion, or backwearing, has therefore been a substantial component of the topographic inversion process.

To the north and east, the Cariri depression is excavated into the softer basal sediments of the post-rift cover, between the Chapada and a generally more elevated peripheral area shaped into the basement and the overlying Palaeozoic sandstones (Fig. 7). It also extends into the rift and pre-rift series, below the high sandstone scarp scalloped by large erosional re-entrants (Crato, Barbalha, Porteiras: A1 type) (Figs. 9 and 10a). Its morphology is complicated by the presence of a narrow outlier in the east (Serra da Mãozinha), and by various fault-line scarps carved out of exhumed rifted structures. These basement hills or ridges are locally capped or surrounded by pre- or post-rift sandstones, and protrude from the scarp (Serra da Boa Vista–Serra de Juá; Fig. 3a) or from the depression floor (Serra do Horto). Basement rocks also locally form steep hillslopes and ridges facing the sedimentary scarp (Nova Olinda, Milagres and Jardim–Jati areas). In weaker basement rocks, some of these have been bevelled down to the level of the depression floor. Such is the case of an outcropping strip of micaschist, which forms a low step, ca. 440 m a.s.l., south of the São Pedro and Faustina orthogneiss ridges (Fig. 6). The irregular width of the depression — from zero west of Nova Olinda to more

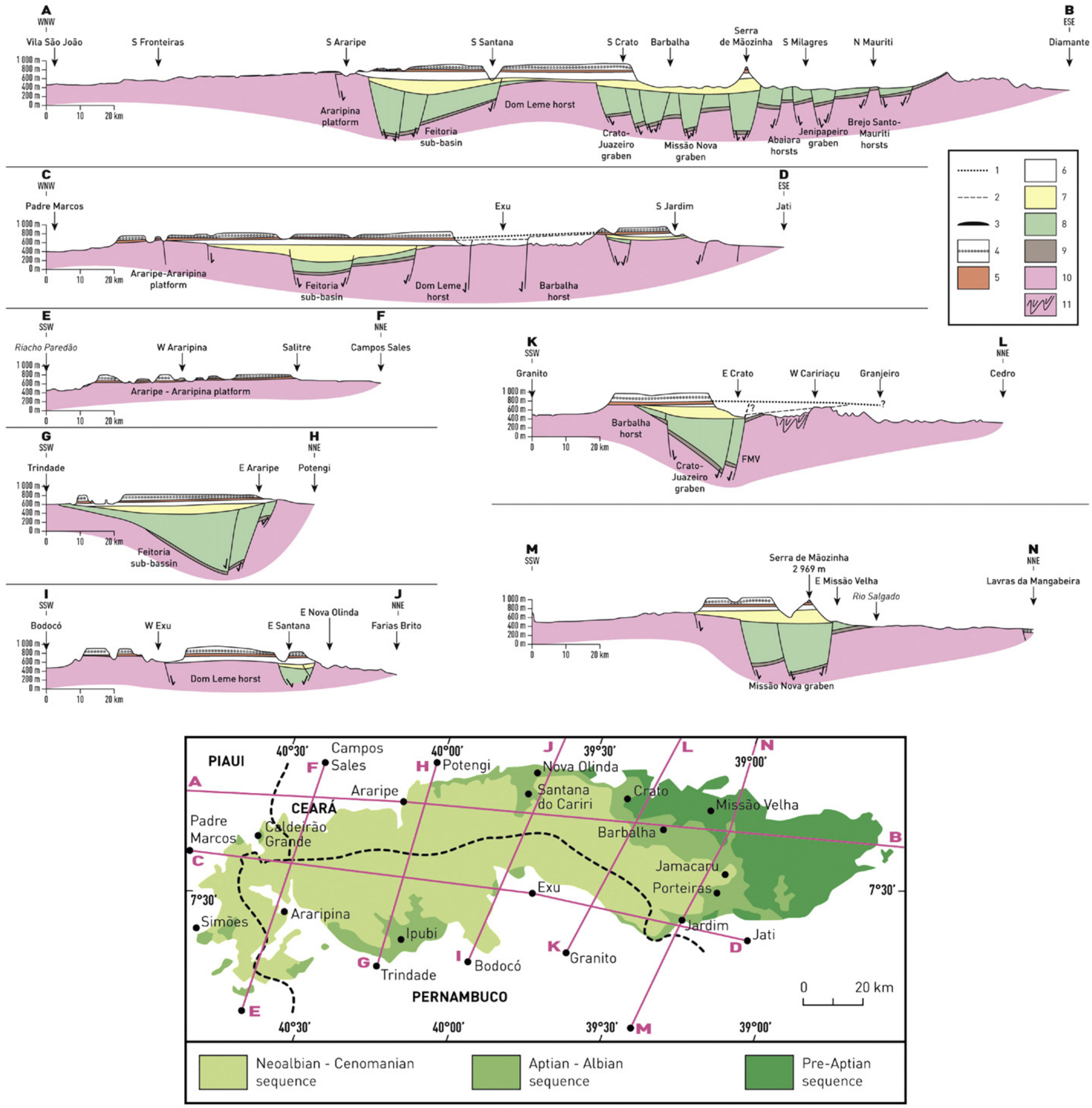

Fig. 7. Geological profiles in the Chapada do Araripe, with location map. 1: Sub-Cenomanian erosion surface; 2: Aptian–sub-Albian unconformity; 3: Lateritic cover (Palaeogene); 4: Exu sandstones (Albian–Cenomanian); 5: Arajara–Araripina Formations (Albian); 6: Santana Formation (Late Aptian–Albian); 7: Rio da Batateira or Barbalha Formation (Late Aptian); 8: Cariri Group (rift series, Late Jurassic–Neocomian); 9: Mauriti Formation (Palaeozoic or Jurassic); 10: basement — undifferentiated; 11: basement — micaschist.

than 50 km to the east — reflects the unconformity of the Exu sandstone on the underlying layers and basement. Maximum thickness and outcrop width of the rift and post-rift sediments occurs in the Milagres–Brejo Santo area.

Simpler morphostructural patterns prevail in all other areas. Glint landforms (B type) are predominant, only locally interspersed with short cuesta-like segments where ample concave slopes capped by high sandstone rock faces overlook small strike depressions. This is observed mainly on the south side (A2 type: Ipubi–Trindade, Tabocas: Fig. 3c). Two morphological types (B1, B2: Fig. 9) can be distinguished. Parts of the scarp, locally low (around Araripe, on the north side), exhibit a simple convexo-concave slope profile above the exhumed basement surface (B1a type: between Potengi and Salitre, NW of Araripina). To the west and around the large southwest outliers, more composite outlines appear (Fig. 10b), owing to strong dissection and scalloping related to the presence of a thin basal layer of soft rocks which facilitates the differential erosion, locally forming transitional forms with cuestas (B1b type). The slope profiles appear more irregular due to multiple sandstone ledges (Fig. 10c). Finally, the glint may take the form of a composite escarpment, especially in the south, where the granite of the Dom Leme horst and the adjacent fault blocks are directly overlain by the Exu sandstones (B2 type). Here, southwest of

