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LATE CENOZOIC AND PRESENT-DAY HILLSLOPE EROSION DYNAMICS IN A PASSIVE MARGIN CONTEXT: STABILITY OR INSTABILITY? CASE STUDIES IN NORTHEAST BRAZIL

ABSTRACT: PEULVAST J.-P. & BÉTARD F., *Late Cenozoic and present-day hillslope erosion dynamics in a passive margin context: stability or instability? Case studies in Northeast Brazil.* (IT ISSN 0391-9838, 2013).

Steep slopes form the marginal scarp of the semi-arid northern Brazilian «Nordeste», above depressions or corridors connected to a low erosion plain merging seaward with a coastal erosional-gradational piedmont. Dissected pediments and sparse debris fans visible at the base of some escarpments suggest recent erosive activity and possible slope retreat during the Late Cenozoic, although most of these forms are decoupled from major valleys. We describe the morphostructural patterns of chosen escarpments, in the crystalline basement as well as in the sedimentary cover, and the morphodynamic conditions of their evolution since the Miocene. Only a few scarps show strong structural control. Many of them are mainly inherited landforms, initiated during the Early Cretaceous rifting or the later margin uplift, a situation which suggests long-term stability. Later on, except in one case (the Araripe scarp), only slight or local backwearing took place, associated with downwearing on low surfaces and pediments, probably in diachronic ways. The Neogene clastic sedimentation on piedmonts and coastal areas mainly reflects the occurrence of dry periods inducing widespread stripping of deep soil horizons and erosion of bare rock slopes and surfaces. Dissection stages occurred in periods of more humid climate and/or low sea level. Marks of strong recent or present activity are mainly registered in the rims of the Chapada do Araripe, owing to favorable structural, hydrogeological and climatic conditions. The moderate volumes of Neogene clastic sediments imply overall low uplift and erosion rates until the Present, favorable to morphological and lithological resistance effects in the landscapes. However, slope instabilities are not uncommon, locally leading to well-characterized processes, landforms and deposits of gullying and mass wasting. Therefore, hazards related to slope processes should never be neglected, although only small-scale events were recorded in recent times, and times of recurrence of larger events are probably much longer than the historic times.

KEY WORDS: Tropical geomorphology, Hillslope landforms and processes, Backwearing, Downwearing, Mass wasting, Morphological resistance, Brazil.

INTRODUCTION

Steep slopes form the marginal scarp of the semi-arid northern Brazilian «Nordeste» and bound inner residual plateaus and ridges rising up to 800-1,200 m (fig. 1). They overlook a low composite surface (the so-called Sertaneja surface) merging seaward with a well-developed coastal erosional-gradational piedmont. Only a few of them coincide with geological contacts and/or fault zones. Their location, their straight or sinuous outlines, and the presence or lack of residual landforms in front of them give indications on their origin and evolution. Recent or active mass wasting landforms, dissected pediments and sparse debris fans visible at the base of some escarpments suggest recent and current erosive activity and possible slope retreat, although most of these forms are decoupled from major valleys. Therefore, the question arises of the age, origin, evolution and stability (or instability) of theses scarps, and of the signification of the observed or inferred dynamics in relation with long term trends of evolution. Beyond the indications obtained on types of slope dynamics and on the factors that control their occurrence, this could throw light on duration and more general factors that can explain slope retreat (backwearing) and/or piedmont downwearing outside the main drainage axes, *i.e.* a fundamental issue in the understanding of planation processes and long-term landform evolution in tropical areas. In order to treat these issues in a context where various factors (lithology, neotectonics, climatic and eustatic changes) can be consid-

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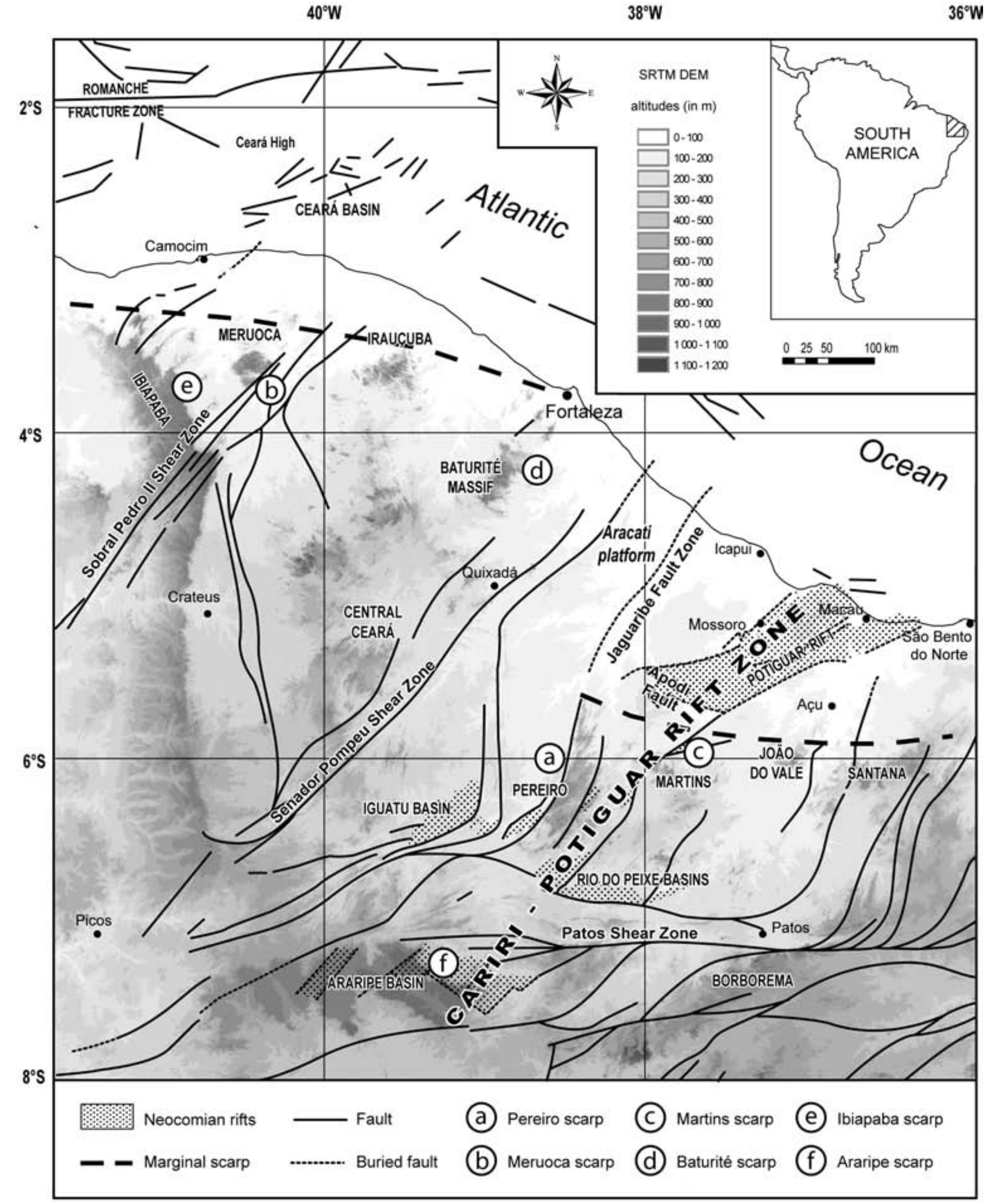

