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Morphostratigraphic constraints and low temperature thermochronology: Lessons from a review of recent geological and geomorphological studies in northeast Brazil

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ABSTRACT

In the last decade, detailed geomorphological analyses of northeast Brazil led the authors to publish a model of landscape development in which long-term landform evolution was driven by regional swell-like uplift post-dating Early Cretaceous intracontinental rifting and the formation of the Atlantic passive margin in Aptian times. The post-Cenomanian uplift caused an inversion of Cretaceous basins and generated a landscape in which the most elevated landforms correspond either to resistant post-rift sedimentary cover, or to residuals of Cretaceous rift shoulders, above a low erosion surface. Since no evidence of a former post-Cenomanian sedimentary cover of significant thickness was found outside the coastal fringe, we could evaluate the uplift to 600 m at most and the mean erosion rates to 10 m/Ma or less. However, according to models based upon the results of thermochronological analyses (apatite fission tracks analysis-AFTA), two slices of 1000 m to 2500 m would have been deposited over the present pile in the south part of the study area, respectively in Campanian and Oligocene-Miocene times, before being totally removed. We examine here the diverging scenarios of geomorphic evolution respectively based upon morphostratigraphy (our model) and upon low temperature thermochronology, submitting them to available evidence provided by an updated and geographically extended review of geomorphological and sedimentological data, and trying to decipher some of the reasons that might lead to disputable geomorphic interpretations. We stress the fundamental importance of taking into account all the available results of geomorphological and geological approaches in any interpretation of thermochronological and other analytic methods used for reconstructing long-term landscape evolutions. This is one of the conditions for reinforcing the trust one can have in their results, which may bring complementary or unique information, peculiarly in places where sedimentary or volcanic markers are missing.

1. Introduction

Although covering a larger area, the present work is partly based upon some of our previous studies on landform evolution in the northern part of Northeast Brazil (e.g., Peulvast et al., 2008; Peulvast and Bétard, 2015a,b). This region is mainly organized along the Equatorial Atlantic continental margin and around the Cretaceous Cariri-Potiguar rift zone (Ceará State and surroundings). Its landforms were studied by the means of extensive fieldwork and morphostructural mapping (Peulvast and Claudino Sales, 2003) followed by morphostratigraphic analysis (Peulvast et al., 2009). There, as well as in the southern part of the extended study area (São Francisco River bend region, North Tucano-Jatobá basin), fieldwork and DEM studies were completed by an updated review of regional studies on sedimentary geology and long-term geomorphology.

In our scenario of geomorphic evolution proposed in the northern "Nordeste", landscape development was driven by regional swell-like uplift after the formation of the Atlantic passive margin in Aptian times (Peulvast et al., 2008). Limited post-Cenomanian uplift caused a shallow inversion of Cretaceous basins and generated a landscape in which the most elevated landforms (1000–1200 m a.s.l.) correspond either to resistant Mesozoic post-rift covers, or to residuals of syn-rift Cretaceous footwall uplands. Low Cenozoic denudation depths favored a re-exposition of Palaeozoic and Mesozoic land surfaces (i.e.

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exhumation of stratigraphic unconformities) and created a low planation surface below residual ridges and topographically inverted sedimentary basins. Crustal uplift and denudation reached 600 m at most and did not exceed mean rates of 10 m/Ma.

Obtained by morphostratigraphic methods (Peulvast et al., 2009), and completed by the use of morphopedological data, these results differ significantly from those of thermochronological studies (apatite fission tracks analysis-AFTA) reported for the Araripe basin (Morais Neto et al., 2005–2006), with derived estimates implying burial by a considerable thickness of sedimentary rocks followed by 1.5 km of post-rift denudation, i.e. two to three times as much as our maximum 0.6–0.7 km estimation. To the south (Reconcâvo-Tucano-Jatobá or RTJ basin), other publications based upon thermochronological results suggest that slices of 1000 m to 2500 m would have been deposited over the present pile and then totally eroded, at two different periods ("episodic burial and exhumation model": Japsen et al., 2012a,b; Green et al., 2018). However, the lack of remnants of post-Cenomanian sediments in the study area outside the Potiguar basin, and our previous study of the modalities and rhythms of geomorphic evolution suggest that no important younger sedimentary cover ever existed there. Therefore, either our morphostratigraphic results are wrong, or the published interpretations of thermochronological data are disputable and deserve to be discussed.