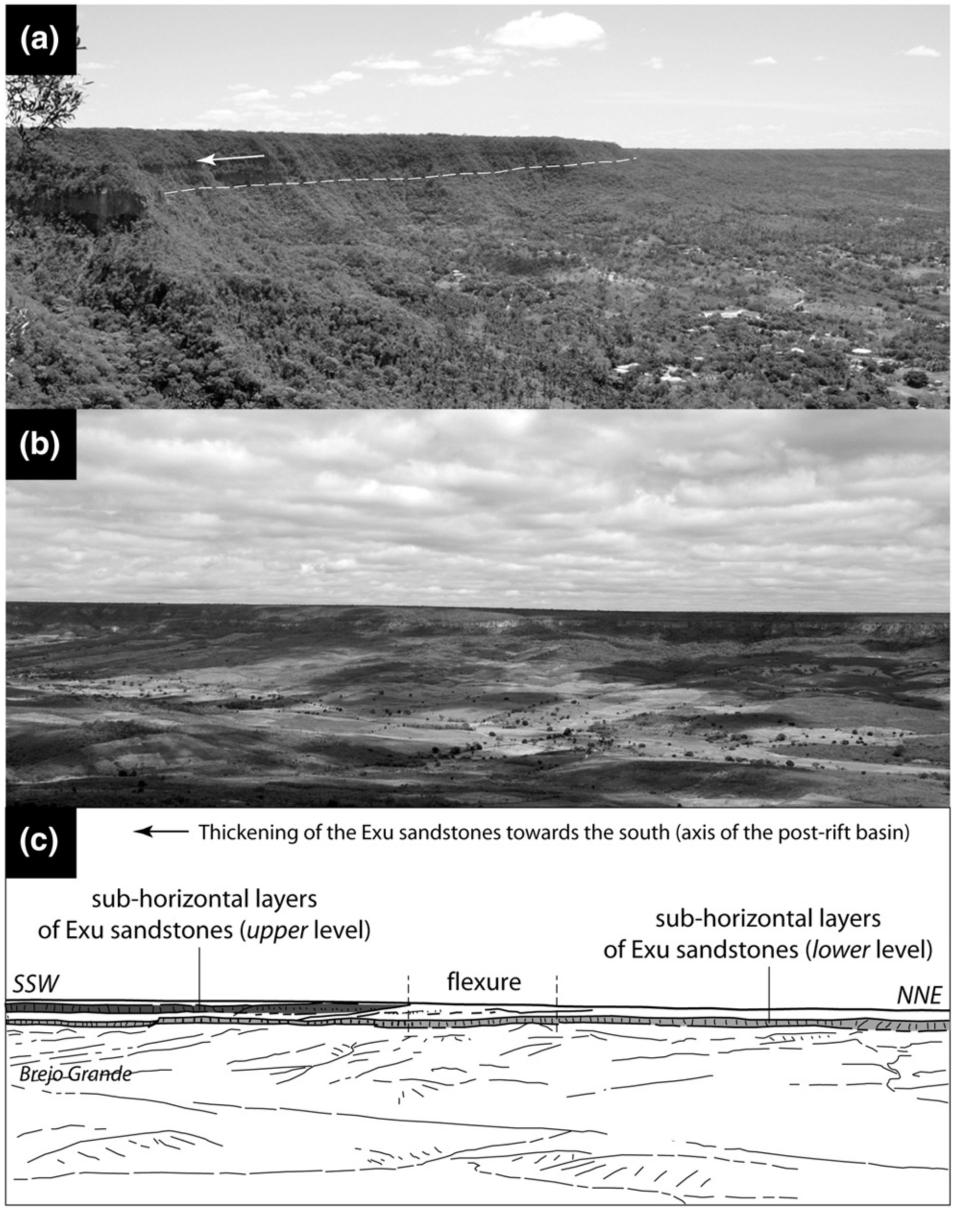

Fig. 8. The Exu sandstone and its structural features at the top of the Chapada do Araripe. (a) Belmonte, Crato. Centripetal dips in the Exu sandstones (dotted line: base of the Exu sandstones; arrow: dip direction); (b) Brejo Grande box canyon, Santana do Cariri; (c) interpretative sketch of (b): slight centripetal dip and progressive unconformity within the Exu sandstones. In both cases, the deformation decreases upward, probably indicating syn-sedimentary deformation. Credits: J.P. Peulvast.

Araripina and around Bodocó, Exu and Granito, the basement is exhumed along the unconformable contact with the sedimentary cover in the form of a narrow granitic erosional bench deeply dissected into rocky hills and tors, ~150–200 m above the basal pediments (Figs. 3b and 10d).

3.2. Stepped surfaces, soil distribution and topographic inversion

Geological profiles provide indications about the nature of the stepped surfaces identified at the periphery of the Araripe basin (Fig. 7). The topographic asymmetry between the north and south sides of the Chapada, i.e. between the Jaguaribe–Salgado and São Francisco drainage basins, reflects that of the piedmonts, which contrasts with the uniformity and the consistently westward-declining altitudes of the high plateau and its outliers. To the south, the basal pediments of the B2 glint connect to a broad erosion surface gently sloping towards the São Francisco River. This low surface bevels the crystalline rocks of the basement, particularly the metamorphic host rock of the Exu–Bodocó granite intrusion (Fig. 3b) and the small sedimentary basins of Cedro and São José do Belmonte. The surface extends 150–200 m below the late Albian unconformity and reflects the post-Cenomanian formation of a large and weakly dissected erosion surface, accompanied by vigorous stripping of the sandstone cap and by the formation of large embayments in the plateau. Narrow NE–SW residual ridges of metamorphic rocks are preserved over the surface, in the Ouricuri region. This surface is the only one identified on this side of the Chapada. Its altitudes (530–400 m) are slightly greater than in the inner parts of the Sertaneja Surface which occurs to the north, i.e. in Ceará, Paraiba and Rio Grande do Norte (Peulvast and Claudino Sales, 2004). No clear connection between the two surfaces has been ascertained because their apparent continuity between the east end of the Chapada and the Borborema plateau is complicated by the presence of a wide depression in sedimentary rocks along the Salgado River. Parts of it, between Ouricuri and Trindade, are covered by a lateritic caprock (Fig. 6).

To the west (Fronteiras–Simões area, Piauí: Fig. 2), in the more depressed Parnaiba drainage area, many residual quartzite and gneiss

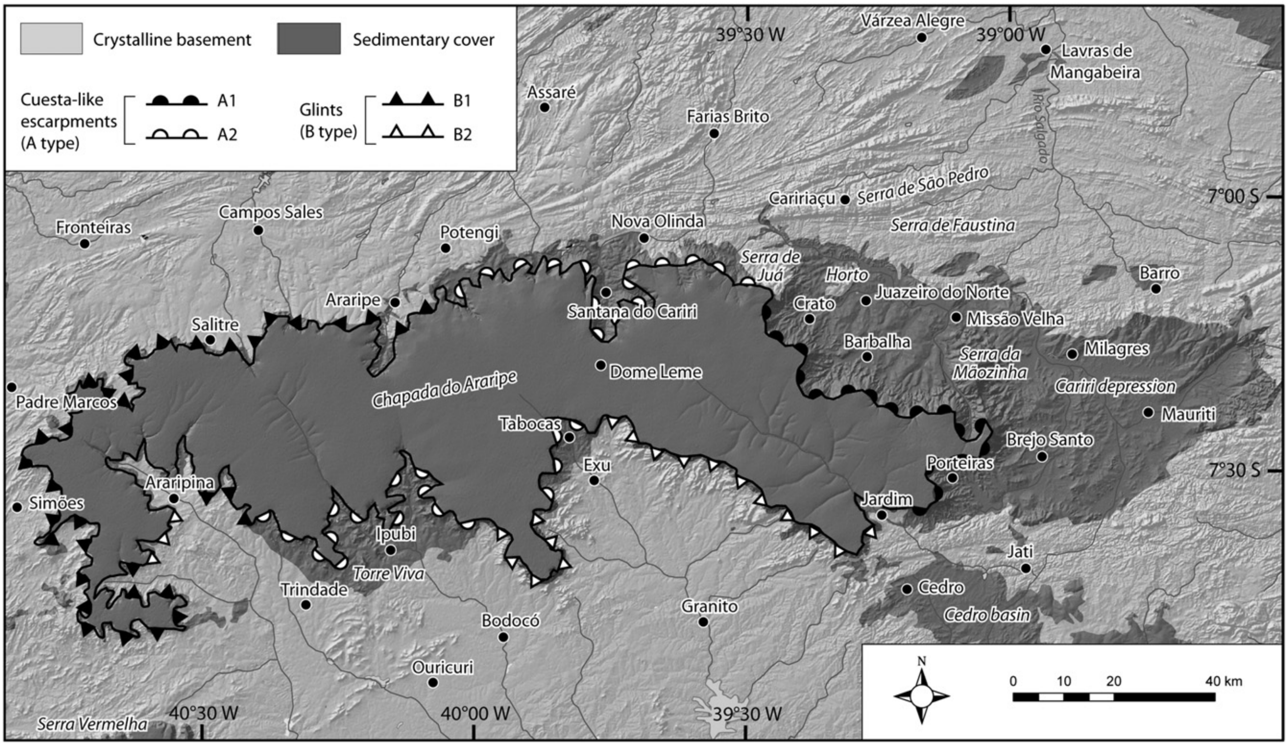

Fig. 9. Typology of erosional scarps around the Chapada do Araripe. A1: Cuesta-like scarp overlooking strike valleys; A2: cuesta-like scarp with deep box valleys but lacking wide strike valley; B1: glint overlooking wide strike valleys or exhumed basement surfaces; B2: glint and composite scarp.

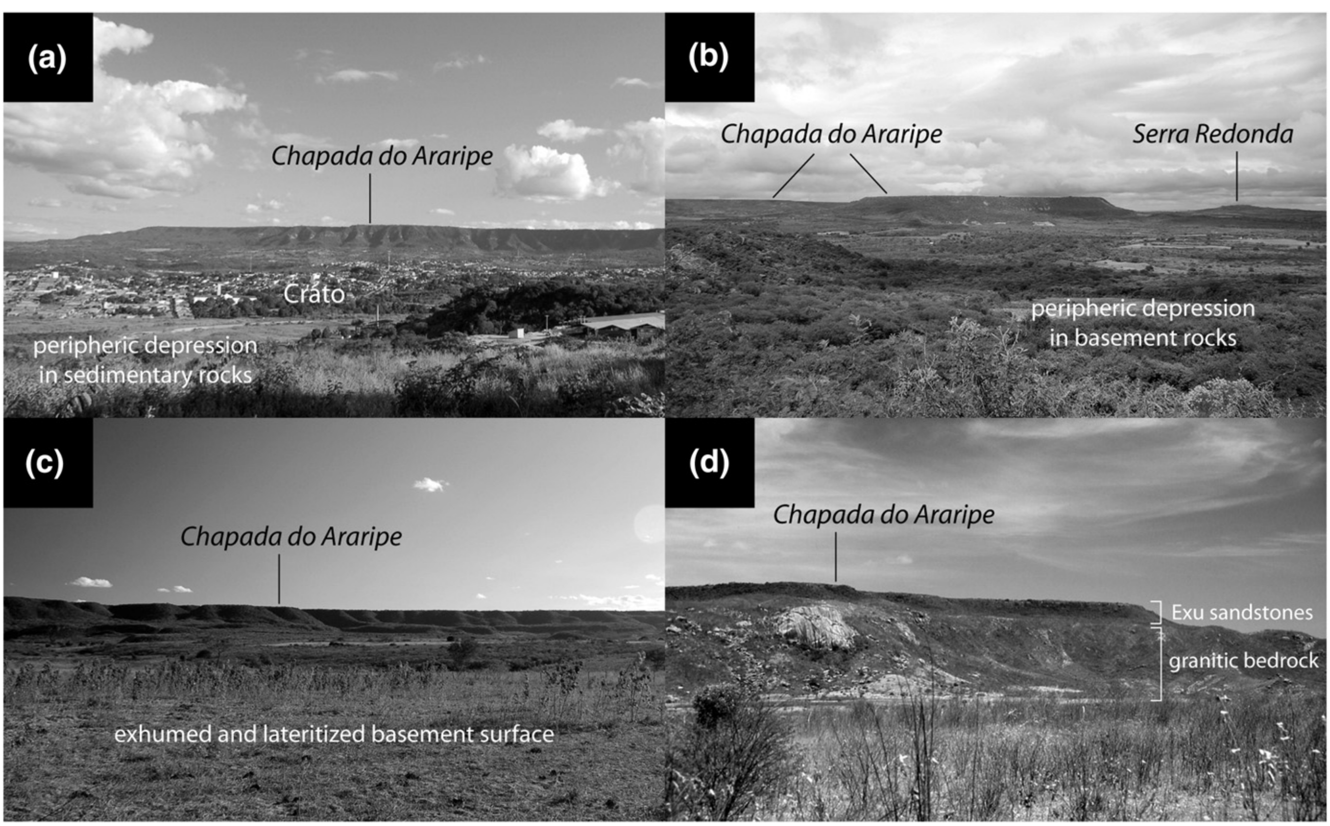

Fig. 10. Morphostructural types along the rim of the Chapada do Araripe. (a) Cuesta-like scarp (A1 type) above Crato, from Monte Alegre. Alternating landslide scars and sapping funnels; (b) sandstone scarp and outlier (Serra Redonda) in a glint segment (B1a type), NW of Araripina; (c) glint over exhumed and lateritized basement surface near salitre (B1b type); complicated pattern of stepped rock faces to the west (right side): effects of mass movements (large slumps); (d) glint and composite scarp west of Exu (sandstone crag over granite bench; B2 type). Credits: J.P. Peulvast.