FIG. 1 - Location map of the study area, showing relationships between topographic patterns, tectonics and Early Cretaceous rift structures. Topography derived from the SRTM DEM.

ered, we describe the morphostructural patterns of chosen escarpments, as well as the present and past morphodynamic conditions of their evolution, especially since the Neogene. We discuss their implications on origins and conditions of shaping, evolution, preservation or reworking of scarps and piedmonts on a stable, passive margin.

STUDY AREA AND MORPHOSTRUCTURAL CONTEXT

Regional landscapes and geology

The study area is part of the Brazilian Equatorial continental margin, formed in Aptian times (Matos, 2000). Onshore, a Precambrian basement is organized around NE-SW shear zones, some of which were reactivated by pre-opening rifting (Cariri-Potiguar rift zone) and then intersected by the transform passive margin (Potiguar basin area). A thin dissected layer of Cenozoic sediments (Barreiras Group) is preserved over a 10 to 80 km wide coastal strip, forming low-lying plateaus or «*tabuleiros*» (10-60 m) at the foot of two offset segments of a discontinuous marginal scarp. The slightly dissected coastal lowlands merge inwards with vast corridors and plains (the Sertaneja surface) that extend far into the semi-arid interior between flat or rugged plateaus and ridges of moderate altitudes (800-1,200 m), shaped into a wide flexural uplift zone (Peulvast & *alii*, 2008 a). Our study deals with high hillslopes distributed on both the marginal escarpment and on inner scarps overlooking the low surfaces.

The two segments of the marginal escarpment respectively intersect the NW rift shoulder of the Cariri-Potiguar rift zone, and the eroded remnants of the southern Potiguar rift shoulder (fig. 1). The offset zone partly corresponds to a post-rift subsidence area (Potiguar basin). However, no direct tectonic control of scarp outlines is observed. Erosional retreat and shaping from remote structures, fault zones or marginal flexure, must be considered in most cases (Peulvast & Claudino Sales, 2004; Peulvast & *alii*, 2008 a).

Like those of the marginal escarpment, the slopes of inner scarps and inselbergs are generally steep. Sharp basal knicks or short concavities link them to narrow pediments or slightly dissected or rolling surfaces, parts of the Sertaneja surface. Marks of active dissection and mass wasting are observed in some of them, in spite of general disconnection between the slopes, incised by gullies or short valleys, and the main river trunks, incised 20 to 50 m into the piedmonts and the coastal «*tabuleiros*», 5 to 30 km from the scarps. In order to get a representative set of morphostructural contexts and of controls on the types of dynamics and on geomorphic evolution, we analyze several examples belonging to the marginal as well as to inner scarps.

Morphostructural typology of studied scarps

Some of the studied scarps were already chosen for evaluating possible neotectonic controls on their recent evolution (Peulvast & *alii*, 2006). But our study also deals with other high hillslopes more clearly formed by differential erosion:

- a: The western edge of the granitic Pereiro massif, a 120 km long, 400-500 m high, straight and continuous scarp overlooking the slightly dissected floor of the low Jaguaribe depression (fig. 2A). All along the scarp, the coincidence of his outline with the intrusive contact clearly indicates a contribution of differential erosion associated to the formation of the lower surface.
- b: The straight SE scarp of the Meruoca granitic massif, 600 m high, overlooking the Acarau River corridor hollowed along the Sobral-Pedro II shear zone (fig. 2B). In spite of the local presence of perched valleys and triangular facets similar to those of fresh fault scarps, outstanding erosive remnants are found on the opposite block, suggesting that this scarp mainly displays differential erosion features and thus may be interpreted as a fault line scarp (Peulvast & *alii*, 2006).
- c: The discontinuous basement scarp, topped by sandstone mesas, that forms the northern edge of aligned spurs and buttes south of the Potiguar basin (*e.g.*, Serra do Martins; fig. 2C). It overlooks the Chapada do Apodi, a low surface bevelling Turonian limestones, beyond a wide depression underlain by the exhumed basement. It corresponds to a residual fault scarp which has retreated from remote rift structures (Carnaubais and Apodi faults), mainly before the deposition of the post-