Our aim is neither to criticize the interest of thermochronological methods and techniques applied to relatively stable environments, nor to contest their primary results. We rather aim to explain the discrepancies between both types of scenarios in the light of our morphostratigraphic analysis and to discuss the arguments for diverging interpretations and evolution models. After a brief account of the geomorphological features in the study area, we present a summary of diverging versions of the geomorphic history, first those which are based upon morphostratigraphic constraints, and then the thermochronological and geophysical data that were used by some authors to elaborate an alternative model of regional geomorphic history, with much greater values of denudation depths and rates. Recently published data on stratigraphy and sedimentology in Mesozoic basins are used to complete our interpretations of such discrepancies. Discussing the opposite arguments and comparing both sets of results and interpretations lead us to consider that the past existence of thick post-Cenomanian sediments outside the RTJ rift and over the preserved remnants of Mesozoic post-rift cover should be questioned and that the most serious problems lie in the interpretation of thermochronological data in terms of geomorphic evolution.

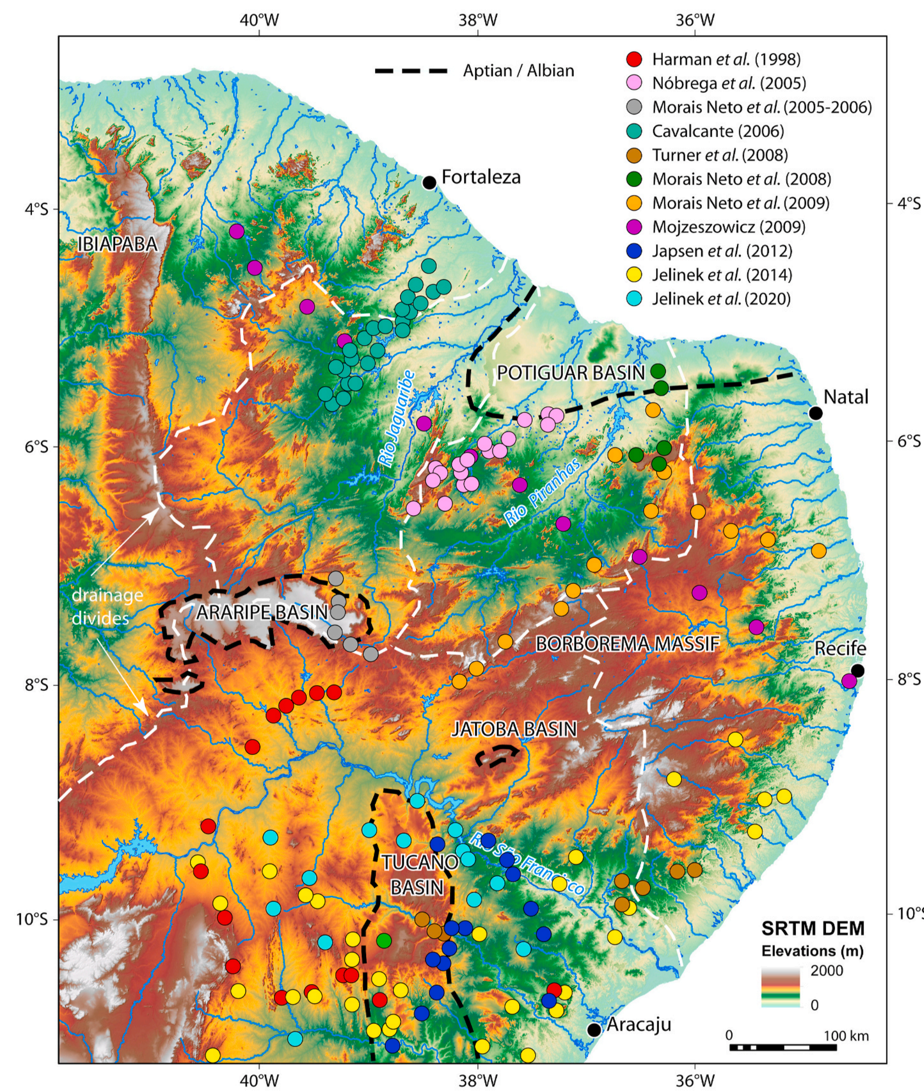


Fig. 1. Topography and drainage of the study area, and location of AFT samples from previous thermochronological studies (detailed AFT data and ages are provided as Supplementary Material). White dashed lines are the main water divides of present-day hydrographic basins.