ridges are preserved over a slightly lower (450–350 m) and more dissected surface, between the B1 Mesozoic scarp and the faintly outlined rim of the Parnaiba basin. The basal post-rift unconformity is only exhumed and preserved close to the scarp (Fig. 7, CD, EF).

Stepped systems of landforms are more clearly identifiable in the north. Four steps appear below the Chapada, mainly cut into the crystalline basement, at decreasing altitudes from west to east.

Step 1 is the highest. It corresponds to the smooth tabular surfaces identifiable on the DEM (Fig. 2) along the foot of the scarp. They form a 10 to 30 km wide strip between Nova Olinda and Salitre, and slope gently northward from 700 to 620 m a.s.l. Slightly lower than the geometric continuation of the sub-Exu or Araripina unconformity (Fig. 7), and capped by a thick lateritic crust, this hanging and dismantled piedmont is an erosion surface whose extent and shallow entrenchment bear evidence of an early stage of erosion of the northern border of the sandstone cap, and therefore of the early stages of topographic inversion of the former fluvial plain (Fig. 11a).

Step 1 is ancient piedmont dissected by tributaries of the upper Jaguaribe River into low mesas. These overlook Step 2, a more rugged surface which extends several tens of metres below. Well exposed around Campos Sales and north of Araripe, this lower surface exhibits sparse tors and shallow grus (Fig. 11b). It has been interpreted as the ancient weathering front exhumed from beneath the laterite cap, therefore as an etch-surface resulting from the degradation by downwearing processes of Step 1 (Bétard et al., 2005). Identified as far as Caririaçu to the east, slightly below 700 m a.s.l., this etch-surface is itself dissected by the same rivers flowing off the Chapada, and, to the east, by those of the Salgado catchment. In this area, it forms residual plateaus and WSW–ENE structural ridges interspersed with narrow parallel corridors excavated into the less resistant basement rocks. The most salient among these ridges, for instance the São Pedro orthogneiss ridge, overlook the lowest surface, i.e. Step 3.

Step 3 takes the form of narrow dissected pediments at the northeast periphery of the Araripe basin, between 400 and 440 m, mainly on the micaschist outcrops around the upper Salgado River and its tributaries north of Juazeiro do Norte (Figs. 6 and 11c). Map-based correlations indicate that it connects northward to inner parts of the Sertaneja Surface. The pediments developed on the opposite side of the Cariri sedimentary depression and around the eastern tip of the Chapada also belong to Step 3 (Fig. 11d). Drainage entrenchment into this lower surface is limited to the softest rocks of the basement and basin, and the remnants of the upper steps are systematically preserved upstream of the knickpoint line that separates the lower courses from beneath the upper shallow valleys of the Jaguaribe and Salgado tributaries (Fig. 6).

Finally, Step 4 corresponds to valley floors and depressions in the soft sediments of the Cariri depression. They have dissected the pediments into convex hills (micaschist) or inclined plateau strips (foot of the Chapada, between Crato and Jardim). Irregular unconformity surfaces are only preserved on the top of basement hills that have been exhumed from beneath the post-rift sediments (Serra de Juá, Horto).

The present soil distribution widely reflects this stepped system of landforms. Only non-indurated ferralsols occur on the top of the sandstone plateau. Because ferralsols generally develop under conditions of humid tropical climate, these ancient soils are out of equilibrium with current bioclimatic conditions. Below the plateau, the most elevated palaeolandforms on basement bedrock are covered by plinthosols marked by an indurated lateritic horizon (Fig. 6). Where the ancient weathering front is exposed, only lixisols and chromic luvisols occur on the exhumed etch-surface, associated with sparse tors and shallow bisiallitic grus. The lower topographic levels are characterized by the same soil taxa associated with lithic soils, in accordance with the semi-arid conditions that prevail in the study area.

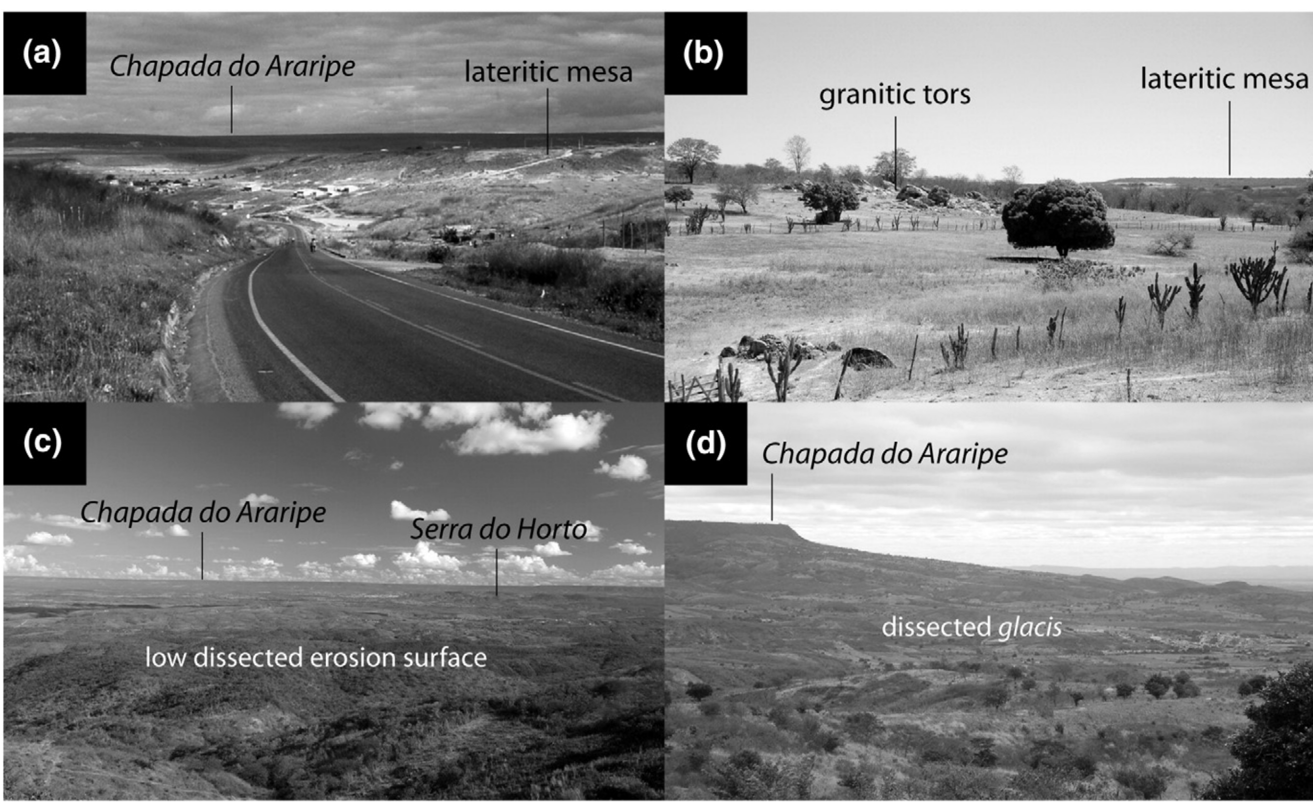

Fig. 11. Stepped erosion surfaces below the Chapada do Araripe. (a) The Chapada do Araripe (background) and its dissected lateritic piedmont at Araripe (Step 1); (b) The lateritic piedmont of the Chapada do Araripe (mesa in the background) and the underlying exhumed etch surface, with grus and tors (Step 2), near Campos Sales; (c) The low dissected erosion surface beveling micachists to the north of the Cariri depression (Step 3). On the right side: Horto hill (exhumed remnant of an eroded granitic rift shoulder). In the background (SE): the Chapada do Araripe; (d) Dissected pediments below the Exu sandstone cornice at Porteiras (Step 3, eastern tip of the Chapada do Araripe). Credits: J.P. Peulvast.