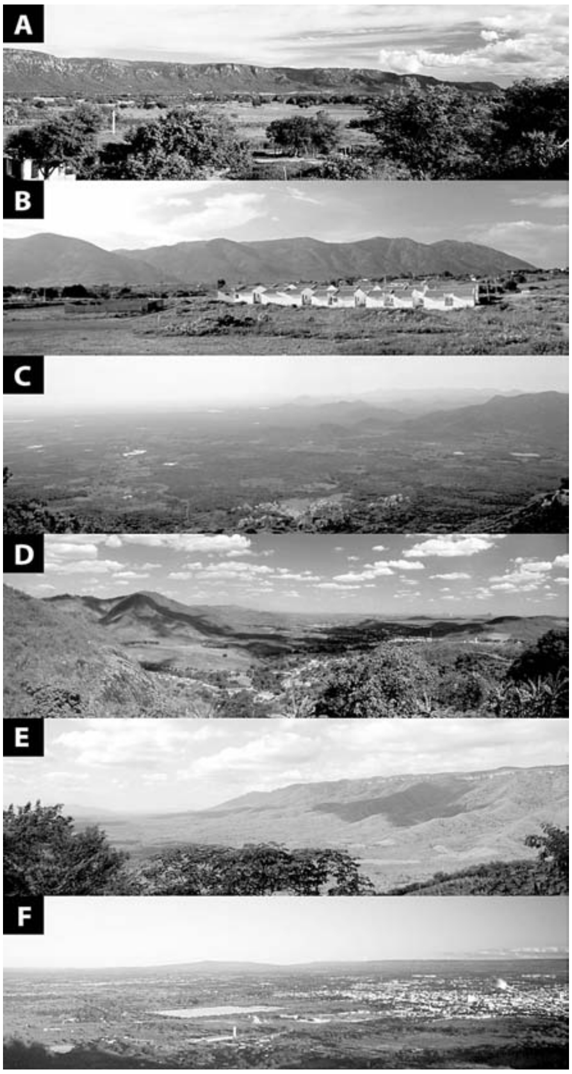

FIG. 2 - Views of scarps and hillslopes described in this study. A: The Pereiro fault scarp, seen to SE from the BR 116 road between Icó and Jaguaribe. Note the low sinuosity of the escarpment, which coincides with the outer limit of a syn-orogenic granitic intrusion. Presence of short steep and hanging valleys, with small alluvial fans. Pediment on gneiss in the foreground. B: The SE fault or fault line scarp of the Serra da Meruoca. The slope angle of the facets (25-30°) is slightly lower than on active fault line scarps, whereas the low sinuosity and the location of the scarp on the fault line may be explained by strong lithological control as well as by neotectonics. C: The north edge of the Serra do Martins, a residual fault scarp, as seen to the east. Knick, marble buttresses (foreground), inselbergs at the contact with the Sertaneja surface (which derives from the exhumed pre-Cenomanian surface). In the distance, to the ESE: the Serra João do Vale, another remnant of the southern shoulder of the Potiguar rift. D: The Baturité embayment, seen to the east from the Jesuit convent of Baturité. Its dissected floor connects to the Sertaneja surface, which is overlooked by a few inselbergs (to the right: Pedra Aguda, microgranites). Apical parts of former pediments at the base of the sinuous scarp, dissected by one of the rivers coming from the hanging valleys of the massif. E: The Serra da Ibiapaba, above Freicheirinha, to the south. Glint in which the Paleozoic sandstones of the Parnaiba basin (Serra Grande Formation) form the upper ledge above the concave slope that connects to pediments shaped into the weakly resistant sediments of the molassic Ubajara graben. Note the dissection of the pediments without significant scarp retreat. F: The northeast rim of the Chapada do Araripe, as seen from the Horto hill, to SE. Beyond the Cariri depression and the city of Juazeiro do Norte, the cuesta-like escarpment, 600 m high, and the Serra da Mãozinha, the unique outlier present on the northern side of the sandstone plateau. Photos: J.-P. Peulvast.

rift cover that they slightly deform owing to local fault reactivation within the Potiguar basin during the Cenozoic (Peulvast & Claudino Sales, 2004; Peulvast & *alii*, 2008 a).

- d: The 500-600 m high escarpment that forms the eastern edge of the Baturité and Aratanha massifs, south of Fortaleza, devoid of clear structural control. Most peaks, culminating ridges, and outstanding escarpments are shaped into the folded quartzite layers which form the skeletal structure of the massif. No fault line is identified along the sinuous scarp and its multiple embayments, located 50 km NW from the NE-SW Senador Pompeu shear zone and from the Choró River (fig. 2D). Even along the straight eastern scarp of the Aratanha massif, to the north, we consider the outlines as erosional.
- e and f: The highest scarps (400-600 m) of the two main sedimentary plateaus of Ceará, the NS Ibiapaba glint, to the west (fig. 2E), and the northern margin of the Chapada do Araripe (fig. 2F). The Ibiapaba glint reaches its maximum heights in the north, above Freicheirinha and Mucambo (600-700 m); one or several sandstone cornices form its upper part, stressing strong resistance differences between the sandstones and the underlying basement rocks (gneisses, granites, migmatites; molassic metasediments of the Ubajara Group), often deeply weathered. The second scarp is a cuesta-like escarpment shaped into the upper layers of the Mesozoic series that fill the eastern part of the Araripe basin. Known as Araripe Group (Ponte & Ponte Filho, 1996), this near-horizontal series is composed of fluvial, lacustrine and marine sediments of Late Aptian to Cenomanian age, where 250-280 m weakly resistant rocks are overlain by massive and resistant sandstones (150-250 m) forming the upper ledge of the scarp.

METHODOLOGY

Most hillslope landforms were studied by the means of elements of the methodology we used in the analysis of the escarpment of the Chapada do Araripe (Peulvast & *alii*, 2011). Here, landforms and deposits related to large-scale mass movements were mapped from field study, and from the interpretation of various types of photos (air photos at 1:15,000 in the Crato area) and satellite images (Landsat TM and ETM+). High-resolution images combined with the SRTM DEM in the Google Earth data set were used, in particular through 3D visualizations. The criteria of identification were the distribution of specific medium- to small-scale topographic features (landslide scars, tongues with convex profiles, partly filled valleys with twin river courses along the contacts between thick tongues and both valley side walls), and more indirect indications (vegetation, spring location...), combined with data on surface roughness and sedimentary features of mass movement deposits obtained from field work. Geological profiles and GIS-based geomorphological mapping helped in determining semi-quantitative, often minimal, evaluations of the volumes of deposits based on measures or of length, width, and mean thickness, this last one being based upon the study of all visible sections along each deposit. Combined with the use of available data on climate and hydrogeology, and of morphostratigraphic indications on the succession of deposits and landforms, these data led to obtaining preliminary indications on the significance and relative chronology of these features during the Late Cenozoic, and on related types of scarp evolution. The typology of mass movements that was used is mainly based on Dikau & *alii* (1996).