2. The study area

2.1. Main topographic features

Comprised between 3° and 10° S, and 36 and 41° W, the study area forms the northern part of the Brazilian Northeast, or “Nordeste”, and mainly belongs to the structural Borborema Province (Almeida et al., 1981) (Fig. 1). To the north (Ceará and western parts of the Rio Grande do Norte and Paraiba States), a 400 km wide hemicycle with a roughly concentric pattern of highlands, corridors and low plains (Peulvast and Bétard, 2015b), is mainly drained by the Jaguaribe and Piranhas rivers and their tributaries. This Jaguaribe-Piranhas Hemicycle (JPH) is bounded to the west and the south by high plateaus, the Serra de Ibiapaba and the Chapada do Araripe (*ca* 1000 m a.s.l.) whereas it is intersected to the north by two offset EW alignments of mountain slopes forming a very discontinuous escarpment along the Equatorial Atlantic margin.

To the southeast and the east, the Borborema massif (1200 m a.s.l.) separates the JPH from the lower São Francisco depression (Pernambuco and northern Bahia States) and from the stepped plateaus and lowlands of the east coast (Pernambuco, Alagoas and Sergipe States: Monteiro and Corrêa, 2020). Here, the São Francisco River forms a large bend from NE to SE direction between the Araripe and northern Diamantina plateaus. It is deeply incised on its way to the South Atlantic Ocean through the low plateaus and ridges of a wide inland depression and more elevated tablelands and mesas corresponding to the Tucano-Jatobá basin (600–1000 m a.s.l.). The whole region climatically belongs to the semi-arid “Nordeste”, but the coastal strip and the inner mountains are characterized by more humid tropical climates, with more or less degraded forest environments.

2.2. Geological and morphostructural settings

Landforms more or less in conformity with the tectonic framework coexist with features of topographic inversion and drainage anomalies. The northern highlands, arranged in the half rings described by Peulvast et al. (2008), comprise parts of the Mesozoic Cariri-Potiguar rift basins (Araripe) as well as parts of their shoulders (Central Ceará highlands, Borborema). Interior lowlands also extend both on rift basins and faulted basement (Fig. 2). These discrepancies, also represented to the south (topographic inversion of the post-rift layers in the Jatobá and Tucano basins, epigeny of the São Francisco River through the Jatobá basin) reflect various types of structural controls and show interferences between tectonic and erosion histories (Peulvast and Bétard, 2015b).

To the north, the Ceará segment of the Brazilian Equatorial coastline is a passive continental margin formed by the transform opening of the Equatorial Atlantic in Aptian times (Matos, 2000). Onshore, the present structural pattern is organized around a discontinuous NE-SW set of