3.3. Modes of scarp retreat

3.3.1. Sapping, linear erosion and scarp retreat

Sapping 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. Permanent or seasonal water saturation of parts of the sediment pile contributes in a complex way to its mechanical erosion (Peulvast et al., 2011). In the northeastern and eastern parts of the Chapada, two aquifers are crosscut by the scarp. They correspond to the Arajara sandstone and the base of the Exu Formation, and to the Crato limestone, respectively (Costa, 1999; Fig. 5). Beneath the dry surface of the Chapada, where infiltration of rainwater is facilitated by the permeability of the rock mass, the first aquifer presents many characteristics of a karstic system, such as short caves and high-discharge springs located along fracture lines. Below these strata, the clays, marls and gypsum of the Romualdo and Ipubi Members form an aquiclude (Santana aquiclude) and behave as a thick plastic level, the surface of which, when exposed, generally appears chaotic and is commonly affected by shallow, small-scale slumps in valleys and road cuts. Combined with the mechanical weakness of the underlying gypsum, these characteristics probably explain the importance of sapping and deep-seated mass movement along the scarp (Figs. 12 and 13). The same situation occurs in the Nova Olinda–Santana do Cariri sector, as well as in the Tabocas and Ipubi areas (Fig. 2). To the west, the Araripina Formation probably plays the same role, reinforced by the imperviousness of the underlying basement.

The sapping effects are mainly visible along the A1 and A2 scarp segments, but also affect parts of the glints, particularly the B1 type, i.e. in segments where the sandstone aquifer surmounts the aquiclude formed by soft layers belonging to the basal Exu layers (Araripina Formation) or to the Santana Formation. Box canyon-head retreat into the plateau is strongly coupled to the vertical denudation that has produced Steps 2, 3 and 4 in the landscape.

Spring sapping has 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 (Fig. 2). Abundant springs located at the base of the scarp contribute to the retreat of the sandstone ledges that surround the wide scallops and minor alcoves in the scarp face. In most places, chaotic topographies developed in the lower slopes (Fig. 12a) also indicate a widespread contribution of mass movements to the scarp evolution process and to widening of the box canyons (Peulvast et al., 2011). Similar landforms (with similar widths and depths: 250–400 m) characterize the shorter box canyons that dissect the NE and eastern parts of the plateau in thicker post-rift series.

In contrast, except for the head of the Tabocas depression and the region of Ipubi (Fig. 3c), the southern canyons and box canyons are generally narrower, with more irregular patterns suggesting a less prominent contribution from spring sapping. However, some of these minor landforms are also produced by sapping. In the Crato and Barbalha re-entrants, several highly scalloped segments display "spur-and-funnel" topography (Peulvast et al., 2011; Fig. 10a). Each funnel contains one or more springs and corresponds to a valley head incised in the lower pediments. Up to 12 funnels, some of which are separated by minor spur ridges, are observed in each scarp segment. Their widths vary between 300 and 1000 m, and their depths between 200 and 250 m. Small creeks contribute to evacuate the material produced by weathering of the debris fallen from the sandstone crags (Fig. 12b). This type of topography is also locally identified in the Buriti box canyon, Santana do Cariri (Fig. 12a). Below these cirques and alcoves, the valley floors widen into the soft post-rift sediments, between pediment remnants. Whereas these pediments present slightly concave and relatively steep slopes in the deepest depressions (Cariri depression, from Crato to Porteiras, Santana box canyon), they are wider and less inclined in the shallower depressions of the south side (Ipubi region), where vertical incision has been less intense. In this case, the

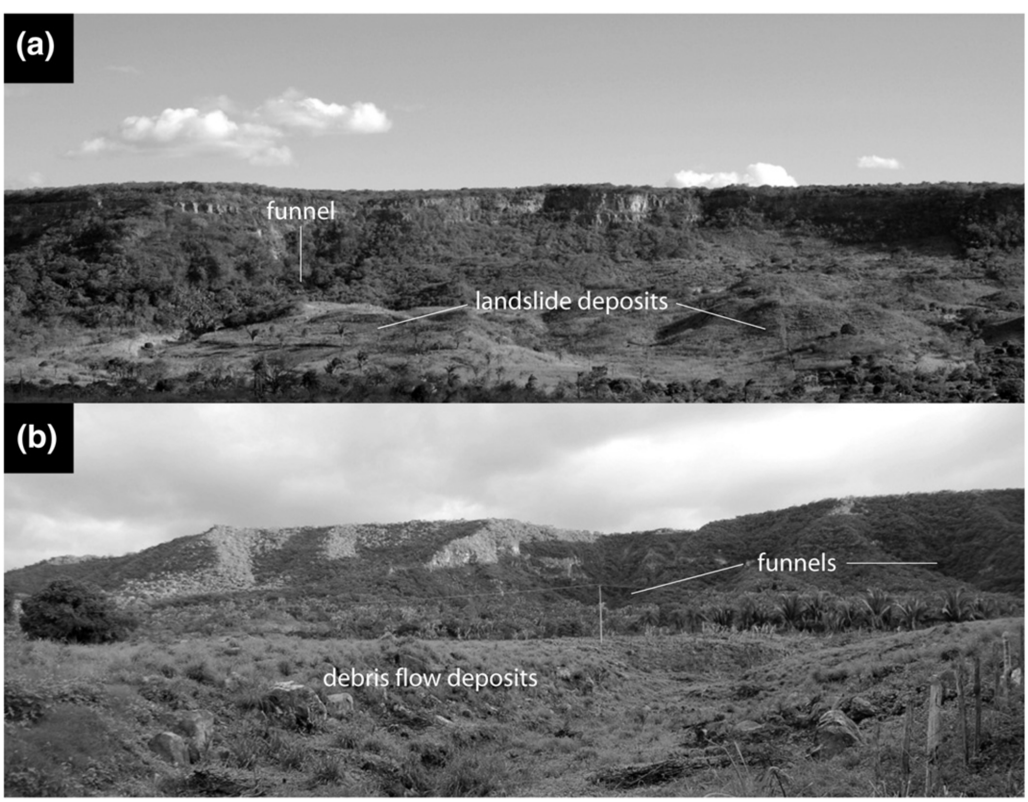

Fig. 12. Sapping-related landforms and scarp retreat. (a) Sapping funnels (background) and landslide deposits in the Buriti box canyon, Santana do Cariri; (b) spur-and-funnel topography at the Chapada rim at Granjeiro (Crato). In the foreground, small creek incising debris-flow deposits. Credits: J.P. Peulvast.

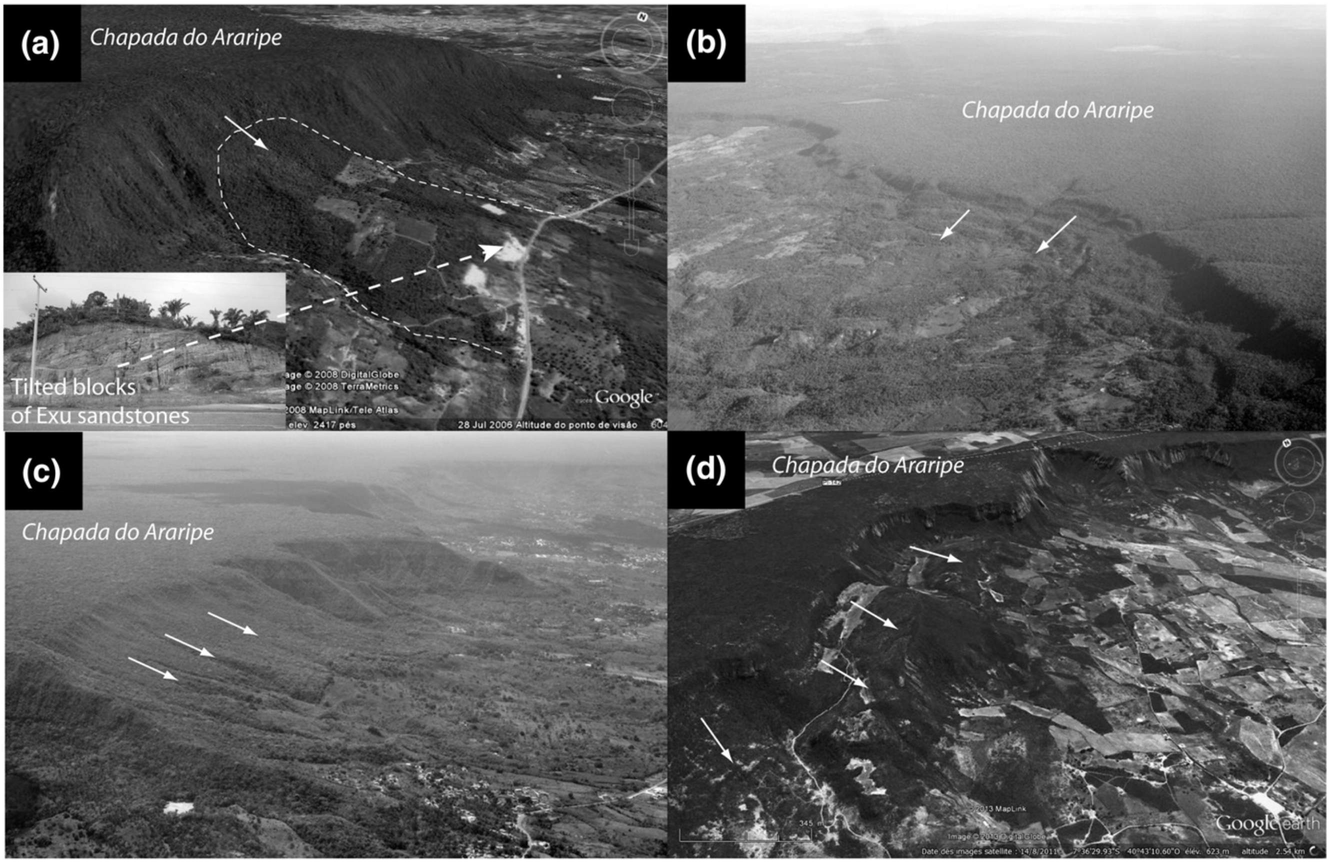

Fig. 13. Landslide scars and their deposits along the rim of the Chapada do Araripe. (a) Large rotated and tilted block on the NE rim of the Chapada at Meio (Barbalha); (b) Sitio Flores, SE of Barbalha: a 1 km-long slide scar splits into various benches reflecting the large (hectometric) retreat of the plateau rim; (c) Carretão (Crato): a 1.5 km-long and 180 m-high scar at the head of a large slump which was continued by a huge debris avalanche; (d) wide tilted sandstone blocks between the plateau and the valley floor on the north side of a short box canyon at the western tip of the Chapada do Araripe, west of Araripina (Google Earth). Credits (photos): J.P. Peulvast.

development of pediments was accompanied by intense dismantling of the sandstone cap, leading to the formation of a deeply scalloped scarp and of butte-and-mesa landscapes, well illustrated by the Torre Viva butte (Fig. 3c).