Only parts of these techniques were used in most other study sites. They were completed in all cases by morphostructural mapping, partly based on the use of data from the digital geological map of Ceará (CPRM, 2003) and, in several cases, by measures of scarp sinuosity at regional scale (detailed results in Peulvast & *alii*, 2008 b). Measured on 1:500,000 maps published by DMAAC, St. Louis, Missouri (sheets ONC M-28), the sinuosity S is defined as the ratio of the contour to chord distance. If scarp formation and retreat may be considered as having occurred from more or less remote structures, fault zones reactivated during the Cretaceous rifting or later, in relation to the marginal flexure (Peulvast & Claudino Sales, 2004), differences of sinuosity might reflect differences in age and rate of retreat (Matmon & *alii*, 2002) as well as structural controls.

RESULTS

Morphodynamic data: recent and present-day hillslope dynamics

Basement scarps

Whereas most granitic and migmatitic escarpments display steep and bare walls, frequently shaped into rounded domes or sharp needles (Pereiro, north of the Baturité massif; fig. 3A), or steep facets with straight profiles (Aratanha, Meruoca SE; fig. 2B), the wall morphology is more irregular in the sinuous scarps shaped into metamorphic rocks (Baturité E; fig. 2D). High rock walls are visible in the western and southern slopes of this massif, where they are cut into thick quartzite layers dipping opposite to the slope inclination (Pico Alto, Capistrano; fig. 3B). However, minor, non-coalescent alluvial fans are found at the base of both types of scarps, below short and steep valleys or gullies. In several locations, mainly in the driest and least vegetated parts of granitic massifs (northern Meruoca walls; fig. 3C), we found fresh forms and deposits of debris flows, probably formed after heavy rains of recent active rain seasons (2003, for instance). Their sparse distribution reflects that of fracture zones or benches where significant volumes of saprolite (mainly grus and blocks) were temporarily retained in otherwise steep walls before being removed. The same was observed below many quartzitic ledges, where waste volumes may locally be important (western margin of the Baturité massif, west of Aratuba).

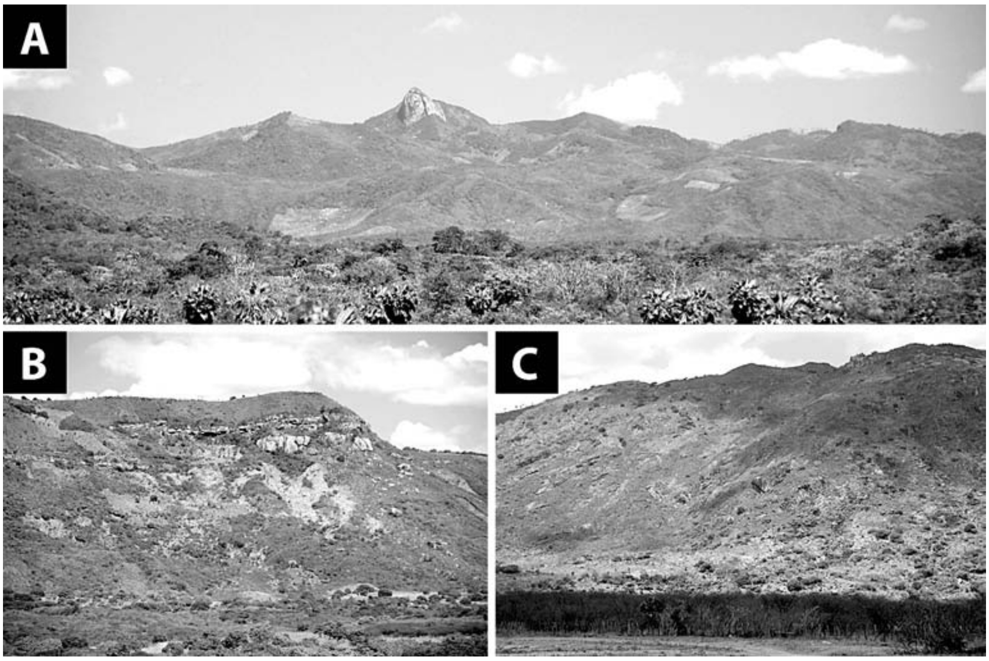

FIG. 3 - Scarp morphology and hillslope processes in basement rocks. A: The northern scarp of the Baturité massif, near Palmacia. Migmatite ridges and domes (sugarloaves) shaped by cooperation of deep weathering and saprolite stripping into the most dissected part of the massif. No identified fault-line between the mountain and the erosion plain visible in the foreground. B: Quartzite scarp above the Capistrano embayment, eastern rim of the Baturité massif. Mass wasting and rockfall deposits. C: Mass wasting and debris flow deposits in the eastern edge of the granitic Meruoca massif near Massapê. Recent and active saprolite stripping, probably enhanced by human activity (deforestation). Photos: J.-P. Peulvast.

Only a few scarp gullies and deposits are connected to the drainage system of the surrounding pediplains, since the entrenchment of lower river segments is observed at distance from the scarps. Most alluvial fans are built or preserved on proximal, non-dissected remnants of pediments. However, some mountain valleys are continued through dissected remnants of pediments, mainly along sinuous scarps, even far from the coast (80 to 120 km: Baturité, Serra do Martins, Ibiapaba glint; fig. 2E), showing that slight vertical incision could occur in some proximal parts of the piedmonts, after late pedimentation stages. However, in the Ubajara and de Viçosa do Ceará regions, where the sandstone ledge of the Ibiapaba glint is particularly high, no significant retreat linked to this vertical incision could be observed, except in the main sapping alcoves.

Tableland scarps: the rims of the Chapada do Araripe

The morphology of the north and NE rim of the Chapada do Araripe above the Cariri depression displays the most spectacular marks of a fast and active evolution, which seems to be exceptional in this part of the semi-arid Brazilian «Nordeste» (Peulvast & *alii*, 2011). Reaching 900-1002 m in altitude, the eastern part of this plateau is one of the humid and forested massifs («*brejos de altitude*») that overlook the semi-arid plains of the «*sertão*» (Cavalcante, 2005; Bétard, 2007). The depression floor lies at 400 m a.s.l., *i.e.* 500-600 m below the crest. Over a length of 25 km, the escarpment forms two large adjacent reentrants (Crato, Barbalha), more or less semi-circular and 10 km wide each, which open to NE. The 250-300 m high wall overlooks short concave slopes, either regular or cut by narrow benches or hummocky topographies, which connect its base (750 m a.s.l.) with wide systems of dissected glacis gently sloping (3.5%) towards the center of the depressions, from 600 to 460 m a.s.l., over 2 to 5 km.