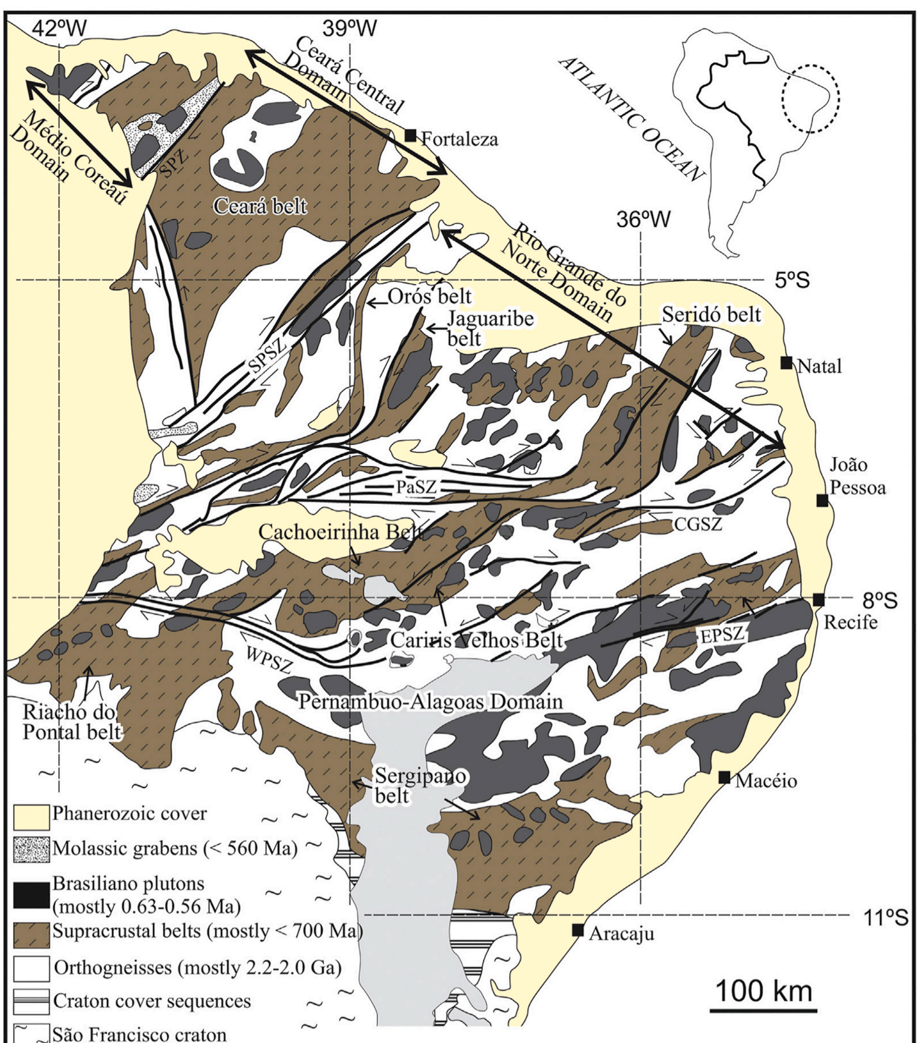


Fig. 2. Simplified geological map of the study area (from Neves, 2015). Abbreviations: SPZ: Sobral Shear Zone; SPSZ: Senador Pompeu SZ; PSZ: Portalegre SZ; PaSZ: Patos SZ; CGSZ: Campina Grande SZ; WPZZ: West Pernambuco SZ; EPSZ: East Pernambuco SZ.

basins and half grabens – the 500 km long intracratonic Cariri-Potiguar rift zone. Representing failed rift structures of Early Cretaceous age with remnants of their post-rift sedimentary cover (Araripe and Potiguar basins, at both extremities), it is intersected by the transform margin in the Potiguar Basin area (Matos, 1992). Along the coast, a thin dissected layer of Cenozoic continental and coastal sediments (the Barreiras Group) underlies the low-lying "tabuleiros" between the marginal escarpment and the shallow continental shelf.

To the south, the EW Pernambuco shear zone separates the Borborema province from its external or southern domain and from the São Francisco Craton. In this area, Early Cretaceous rifting occurred along the intracontinental Recôncavo-Tucano-Jatobá (RTJ) system of half grabens, before the final opening of the South Atlantic to the south and to the east. In spite of a 150 km wide hiatus between the Araripe and Jatobá basins, this ENE-WSW (Jatobá) to NS (Tucano-Recôncavo) aborted rift system appears as a southern continuation of the Cariri-Potiguar rift.

While transtensional conditions had become prevailing in the Equatorial Atlantic domain, the failed Cariri-Potiguar and RTJ rifts had already begun to evolve in post-rift conditions, through thermally induced subsidence (Mello, 1989). Until the Cenomanian or Campanian, and after a 20 My interval of erosion/non deposition, these rifts and the topographically depressed adjoining areas became locations of widespread sedimentation: first lacustrine or transitional continental/marine, finally continental in the Araripe and RTJ basins, or continental and then marine in the Potiguar basin.

The Late Cretaceous regional unconformity shows that widespread erosion of rift shoulders and syn-rift sediments had taken place soon after rifting or during its last stages, before ~114 Ma, followed by thermal subsidence and sedimentation in vast fluvial and lake systems beyond the limits of the syn-rift deposition, especially to the south of the Araripe basin (Socorró, Cedro and São José de Belmonte outliers; Assine, 1994; Hegarty et al., 2002; Valença et al., 2003). This southern area was probably connected with the RTJ basin, as shown by the consistency of the paleoflows to south and southeast in the Aptian Barbalha and Marizal Formations of these basins (Assine et al., 2016). However, in the Potiguar and Araripe basins, a few basement residual ridges and horsts locally controlled the post-rift sedimentation (Sousa et al., 2008; Peulvast and Bétard, 2015a). Later on, the southern half of the study area, including the Borborema plateau and the Araripe, Jatobá and north Tucano basins, underwent stronger uplift, topographic inversion and epigeny phenomena.

3. Morphostratigraphic constraints for the reconstruction of landscape evolution since Cretaceous rifting: an updated overview

3.1. The testimony of stepped landform patterns

Planation surfaces form valuable set of landmarks for reconstructing landscape evolution, analyzing tectonic deformations and evaluating denudation depths. Several planation surfaces are identified in the study area. Many of them are dissected or degraded, or lack dated sedimentary covers. Two main levels are identified (Fig. 3).