Stepped systems of pediments and terraces show that various stages of linear and areal erosion by streams and outflow were involved in the shaping of the piedmonts and in the evacuation of debris from the plateau rim. However, fluvial erosion is not the only process observed in the piedmont valleys. Some of these valleys, mainly in their upstream reaches, are partly filled by elongated tongues (2.5 to 6.5 km) of blocky material interpreted as debris-flow deposits supplied by the scarp (Peulvast et al., 2011). These deposits generally consist of a single layer, 3 to 4 m thick, with fabrics suggesting emplacement by single-event debris flows locally preceded or followed by torrential flow. The presence of one or more terraced debris-flow units along the valleys suggest that repeated events tend to alternate with fluvial erosion, contributing to the vertical incision of the piedmonts and to localized forms of scarp retreat.

3.3.2. Landslides and scarp retreat

In box canyons as well as in many other scarp segments, mass movement has contributed substantially to the scarp retreat process (Peulvast et al., 2011). The cuesta-like landforms and broad strike valleys (A1 type) display the most varied suite of erosional landforms.

The morphology of the north and NE rim of the Chapada do Araripe displays spectacular marks of rapid recession (Peulvast et al., 2011; Peulvast and Bétard, 2013). Over a length of 25 km, the Crato and Barbalha re-entrants exhibit the largest and most diversified range of gravitational landforms and deposits. Simple or complex landslide landforms and deposits occur along concave wall segments. In the best characterized landslides, hummocky slipmasses have advanced over the pediments. Slumps form the simplest category. The slipped masses have often been reworked and extended into flat debris lobes or long debris flows. Large rotated and tilted blocks of sandstone occur in some of them (Fig. 13a). Along most other concave segments of the scarp, coalescent systems of wide (1 to 2 km) and short (generally <1 km) backward tilted blocks or debris lobes were observed, suggesting that large and thick pieces of the sandstone cap were destabilized en bloc from the plateau edge along curved failure surfaces, and were dislocated during displacement. To the SE of Barbalha, a 1 km-long slide scar has been split into various benches reflecting the large (hectometric) retreat of the plateau rim that was associated with the largest of these landslides (Fig. 13b). In all cases, movements have occurred along mechanically weak levels of the sedimentary series (clays, clayey sandstones, marls and gypsum). Having possibly been initiated by shearing and horizontal translation along these levels, as suggested by a section in a translational slide observed in the Batateira Formation south of Barbalha, they combine with rotational sliding along listric fault planes that occur in the overlying sandstone layer. South of Crato, the Carretão debris avalanche, or sturzstrom, has produced a large slumped mass below a 1.5 km long and 180 m high scar (Fig. 13c) and a thinner debris apron that was emplaced over uneven topography. It covers an area of about 10 km^2 and involved a minimum volume of 10^8 m^3 of debris. Although still undated, it may have resulted in sudden scarp retreat over a distance of tens to hundreds of metres (Peulvast et al., 2011).

Mass movement is also involved in the evolution of many other scarp segments, at all scales. Around the eastern tip of the Chapada (A2 type scarp), the features are similar in size to those of the Crato–Barbalha area. Landslide scars and tilted blocks transported over the highest parts of the pediments are clearly identifiable (Barbalha W, Serra da Mãozinha, Porteiras…). In the B1-type glint segments, to the west, the slipped masses are widespread. They form systems of simple or multiple topographic benches along the scarp in the form of spurs, sandstone outliers and in box canyons. As shown by the study of road sections in the scarp and along the sides of the Araripina canyon, between Araripina and Padre Marcos, these benches correspond to tilted sandstone blocks that have slid along listric faults parallel to the plateau rim over the underlying argillaceous rocks of the Araripina Formation. They provide evidence of generalized scarp destabilization and have certainly contributed to the intense dissection of the western tip of the Chapada and to its fragmentation into buttes and mesas. Locally, wide pieces of the plateau have slid "en bloc". Here, they form backward tilted rock benches and convey the impression of a double sandstone scarp (Salitre, Fig. 10c).

Some of the most spectacular sets of gravitational landforms occur along the north rim of the Serra Vermelha, which has been deeply scalloped by wide erosional cirques. The semi-circular walls of these cirques are fringed by 4 to 5 superposed benches similar to those identified SE of Barbalha, and in short box canyons of the western tip, west of Araripina. Here, wide tilted blocks clearly appear between the plateau and the valley floor (Fig. 13d). In this area, in contrast with the Cariri depression, this process is generally not related to active incision, except on the Piauí side, because the underlying basement plateau is barely dissected.

To summarize, the dominant process of Chapada evolution is lateral denudation. It is ascribable to a conjunction of contingent features such as local stratigraphy, hydrogeology and shallow dips, all of which are highly favourable to scarp retreat. The gently sloping river profiles ensure sufficient energy for an evacuation of the fine-textured debris (clay, sand) produced by the mass wasting and by post-depositional rock disintegration.

4. Interpretation: basin inversion, scarp retreat and long-term landform evolution

4.1. The contribution of tectonic inversion to topographic inversion

Whereas morphostructural evidence, the nature of stepped surfaces and scarp sinuosity along the major part of the Chapada rims plead against the occurrence of local tectonic inversion, for example along branches of the Patos and Pernambuco EW shear zones, the situation is less clear to the NE, above the Cariri depression. Our study emphasizes the importance of differential erosion in the shaping of this depression, but several faults have been identified here and in the nearby basement. Some of them might have been reactivated in recent times, as suggested by some geomorphological features in nearby regions such as the Pereiro massif (Gurgel et al., 2013). Generally, they do not directly deform the post-rift series and the sandstone cap, but one of them, marked by a narrow vertical N160° shear zone, controls a short corridor that separates the Chapada from the thin sandstone cap of the granitic Serra da Boa Vista, NW of Crato (Fig. 5). In this case, a post-Cenomanian reactivation is probable, since the base of the sandstone cap is clearly higher on the NE wall than on the opposite side. Both compartments were later bevelled to similar altitudes on the edge of the Chapada. Other clues for recent tectonic activity were found along a normal fault that cuts the Muriti waste deposit between Crato and Juazeiro do Norte (Peulvast et al., 2011). The vertical throw to the south observed along this WNW-trending fault is 0.5 m and may represent a reactivation of one of the northern boundary faults of the Araripe basin. Fault movement has affected an undated debris apron and records a seismo-tectonic event which may indicate local neotectonic activity. Both structures seem to belong to the same S-shaped fault line, and indicate slight subsidence of the Chapada compartment relative to the slightly uplifted NE border of the basin, which was exhumed from beneath a thinner cover. This fact might have contributed to better preservation of the sandstone cap in the axis of the basin than on its NE border, and therefore to topographic inversion, but it rules out any likelihood of fault-controlled local uplift of the plateau relatively to its surroundings.

The elevated position of the Chapada rather corresponds to a tectonic inversion of regional proportions, perhaps better termed epeirogenic inversion. In the whole of Ceará, post-Cenomanian uplift caused an inversion of the Cretaceous basins and generated a landscape in which the most elevated landforms correspond either to resistant Mesozoic sedimentary caprock or to eroded stumps of syn-rift Cretaceous footwall uplands (Peulvast et al., 2008). A recent study of the granitic Serra do Pereiro, 150 km to the NE of the Chapada do Araripe (Fig. 1), points out the possibility of differential tectonic uplift along reactivated Brasiliano shear zones (Gurgel et al., 2013). However, slip rates measured along the most active faults of northeast Brazil, which are located in coastal areas (0.0075 to 0.01 $mm \cdot yr^{-1}$ since the Miocene), amount to 180 m of vertical displacement in Cretaceous units in the Paraíba basin (Bezerra et al., 2001; Nogueira et al., 2010). Such values suggest rather minor and localized neotectonic contributions to the formation of ridges and mountains in the landscape at some distance from the most active seismic zones. Even the presence of lateritic remnants on the Pereiro plateau, possibly as old as 20 Myr (Lima, 2008), does not clearly support evidence of strong local uplift, given that laterite can form in various topographic and altitudinal contexts (Rossetti, 2004). Moreover, a neotectonic origin would not be compatible with the presence of an exhumed and undeformed palaeopiedmont of Cretaceous age at the northern tip of the Serra do Pereiro (Peulvast and Claudino Sales, 2004). Morphostructural patterns have been carefully analysed throughout the region and always reflect strong lithological controls on such ridges. This feature, therefore, rather suggests long-term preservation of scarps (inherited fault scarps, some of them possibly buried and later exhumed), as well as height enhancement of fault-line scarps and other lithologically controlled scarps (Peulvast et al., 2006; Peulvast and Bétard, 2013) during a long-term process of downwearing and differential erosion in response to regional uplift.