The Crato and Barbalha re-entrants, where the scarp is the highest, display the most spectacular and diversified landforms and deposits related to gravitational dynamics. Simple or complex landslide landforms and deposits are found along concave wall segments. In the best-characterized landslides, prominent deposits form thick hilly lobes over pediment roots. Slumps are the simplest of them. They are often prolonged by flat lobes of waste or long debris flows. Large rotated and tilted blocks are identified in some of them (Meio; fig. 4A). 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 dislocated during their movement. To the SE of Barbalha, a kilometer long slide scar splits into various benches reflecting the large (hectometric) retreat of the plateau rim associated with the most important of these landslides (fig. 4B). In all cases, movements occurred along mechanically weak levels of the sedimentary series (clays, marls and gypsum). Possibly initiated by shearing and horizontal translation along these levels, they are combined with rotational sliding along listric fault planes developed in the thick overlying sandstone layer.

Below systems of semi-circular funnels or alcoves carved into other parts of the walls in the main amphitheatres, or downstream of slumps and debris tongues, the floors of some of the main valleys are partly occupied by elongated tongues of block-rich material emplaced by large debris-flows (fig. 4C). In the alcoves, the sandstone walls only bear scattered marks of recent block falls or rockslides. Minor accumulations of waste, weathered

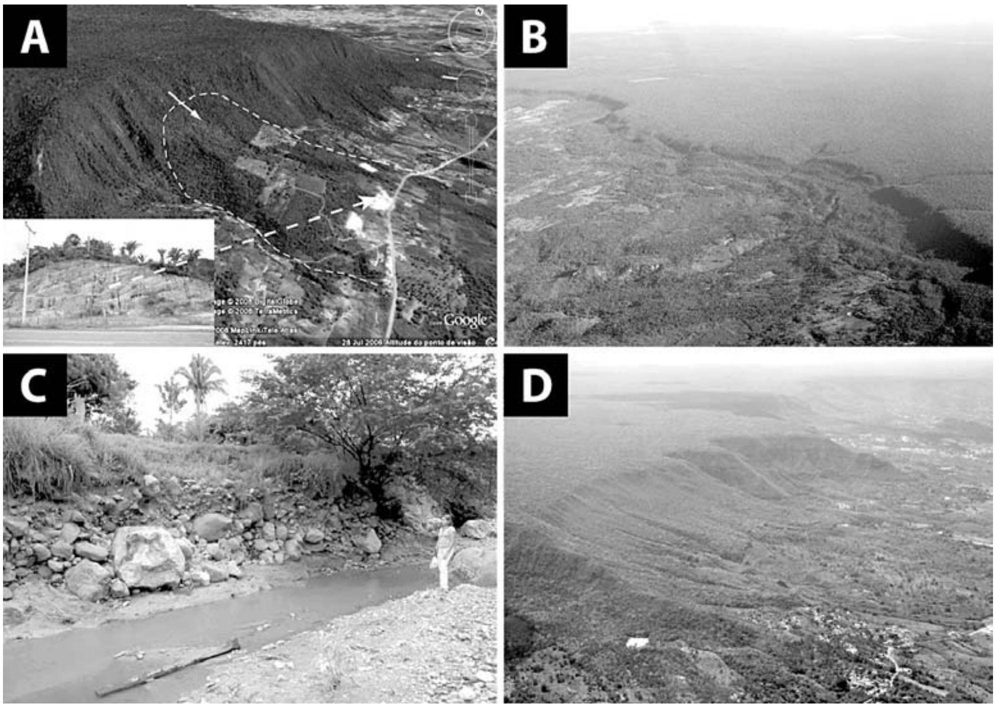

FIG. 4 - Mass movement landforms and deposits in the sandstone scarp of the Chapada do Araripe. A: The Meio rotational landslide (Barbalha), as seen by Google Earth. The photo shows a section in a huge block of Exu sandstone tilted to SW. B: Stepped tilted blocks SSE of Barbalha (Flores): a km long landslide scar splits into various benches reflecting a large (pluri-hectometric) retreat of the plateau rim. C: Debris flow sediments: the lower Salamanca debris-flow, upstream of Cabaceiras. D: The head of the Carretão landslide, south of Crato, seen to NW: large scale slump, below a 1.5 km long and 180 m high scar with smooth concave outline and profile. The angle of slope decreases downward from 30 to 25-20°. Below, a chaotic topography with 60 to 80 m high hills incised by four deep and narrow valleys disconnected from the scar extends over a width of 2 km. In the background: spur and funnel topography, at the head of large debris flows. Photos: J.-P. Peulvast.

sandstone blocks in abundant matrix of reddish clayey sand, are found below, and spring water often flows out from the discontinuous talus. Therefore, no significant reconstitution of a colluvium reserve seems to have occurred after the stripping events at the origin of the debris flows. Measured lengths vary from 2.5 to 6.5 km, for vertical ranges of 250 to 350 m. Their widths are generally between 150 and 250 m but debris flow deposits form a 800-1000 m wide lobe between the Riacho Saco twin valleys. Using observed thicknesses, minimum volumes of 2.5 Mm^3 may be suggested for the biggest of them (Grangeiro, Luanda-Lameiro, Salamanca).

Finally, the head of the Carretão landslide, south of Crato, appears as a large-scale slump, below a 1.5 km long and 180 m high scar with smooth concave outline and profile (fig. 4D). Below, a chaotic topography with 60 to 80 m high hills incised by four deep and narrow valleys disconnected from the scar extends over a width of 2 km down 540 m a.s.l. Formed by large tilted sandstone blocks in the upper part of the landslide, it is continued by a thinner debris apron that was emplaced over a differentiated topography, possibly at high speeds, as shown by ascending movements (Lucchitta, 1978; Fort & Peulvast, 1995), forming a debris avalanche or Sturzstrom (Angeli & *alii*, 1996). The estimated area of the deposit is ~10 km^2 at minimum. The mean thickness probably represents several tens of meters in the slump area, and at least several meters (locally 10 m or more in the valleys) in the debris apron. These conservative figures indicate a minimal volume of 100 Mm^3.

Ancient hillslope deposits: the Neogene legacy

In basement areas, remnants of older waste deposits were mapped on parts of the Sertaneja surface, at some distance from the scarps, up to tens of kilometers. Deposits of argillaceous, often ferruginous, sands and gravels of alluvial to colluvial origins were mapped on slightly dissected pediplains at low altitudes, *e.g.* on proximal parts of the Jaguaribe pediplain and of the coastal piedmont, around the Baturité massif. Sparse deposits of coarse quartz and quartzite pebbles and gravels, several meters thick, are also found in proximal and even distal locations, on dissected fans and pediments (fig. 5), and high fluvial terraces, in the same areas as well as south of the Potiguar basin. All of them reflect the occurrence of periods of active slope erosion and alluvial fan construction on proximal parts of the low surfaces. A slight entrenchment of valleys now places these deposits on interfluves, 20 to 30 m above the present valley floors and cuts them from their source areas, scarps and inselberg slopes located up to 20 or 30 km away. This dissection, similar to that of the Barreiras sediments, may suggest a stratigraphic relationship between both sets of deposits.

The Barreiras sediments overlie the weathered basement of the coastal piedmont, and also unconformably cover Late Cretaceous sediments in the Potiguar basin. Reduced to dissected remnants disconnected from source areas, these deposits of Miocene to Pliocene age (Arai, 2006), and of limited thickness (10-80 m), slightly dip seaward, where they form the so-called «*tabuleiros*». Inland, layers of reddish to white argillaceous sands contain minor amounts of quartz gravel, and more clay beds at depth. Several sea cliff outcrops also expose coarse deposits, mainly in the vicinity of present river mouths and of mountains approaching the coast (*e.g.*, to the west of Fortaleza).

These deposits belong to a piedmont system whose inner, eroded parts are exposed almost in the same plane as

FIG. 5 - Remnant of detrital deposits on the western piedmont of the Baturité massif. Rich in rounded quartz pebbles and gravels embedded in a sandy-clay matrix, this fanglomerate deposit was identified a tens of meters above the surrounding present valley floors, 5-6 km from the western scarp of the Baturité massif. Photo: F. Bétard.

that of the «*tabuleiros*». Their weathered substrate is clearly identifiable at the coast and along shallow valleys incised down to the basement. Generally flat, it is locally irregular, with low rounded hills and inselbergs protruding through the cover. Its buried distal parts as well as exposed proximal elements intersect each other at low angles and locally comprise slightly dissected surfaces. Both buried and exposed parts, the final shaping of which probably provided the Barreiras deposits, are diachronous in age. Such a piedmont geometry implies some kind of non-cyclic evolution during the Neogene, such as described in distal parts of uplifting areas, in wide flexural zones where interplay between moderate uplift and variations of the base level only allowed a slow process of etch-planation and remained insufficient for triggering stages of deep river entrenchment until the final dissection (Peulvast & Claudino Sales, 2005).

Inland, particularly in the Cariri region, a more typically cyclic evolution, associated with relief inversion of the Araripe sedimentary basin, may be considered, since the Sertaneja erosion surface and related depressions are clearly inset below the well dated infra-Albian and Cenomanian surfaces (Peulvast & *alii*, 2008 a). As shown by the pediments widely developed in the Crato area and by the now dissected surface that bevels the micaschists of the basement to the north, a partial planation episode interrupted the inversion process, after a post-Paleogene phase of vertical erosion of 200 to 300 m. This phase of deep denudation and related scarp retreat of the Chapada above the peripheral depression could be synchronous with aridification observed in northeast Brazil since the middle Miocene (Gunnell, 1998; Harris & Mix, 2002).

Later dissection of the low surfaces, probably connected to that of the so-called Sertaneja surface (Peulvast & Claudino Sales, 2004), and accompanied by scarp exaggeration and retreat, seems to correspond to a Late- and post-Miocene stage of vertical erosion observed in the whole Ceará region (Peulvast & *alii*, 2008 a). In the Crato-Juazeiro do Norte depression, the vertical erosion is also controlled by the outcrop level of resistant sandstone layers, which form the outer skirt of the sedimentary depression (Mauriti Formation) and a local base level hardly deepened by the only fluvial outlet of the depression, *i.e.* the Rio Salgado (Missão Velha waterfall).

DISCUSSION

Structural controls on scarp evolution and hillslope dynamics

The long-term morphostructural context is that of shallow basin inversion that has occurred in the Ceará area of NE Brazil since Cenomanian times. Uplift resulted in the topographic inversion of the post-rift basins, exhumation of buried surfaces/stratigraphic unconformities, dissection of the residual Cariri-Potiguar footwall uplands, and expansion of the erosional Sertaneja and coastal plains. Resulting long-term denudation rates in this setting were <10 m/Ma (Peulvast & *alii*, 2008 a). These low post-rift denudation rates are explained by a conjunction of four factors that also influence the conditions of scarp formation and evolution: (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, 1993b) in which the development of high angle slope systems favorable to intense erosion is impeded; (iii) the lithological heterogeneity of the basement and its cover, with resistant bedrock outcrops (*e.g.*, sandstone, limestone, granite) explaining the widespread preservation of residual topography still upstanding on the Sertaneja erosional plain and occupying over ~50% of its surface area; (iv) the long-term semiarid climate in NE Brazil, probably in existence for the last 13 Ma at least (Harris & Mix, 2002).

The types of structural controls on scarp evolution and hillslope dynamics differ according to the nature of the bedrock: crystalline or sedimentary. Among the basement scarps, two main types were analyzed. In the first one (examples a and b), a coincidence with intrusive contacts, highlighting differential erosion features, suggests limited possibilities of scarp retreat. Both granitic scarps are disconnected from the main valleys excavated along master faults (Jaguaribe, Acarau) by 5 to 15 km wide pediments. In the second case (c and d), important scarp retreat by dissection and dismantling of old Cretaceous rift shoulders or large flexure hinges might have occurred during the Late Cenozoic together with the formation of erosion piedmonts (fig. 2D), possibly helped by the marginal flexuration that reduced the thickness of the rock slices to be removed in the vicinity of the coast and of the basins. However, the high sinuosity of these scarps (S>2) seems to correspond to the complexity of local structural control that fixed scarp outlines in a long-lasting evolution: such controls are best explained in a context of evolution by etch-planation and downwearing limited to the most easily weathered rock volumes.