This post-Cenomanian crustal deformation mimics the geometry of a broad monocline between the Ceará coast, to the north, and the Chapada do Araripe, with a half wavelength of ~300 km (Fig. 14). As shown by the current elevation of marine Albian layers occurring 700 m above present sea-level (Baudin and Berthou, 1996; Neumann, 1999), the Araripe basin was the most vigorously uplifted portion of the landscape. Assuming that sea level rose from +50 to +60 m in Albian times (Miller et al., 2005), this suggests minimal post-Albian crustal uplift of 600–650 m, which is comparable to values proposed by Magnavita et al. (1994) in the Recôncavo–Tucano–Jatobá area. In the absence of evidence of significant erosion of the Exu sandstone caprock (Baudin and Berthou, 1996; Arai, 2000), the ~650 m of post-Albian crustal uplift in the area now forming a major drainage divide ca. 300 km from the coast also estimates minimum long-term surface uplift of this part of the Brazilian shield. The flexural style of this uplift explains the elevated position of the former Cenomanian fluvial plain relatively to the northern plateaus, where the former basin edge was slightly tilted northward and then destroyed by subsequent stages of denudation and differential erosion (Fig. 7, KL).

Partly related, at least in its latest stages, to Cenozoic uplift of the Borborema plateau, perhaps as a result of regional magmatic underplating, this inferred epeirogeny is possibly still ongoing. According to Oliveira and Medeiros (2012), indications of post-depositional deformation of Barreiras Formation strata along the coast, of late Quaternary fault reactivations, and clues from apatite fission-track (AFT) analysis suggesting the existence of a cooling stage between 20 and 0 Myr (Morais Neto et al., 2009) may all suggest continuing epeirogeny.

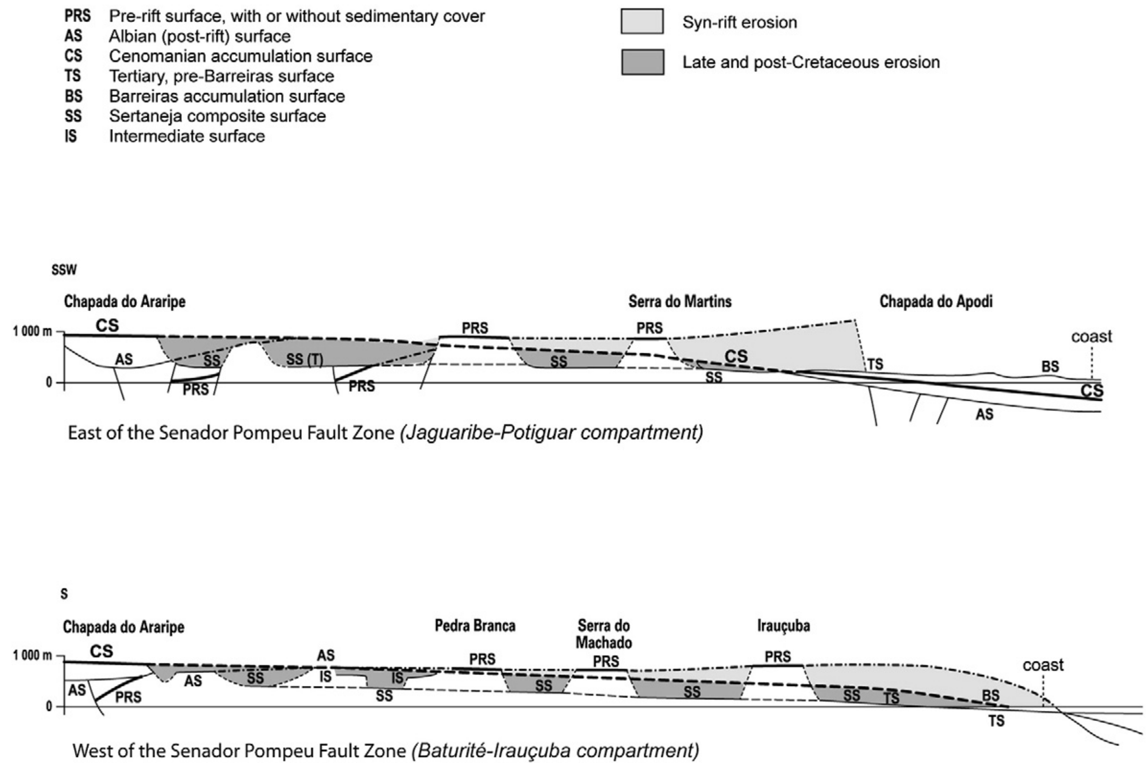

Fig. 14. Synthetic cross-sections of the equatorial margin of northeastern Brazil. Note the landform systems and uplift style from the Chapada do Araripe to the coast on both sides of the Senador Pompeu fault zone.
After Peulvast et al. (2008).

4.2. Stepped landforms and soils: chronological indications of basin inversion and denudation history

Chronological evidence of basin inversion and denudation history can be obtained from morphostratigraphic and morphopedological evidence, mainly north of the Chapada, where stepped landforms and other landmarks (laterites, soils and surface deposits) allow a reconstruction of palaeolandscapes, erosional history, and correlations with the regional system of stepped landforms (Fig. 14).

The post-rift sedimentary sequence records the persistence, in Albian times, of landscapes of low hills, and shallow lakes or lagoons, temporarily connected to the sea from the Parnaiba, Potiguar and/or Tucano–Jatoba basins, under warm and dry climatic conditions (Petri, 1987; Assine, 1994; Baudin and Berthou, 1996; Neumann, 1999; Arai, 2000). The unconformable deposition of the Exu Formation on the older post-rift series and the basement suggests a progradation to the west of a vast inland delta, i.e. a system of meandering or braided channels between low hills or ridges, under a regime of flash and/or seasonal floods typical of an arid climate (Martill, 1993; Assine, 1994). Although a few outliers indicate the former extent of the Exu Formation beyond the present boundaries of the Chapada, particularly in the southwest (Serra Vermelha), no remnant of this cover is found outside a zone contained between the E–W Patos and Pernambuco lineaments, which may have controlled the configuration of the last post-rift subsidence area (Figs. 4 and 5). According to Assine (2007), syn-depositional deformation has occurred. In the central parts of the basin, slight subsidence is suggested by progressive angular unconformities between the thick sandstone layers visible in valleyside exposures of the Crato erosional re-entrant (Luanda–Coruja; Fig. 8a) and of the Santana do Cariri box canyon (Fig. 8b and c). This powerful rhexistatic phase seems to have occurred at the close of the post-rift sedimentation, and was probably associated with active uplift and erosion of the Borborema plateau before the broader regional uplift — which began in the late Cretaceous (Baudin and Berthou, 1996; Arai, 2000; Valença et al., 2003; Peulvast et al., 2008).

The exhumation of surrounding basement surfaces probably began early, as shown to the NW of the Chapada by the widespread occurrence of laterite of probable pre-Neogene age (Fig. 6). According to available palaeogeographical reconstructions (Tardy and Roquin, 1998), conditions favourable to laterite formation seem to have occurred in northeast Brazil only during the Eocene, whereas later and drier periods during the Neogene (Thiry et al., 1999) would have only allowed sporadic formation of ferruginous gravels and plinthites in lixisols at low altitude. This interpretation of the age of laterites is consistent with absolute ages obtained by U–Th/He dating of detrital grains of goethite found in allochtonous laterites in the coastal areas of northeast Brazil (Lima, 2008), indicating ages ranging from 43.2 $\pm$ 4.3 to 21.6 $\pm$ 2.2 (i.e., middle Palaeogene). Consequently, the lateritization event responsible for the presence of extensive laterites on basement rocks NW of the Chapada implies a rapid exhumation of the basement palaeolandforms just below the sandstone plateau, probably during the late Cretaceous or the early Cenozoic.

A second stage of topographic inversion occurred in the Oligocene and later. This would have coincided with the major stages of river incision and plateau degradation, resulting in the partial exhumation of exposed weathering fronts (or "etch surfaces") on the northern side of the Chapada (Fig. 15). As evidenced by the wide extent of pediments in the Crato area, a partial planation episode interrupted the inversion process after a post-Palaeogene phase of denudation of 200 to 300 m. This previous phase of deep erosion and related scarp retreat of the Chapada above the peripheral depression could be synchronous with the onset of drier climates recorded in northeast Brazil since the middle Miocene (Gunnell, 1998; Harris and Mix, 2002). Later dissection of the low surface, probably synchronous with that of the Sertaneja Surface (Peulvast and Claudino Sales, 2004) and accompanied by scarp retreat and vertical growth, seems to coincide with a late- and a