In sedimentary scarps (e and f), the outlines, profiles and possibilities of retreat are mainly controlled by the respective thicknesses of resistant and soft (and/or weatherable) rocks, and by local dips, especially in the cap layer (Peulvast & Vanney, 2001). Weak dips are more favorable to active retreat, at least locally, in the form of sapping and development of box-canyons such as those that indent the rim of the Chapada do Araripe to the north (Santana do Cariri), the east (Jardim) and the south (Ipubi). This pattern allows the dissection of the plateaus in elongated promontories and outliers as well as the shaping of wide orthoclinal depressions (fig. 2F). On the contrary, higher dips impede or slow down scarp retreat, and the outlines remain weakly indented, except along cataclinal valleys. Observed in the Serra da Ibiapaba, this situation also prevents the preservation of outliers. As shown in the Araripe scarp, these patterns also control the possibilities of deep-seated mass wasting.

Structural controls are also observed in the distribution of present-day morphodynamics among hillslopes. The particular activity observed in the northeast Araripe scarp (slumps and Sturzstrom belonging to the category of deep-seated landslides) is clearly related to the local structural conditions. They are as favorable as those listed by Moeyersons & *alii* (2008) in the Tigray province of Ethiopia: a tabular structure with very weak dips and a superposition of layers with contrasting mechanical and hydrogeological properties. Such conditions are not so well characterized in the Ibiapaba glint, where the sandstone cap generally exhibits stronger dips, less favorable to scarp retreat (Peulvast & Vanney, 2001), whereas the underlying basement is more heterogeneous and often more resistant, in spite of local deep weathering (fig. 6). In the northeast Araripe basin, the layers of gypsum of the Ipubi Formation, as well as the marls and clays of the Romualdo Member exposed at the base of the scarp probably play a decisive role as weak levels, together with the 20 to 80 m thick Arajara clayey sandstones that underlie the massive Exu sandstone. All slumps described in our study are seated in these layers. Although the total thickness of gypsum layers remains moderate (a few tens of meters at most) the particular role of this rock as a ductile level prone to shearing at relatively low temperatures (Barberini & *alii*, 2005) is commonly recognized and may be involved in major destabilization of slopes when sufficiently thick.

Permanent or seasonal saturation by water of parts of this series is probably also involved in the occurrence of such phenomena. Two aquifers outcrop in the scarp zone, corresponding to the Arajara sandstone and the base of the Exu Formation, and to the Crato limestone, respectively (Costa, 1999). Below the first of them, clays, marls and gypsum layers form an aquiclude («Santana aquiclude») as well as a thick plastic level, the surface of which, when exposed, generally appears chaotic, impracticable during the rainy season, and 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 deep-seated mass movements all along the scarp, although we have also observed generalized mass wasting in the Exu sandstone cliff even in areas where these soft basal sediments are missing. In this case, the presence of fine sediments in basal layers of the Exu sandstone and the strong clayey weathering observed along joints and fractures are probably influential as well.

On crystalline rocks, active or inherited deep weathering becomes the main factor to explain superficial mass movements observed in hillslopes and scarps of the humid Baturité massif and, more generally, of parts of basement landforms where thick saprolites are formed and/or pre-

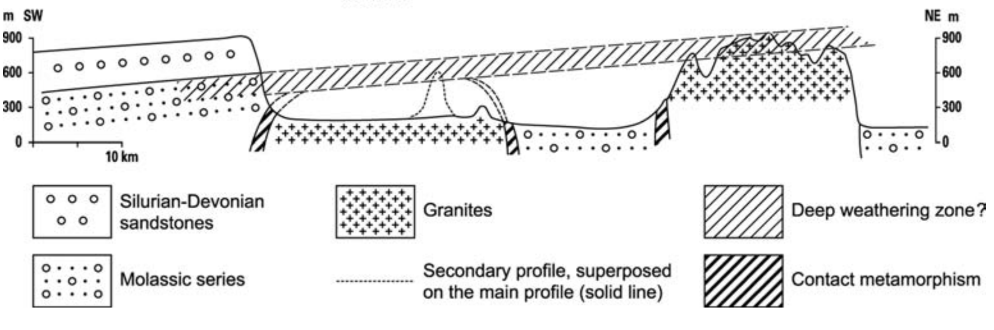

FIG. 6 - The Ibiapaba glint near Ubajara. The high dip angle prevents the formation and preservation of outliers and limits the scarp retreat. The hills and massifs that lie opposite to the scarp are residuals shaped into resistant granites in relation to the development of the low («Sertaneja») erosion surface.

served (Bétard, 2007). Such movements are mainly limited to the flanks of convex hills cut into the ferrallitic saprolites of the summit plateau and, more exceptionally to steeper slopes of the deeply dissected part of the massif, to the north; they do not seem to be extensionally involved in scarp retreat processes at the periphery (Bastos, 2012).

On the contrary, slope evolution is slower in places where lithology and bioclimatic conditions are less prone to deep weathering, allowing the production of minor waste quantities, often containing large blocks prepared by decompression and other processes in rock walls. Only non-coalescent alluvial fans are found at the base of scarps, below short and steep valleys or gullies. In the driest and least vegetated parts of granitic massifs, the sparse distribution of fresh forms and deposits of debris flows reflects that of fracture zones or benches where significant volumes of fine-grained saprolite can have been temporarily retained in otherwise steep walls before being removed. The same was observed below many quartzitic ledges, where waste volumes may locally be important.

Late Cenozoic climate change, hillslope processes and the last stages of scarp evolutions

The Barreiras sediments are part of a large clastic wedge of mainly Late Cenozoic age (Pessoa Neto, 2003) that is found onshore and offshore along the Brazilian margin. As measured on a swath profile in the Potiguar basin area, the mean thickness of this wedge (about 150 m at most on a 100 km wide strip) would represent at most 50 m of vertical erosion on a 300 km wide inland zone (*i.e.*, the mean width of the Sertaneja surface). The eroded slice is probably thinner in the less uplifted coastal areas. Such moderate figures, also suggested by the identification of pre-Barreiras to pre-Cenomanian paleosurfaces on parts of the low surface, are comparable to average values measured from stratigraphy on the post-Cretaceous times (Peulvast & *alii*, 2008 a). They do not imply any Neogene acceleration of erosion and uplift, neither does an investigation of possible neotectonic movements outside coastal sites.