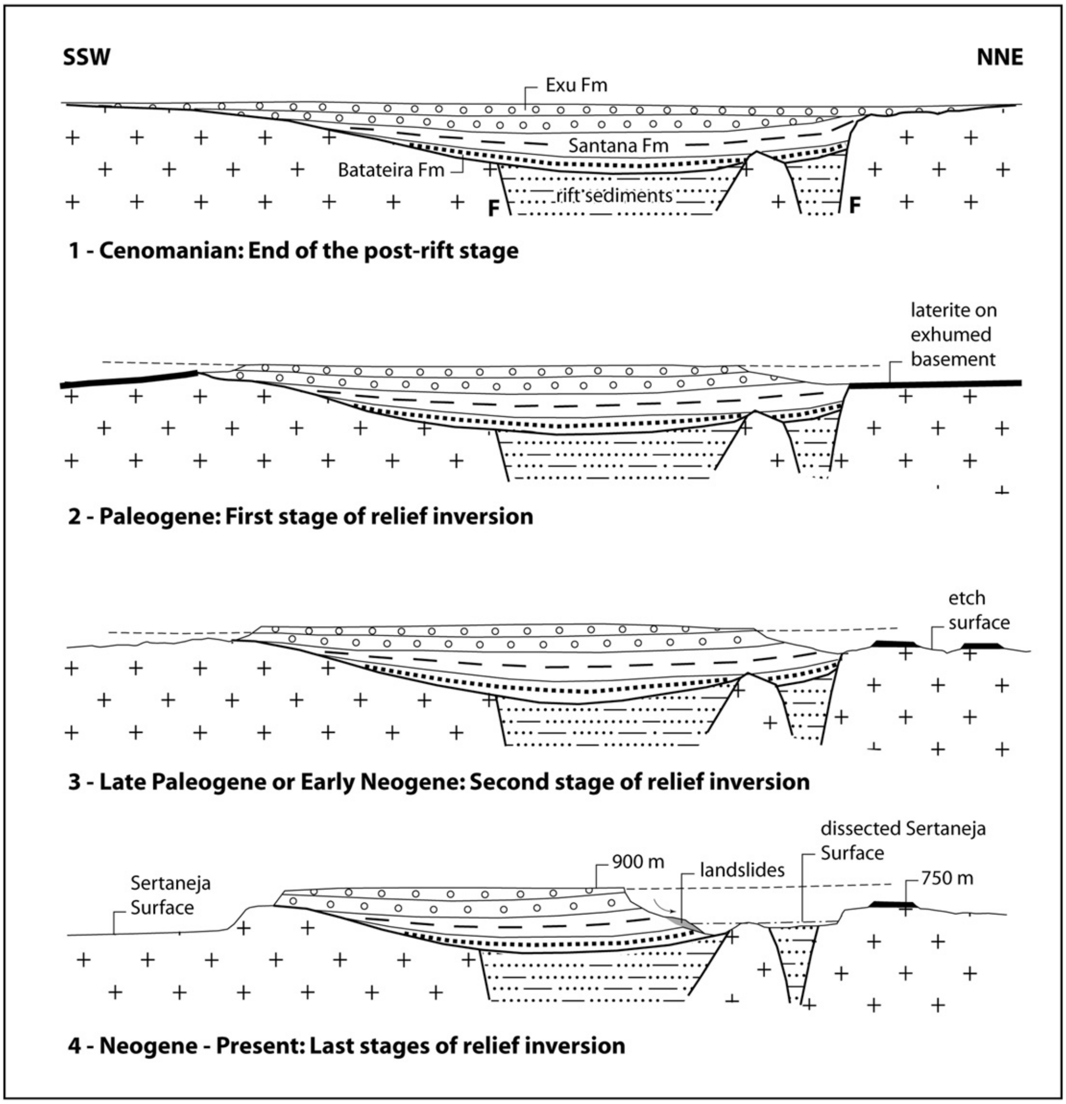

Fig. 15. Reconstruction of the Araripe basin inversion.

post-Miocene stage of fluvial incision that occurred throughout the province of Ceará (Peulvast et al., 2008).

4.3. Landslides and related deposits: repeated mass-wasting events throughout the Cenozoic?

Large-scale gravitational dynamics and mass wasting were involved at least in the last stages of scarp retreat above the Cariri depression. These processes probably also drove the earlier stages of scarp retreat, as suggested by the sedimentological nature of widespread pediment covers and their distribution in distal parts of the dissected soft-rock pediment strips. The mass wasting process likewise correlates with the development of erosional re-entrants and of scarp heightening above increasingly deep valleys and depression. Matrix outwash and post-depositional weathering of coarser clasts prepares the final evacuation by hillslope wash and fluvial transport of sand and finer elements to the Salgado and Jaguaribe river system. Currently preserved sediment deposits only record a small proportion of the scarp retreat process, still to be quantified. It is likely that similar mass wasting participated to this retreat throughout the Cenozoic inversion process.

On the other sides of the Chapada, valley deepening and scarp retreat were controlled by less depressed and more stable local base levels such as the line of knickpoints on the north side, and the remote São Francisco valley on the south. No scarp-height enhancement appears to be occurring under current environmental conditions (with a possible exception at the western tip of the Chapada, at the head of tributaries of the Parnaiba River), but scarp retreat continues in the B1 segments, as shown by a multiplicity of fresh-looking landslide scars and deposits. Here again, final evacuation of slipmass debris affects the finer-grained sediments (sand, clay) produced by in situ weathering and disintegration of the sandstone debris.

5. Discussion: implications of the topographic inversion

5.1. Amplitude of denudation and topographic inversion in the study area and in northeast Brazil

It remains difficult to establish from the morphology of the plateau whether its surface coincides with the last layers deposited in the basin, or results instead from the erosion of an initially thicker sediment pile. The initial thickness of the fluvial sandstones is unknown. The lack of any remnant of post-Exu sediments in the region, including in the post-rift series of the Jatobá–Tucano basin in the south (Magnavita et al., 1994), does not plead in favour of a younger cover, in spite of recent and debatable interpretations of thermochronological results according to which a sediment thickness in excess of 1000 m would have existed over the present pile (Morais Neto et al., 2005–2006; Japsen et al., 2012) before being totally removed.

Maximum post-rift denudation depths in the Araripe basin are provided by the maximum value of topographic inversion observed along the eastern Chapada do Araripe, i.e. ~600 m near the city of Crato. This value is based on the assumption that the topographic surface of the plateau is not very different from the depositional surface of the Cenomanian fluvial sequence. Studies of the organic matter contained in the Albian sediments suggest that no significant overburden was removed by erosion from the exposed upper surface of the Exu caprock (Baudin and Berthou, 1996; Arai, 2000). This point has been discussed in some interpretations of thermochronological studies based on AFT analysis, which suggest the past existence of a much thicker cover. Advocacy in favour of post-Cenomanian deposition would be in weak concordance with the interpretation given by Harman et al. (1998), and later confirmed by Morais Neto et al. (2005–2006), of a first cooling episode beginning between 100 and 90 Ma (late Albian–Turonian, i.e. towards the end of the fluvial sedimentation), and a second during the Oligocene. The first cooling episode would correspond to an exhumation stage which is not compatible with ongoing sedimentation at that time.

According to Morais Neto et al. (2005–2006), the VR value (vitrinite reflectance in organic matter) is reported as indicating maximum heating to 93 °C after the deposition of the Batateira layers (maximal burial of 2.2 km, but before 100 Ma, i.e. before the deposition of the Exu sandstone, which therefore does not seem to have been followed by further burying). The pre-Exu evolution must be taken into consideration in order to understand the signification of these thermochronological data obtained on samples taken at various altitudes, in various layers. The Exu sandstone rests unconformably over the older formations, including the basement, to the south and close to Crato (Ponte and Ponte-Filho, 1996). Some denudation in response to uplift occurred locally before its deposition on the margins of the basin. Since the morphology (including exhumed and still buried palaeolandforms) and structure of this basin are quite complex, with differential movements that persisted until the end of the post-rift period (Baudin and Berthou, 1996), interpretations of the thermal histories of each sample are non-unique and probably insufficient in themselves for reconstructing a regional history of sedimentation, uplift and erosion.

The apatite cooling histories presented by Morais Neto et al. (2005–2006) all report palaeotemperatures of 40–60 °C before the later Cenozoic cooling event. This is interpreted as reflecting a denudation of 1.5 km of sediments, but as discussed by Gunnell (2003) and Peulvast et al. (2008), such results remain in the uncertainty domain of the method, and may also reflect a change in the geothermal gradient during the Oligocene, which was a time of volcanic activity and magmatic underplating in surrounding regions (Oliveira and Medeiros, 2012). This is why we tend to favour the interpretations given by Baudin and Berthou (1996) and Arai (2000), according to whom the sandstone and conglomerate of the Exu Formation terminated the sedimentary history of the Araripe basin.

The second caveat, which is also critical in the “episodic burial and exhumation model” developed by Japsen et al. (2012) for the post-rift evolution of the Brazilian Northeast, relates to the origin of the additional overburden inferred from AFT analysis. The upper Exu layers are horizontal on N–S profiles, reflecting the end of post-rift subsidence. An overburden of 1000 m or so would not have been deposited without further deformation of the underlying layers, unless spread over an area extending well beyond the present limits of the basin. The corresponding volume would have been huge, and its source remains highly uncertain. How would ~1000 m of additional sediment have been provided in a landscape shown by several authors (see Martill, 1993) to have remained surrounded by low hills? Only the erosion of the Borborema highlands, to the east (the source area: Assine, 1994), might have fed such a sediment mass in much larger quantities than the Exu sandstones. The other question is how would such sediments, of unknown nature (clastic or marine?), have spread over the backslope of an uplifting Great Escarpment (that is, if we consider the Borborema as part of such a structure) rather than on its oceanic side (where no such sedimentary record has been detected offshore). What could have been the topographic limits of the basin? And finally, to where would the waste generated by post-depositional stripping of the sediment mass have been conveyed during the later Cenozoic?

In our reconstruction of the regional geomorphic evolution based on the study of existing sedimentary vestiges and outliers, we indicate a discontinuous post-rift cover in large parts of Ceará and its surrounding regions, with temporary marine connections between the Parnaiba, Potiguar, Araripe and Recôncavo–Tucano–Jatobá basins in the Albian (Peulvast et al., 2008). Onshore, reconstructed geological sections indicate maximum thicknesses of up to 600–700 m close to the coast (Potiguar basin) and in the Araripe basin. These values are compatible with the volumes of material that the erosion of the emerged residuals (rift-shoulder stumps…) and the uplifting regions (Borborema) could provide. We also established the compatibility between the partial erosion of this post-rift cover initiated in post-Cenomanian times and the volumes of sediments accumulated in the offshore basins. No morphological or sedimentological evidence of deep post-Cenomanian burial was detected, except for the Turonian limestones of the Potiguar basin, which were deposited in shallow marine conditions, and for accumulations of Cenozoic clastic sediments (Barreiras Group) along the coast. Even the Palaeocene or older fluvial sandstones of the Serra do Martins Formation, preserved on isolated mesas at the northern and eastern periphery of the Borborema plateau (Morais Neto et al., 2009), only reach a few tens of metres in thickness. Moreover, there is no clear evidence of accelerated offshore sedimentation that might reflect the later erosion of thick post-rift sediments (see compilation of stratigraphic logs in Peulvast et al., 2008).