Transient increases of erosion phenomena, recorded by the clastic facies of the Neogene sedimentation, can have been controlled by climatic, tectonic or eustatic factors. Climatic changes induced numerous short-term fluctuations since the Miocene, essential for the regradation of low surfaces by etchplanation and their inward extension (Peulvast & Claudino Sales, 2004; Peulvast & *alii*, 2008 a). The relative increase in clastic supply from the hinterland is probably linked to a marked shift towards aridity at that time, as suggested by Harris & Mix (2002) from a study of the ratio of oxide minerals in the terrigenous sedimentation of the Ceará Rise. The identification of coarse alluvial fans on dissected pediments, below high mountain slopes bearing marks of deep denudation and of strong demolition of rock ledges, and the presence of thick gravel terraces along middle or lower river courses probably reflect the occurrence of periods favorable to widespread stripping of deep soil horizons and even to erosion of bare rock slopes and surfaces, leading to generalized, yet moderate downwearing, and local backwearing.

As suggested by the data published by Harris & Mix (2002), such events may have taken place in dry conditions with discontinuous vegetation cover, allowing the occurrence of debris flows and torrential floods, and they were followed by dissection stages in periods of more humid climate and/or of lower sea level. The diversity of combinations between these sequences, already suspected in the sedimentary history of the Barreiras and Tibau deposits, reflects a complex environmental history in the Late Cenozoic. Although the repeated Pleistocene sea level falls probably explain the final dissection of the piedmonts, this complexity and the short duration of climatic and eustatic events were not favorable to continuous regressive erosion towards the scarps, explaining the frequent disconnection of the main river trunks from the scarps, even those bearing sparse marks of active erosion, especially in the widest coastal and inner piedmonts. As shown by the position of deposits of various ages on pediments and exhumed surfaces close to the scarps (fig. 5), backwearing, if any, was also limited on the same period, even at the head or at the knick-points of the scarce gorges connected to the parts of the drainage system entrenched into the low surface (Baturité).

Conditions of recent evolution of hillslopes and implications for hazard assessment

In the Araripe scarp, large-scale gravitational dynamics and mass wasting are involved at least in the last stages of scarp retreat above the Cariri depression. Probably responsible for earlier retreat stages, as suggested by the nature of pediment covers and their distribution in distal parts of the dissected glacis strips, they are correlative of the recent development of erosional re-entrants and of scarp exaggeration above increasingly deep valleys and depressions. The preserved volumes of deposits only represent a small proportion of the scarp retreat, still to be quantified. Matrix outwashing and weathering of coarse elements prepare the final waste exportation, by fluvial transport of sand and finer elements to the Salgado and Jaguaribe river system. The role of intense, short rainfall events repeated during the rainy season, and causing groundwater saturation in the aquicludes (Magalhães & *alii*, 2010) is probably involved. Compared to the drier, surrounding plains of the Sertão, the northeast edge of the Chapada do Araripe receives higher amounts and intensities of rainfall, which may be considered as a potential factor of landslide triggering. As a working hypothesis, and waiting for «absolute» ages of some of the deposits described here, we also suggest a possible influence of Late Quaternary climatic changes, with wetter periods (prolonged periods of high precipitation) possibly favoring a greater occurrence of large-scale mass movements, such as revealed by paleoclimatic studies on NE Brazil (Behling & *alii*, 2000; Wang & *alii*, 2004). So far, we are still unable to ascertain whether we have still periodically active, or inactive processes.

Owing to contrasted climatic conditions and generally strong weathering in basement rocks as well as in cover sediments, mainly on humid slopes exposed to the trade winds (Bétard, 2007), present-day slope instabilities are not uncommon, locally leading to well-characterized processes, landforms and deposits of gullying and mass wasting. Among them, those of the Chapada do Araripe deserve a special mention, since the adjustment of river- and hillslope profiles does not seem to be achieved and, on the contrary, to depend on the delay in the vertical erosion of a sandstone threshold, in the context of a general Late Cenozoic dissection of the low «Sertaneja» surface (fig. 7). Therefore, in this case, but also in most other investigated scarps, hazards related to slope processes should never be neglected, although only small scale events were recorded in the last decades (Ribeiro, 2004; Bastos, 2012), and times of recurrence of larger events are probably much longer than the historic times (Peulvast & *alii*, 2011). This is precisely what makes them more dangerous.

CONCLUSION

Only a few of the scarps described here show strong structural control. Most of them, straight or sinuous, structurally controlled or not, are inherited landforms, initiated during the Cretaceous rifting (south of the Potiguar basin) or later. Other scarps, e.g. the rims of the Ibiapaba and Araripe plateaus, were formed more recently, as a result of a relief inversion process initiated in the Cenozoic and continued until the Present. Mass wasting deposits, dissected pediments and sparse debris fans visible at the base of many escarpments suggest recent erosive activity and local slope retreat, although most of them are decoupled from major valleys. Followed by shallow dissection and by erosive activity in the scarps, more episodic in crystalline basement than in sedimentary rocks, the Neogene clastic sedimentation on the piedmonts and on coastal areas probably reflect the occurrence of dry periods inducing widespread stripping of deep soil horizons and erosion of bare rock slopes and surfaces, even without tectonic forcing else than a long term trend to slow regional uplift. Dissection stages occurred in periods of more humid climate and/or low sea level. Except in the Araripe scarp, eroded into sub-horizontal sedimentary series, only slight or local backwearing of slopes occurred, associated with downwearing on pediments, probably in diachronic ways. The moderate volumes of Neogene clastic sediments imply overall low uplift and erosion rates during the Late Cenozoic, still to be more precisely quantified, and favorable to morphological and lithological resistance effects in the landscapes. However, slope instabilities are not uncommon, locally leading to well-characterized processes, landforms and deposits of gullying and mass wasting. Therefore, hazards related to slope processes should never be neglected, although only small-scale events were recorded in the last decades, and times of recurrence of larger events are probably much longer than the historic times.

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FIG. 7 - The Missão Velha waterfall, eastern Cariri depression. Exaggeration and retreat of the Araripe scarp (visible in the background) are related to late dissection of the low erosion surface. Here, this process is controlled by the outcrop level of resistant sandstone layers which form the outer skirt of the sedimentary Cariri depression (Mauriti Formation) and a local base level hardly deepened by the only fluvial outlet of the depression, *i.e.* the Rio Salgado. Photo: J.-P. Peulvast.

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