As shown above, the exhumation and partial destruction of palaeosurfaces probably began early around the Chapada, during the Palaeogene. These early stages of topographic inversion might correspond to the first post-rift denudation episode reported by AFT. The second stage, in the Oligocene and later, would correspond to the major phase of river incision and basin inversion. Responding to regional uplift, the differential erosion is also controlled by retreat of the river knickpoints proceeding from the developing low-lying Sertaneja Surface. It reached the lowermost post-rift layers, cutting into the syn-rift formations and even into the underlying basement outcrops of the former rift shoulders (Horto, Serra de Juá, Dom Leme). The corresponding mean denudation rate (7 to 10 $m \cdot My^{-1}$) is similar to that of inferred vertical movements. At regional scale, this low rate is explained by a conjunction of factors that also influence the conditions of scarp formation and evolution (Peulvast and Bétard, 2013): (i) the low magnitude of crustal uplift estimated by the current elevation of marine Albian layers (Araripe, Apodi); (ii) the low amplitude and long wavelength of crustal deformation of an initially low-relief topographic surface, which promotes a phenomenon defined as ‘morphological resistance’ (Brunsden, 1993a,b) in which the widespread development of high-angle slope systems favourable to intense erosion is impeded; (iii) the lithological heterogeneity of the basement and its cover, with a prominent role played by resistant rock outcrops; and (iv) the long-term semi-arid climate of NE Brazil, which has probably been in existence for the last 13 Ma at least (Harris and Mix, 2002).

5.2. Topographic inversion, scarp retreat and formation of the lower topographic levels

The morphology of the piedmonts and surroundings of the Chapada do Araripe displays a mosaic of exhumed surfaces and new erosional topographies, all of which were produced during the inversion process. Given that differential erosion in response to regional uplift was the main mechanism of basin inversion, lithological contrasts between the basement and the overlying series and the various unconformities have been the main controlling factors of this differentiated evolution. It appears from the geological profiles (Fig. 7) that very few exhumed surfaces remain intact and that original post-Cenomanian landform shaping was very efficient, particularly in easily weathered metamorphic rocks such as micaschist. In contrast, the sandstone cap tended to protect the underlying rock surfaces from erosion until processes described in Sections 3 and 4 succeeded in weakening or removing it.

As shown in a recent review of scarp and hillslope geomorphology within the northern regions of northeast Brazil (Peulvast and Bétard, 2013), the backwearing processes involved in the dismantling of sandstone caprock (this study) are uncommon in the case of basement-derived escarpments. The morphology of the lower steps formed around the Chapada do Araripe after exhumation of the basement confirms this observation, particularly Step 3, which may correlate with the Sertaneja Surface or its equivalents on the north and south sides. North of the Cariri depression, the exact coincidence between this surface and a pediment in micaschist now dissected into convex hills (Fig. 11c) suggests that planation processes were limited to these weakly resistant rocks, whereas the São Pedro ridge in orthogneiss remained salient to the north (Fig. 6). This is confirmed by the exhumation of the Horto and Serra de Juá granitic residuals. More generally, the complexity of local structural controls that fixed scarp and residual outlines in the basement (also visible in the structural ridges of Ouricuri, on the south side of the Chapada) are best explained in a context of evolution by etch-planation and downwearing limited to the most easily weathered rock masses. The wide pediment carved below the sandstone plateau south of Exu is uniformly smooth in the micaschist outcrops south of Granito and Bodocó but only cuts into the edge of the granitic intrusion that underlies the sandstone cap. Here, approximate parallelism is observed between the scarp and the exhumed contact between granite and micaschist: it is therefore probable that limited scarp retreat (a few kilometres at most: Fig. 6) impinged on the granite intrusion during piedmont development. It contributed to fix the present contour of the scarp over the Exu reentrant in the form of an upper sandstone ledge which has been slowly retreating above the sub-Albian granitic surface and remains preserved as a narrow irregular topographic bench dissected into hills and tors.

The sandstone cap is deeply weathered and bears marks of shallow fluvial erosion. However, as with most sandstone plateaus around the world, its high permeability reduces the potential for surface runoff. The only exception has been observed close to the northern rim, where episodic outflow occurs along short entrenched channels bearing marks of pseudo-karstic evolution close to the surface (e.g. Ponte de Pedra: sandstone arch). Therefore, the dismantling of the Chapada is mainly the result of slope retreat processes, which operate as spring sapping at the heads of box canyons and in sapping funnels, and which are widespread along parts of the scarp in the form of large landslides. More locally, deep fluvial erosion is also active wherever it could reach the underlying soft rocks at relatively shallow depth, producing systems of canyons and widened valleys along the pre-existing shallow dendritic drainage system on the plateau (Araripina). These processes are most efficient when deep fluvial erosion has cut into thick, soft, impermeable and plastic layers, for example above the Cariri depression in the northeast. The activity observed here (deep-seated slumps and debris avalanches) is clearly related to the local structural conditions. Such conditions are similar to those listed by Moeyersons et al. (2008) in the Tigray province of Ethiopia: a stratigraphy with very weak dips and contrasting mechanical and hydrogeological properties. However, we have shown that it remains very efficient even in segments where scarp retreat occurred over weakly dissected erosion surfaces, for example on the south side of the Chapada.

A formerly wider extension of the basin is demonstrated by the existence of smaller, coeval rift basins to the SE (Cedro, São José do Belmonte: Fig. 5) and of several outliers, mainly to the west and southwest. Moreover, the geometry of the sandstone cap suggests that the limits of the former fluvial accumulation were located well beyond the present rims of the Chapada (Fig. 7). The morphology of the scarp also suggests substantial erosional retreat. The preservation of the sandstone cap along a roughly E–W axis may reflect depocentre distribution during the final post-rift depositional stages. This structure, mainly situated on the south side of the Patos lineament, seems to have guided the configuration of the post-rift subsidence area as well as that of the underlying graben and horst system (Valença et al., 2003). It is also possible that fluvial sediments of the Exu Formation were thinner (and/or less consolidated?) on the feather edge of the original outcrop, where subsequent stripping was easier. Finally, erosion seems to have been more efficient in the northeast (Cariri depression and erosional re-entrants of the Chapada), where mechanically weak sediments reach their maximum thickness below the sandstone cap. This is also the area of maximum uplift. In this area, the adjustment between river and hillslope profiles appears to have been delayed by the arrested vertical incision by the Rio Salgado of a resistant sandstone threshold (Fig. 16). Here, the Sertaneja Surface forms the local base level to this

Fig. 16. The Missão Velha waterfall. Palaeozoic sandstone, Mauriti or Cariri Formation. Background: Serra da Mãozinha outlier. Credits: J.P. Peulvast.

unique fluvial outlet out of the Cariri depression (Missão Velha waterfall). Only the slow retreat and incision of this bedrock knickzone could alter the river longitudinal profiles and sustain or increase the scarp retreat process. The presence of wide alluvial plains such as those of the Batateira, Salamanca and Salgado rivers, upstream of the Missão Velha lock, indicates an important stage of recent or current infilling by sand and clay mainly coming from the scarp and its piedmont, which might reflect temporary sediment ponding by the rock barrier.

6. Conclusion

Based on a combination of morphostructural, morphostratigraphic and morphopedological approaches, our study confirms the view that the Araripe sedimentary basin represents a fundamental landmark for reconstructing the regional morphotectonic evolution of northeast Brazil. The topographic inversion was caused by differential erosion in response to a broad regional crustal upwarp. No clear evidence of local tectonic inversion is observed.

Dismantling of the Chapada is the combined result of deep dissection receding headward from the plateau rims, of slope retreat processes operating locally at the head of box canyons and in sapping funnels, and of widely distributed landslides along parts of the scarp face. Such processes are unusual or underreported in this part of the semi-arid Brazilian Nordeste, which is more commonly associated with downwearing processes. The landslide-driven scarp recession is most efficient when assisted by deep fluvial incision into thick, soft, impermeable and plastic layers, for example over the Cariri depression in the northeast. However, mass wasting remains efficient even in areas where scarp retreat occurs over weakly dissected erosion surfaces, for example on the south side of the Chapada.

The patterns and rates of topographic inversion and scarp retreat appear to be controlled by lithological contrasts and by local conditions of sub-Mesozoic exhumation. Our estimation of the amplitude of denudation and of topographic inversion (0.6–0.7 km) differs significantly from AFT-derived estimates reported in the recent literature, which would imply burial by considerable thicknesses of younger sediment sequences and, at a later stage, 1.5 km or more of post-rift denudation — in the study area as well as in the Tucano–Jatoba basin to the south. Such a complicated scenario, which has not left a single outlier or residual outcrop of evidence, is incompatible with the model of episodic burial and exhumation recently proposed for northeast Brazil. The exhumation and reworking of surrounding basement surfaces probably began early, as shown to the northwest of the Chapada by the presence of widespread laterite exposures of probable Palaeogene age. A second stage of basin inversion began in the Oligocene or later. It corresponds to the major peak of regional uplift, river incision, partial planation and basin inversion. In addition to the regional conditions of lithological or morphological resistance (sensu Brunsden, 1993a,b), the likely long-term regime of scarp recession and height increase was sustained by a range of other control factors such as the architecture and lithological sequencing of the stratigraphic column, the hydrogeology, the low stratigraphic dips, and a seasonally dry climate — all highly conducive to rapid and sustained scarp retreat.

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