The highest surfaces are identified in the Araripe-Borborema region. They are preserved on basement massifs and on parts of the post-rift cover. Among them, a well dated surface, the Cenomanian fill- (and near-structural) surface and its beveled surroundings, incorporates at slightly different levels some elements of exhumed pre-Albian and Lower Paleozoic planation surfaces.

The lower level corresponds to the Sertaneja surface of the regional literature. North of the Patos fault zone, this planation surface is widely developed at low altitudes along the oceanic front and around Cretaceous grabens of the Cariri-Potiguar rift zone. It extends far inland along the main rivers (Jaguaribe plain), up to the Araripe basin. Deeply inset below remnants of high surfaces, it is clearly post-Cretaceous in age, but

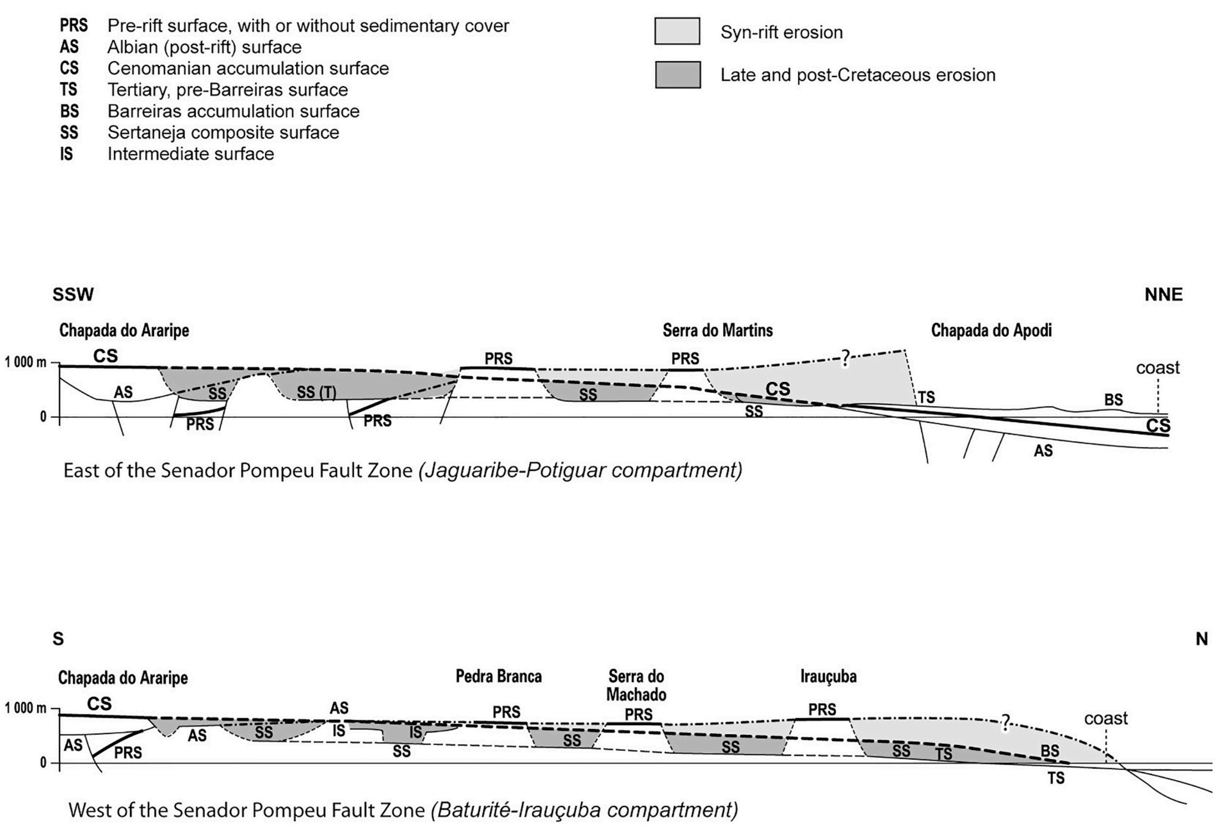


Fig. 3. Stepped planation surfaces in the northern part of the study area: synthetic profiles (from Peulvast et al., 2008).

it locally coincides with exhumed pre-Cretaceous land surfaces in its distal parts. Probably shaped and reworked during the Cenozoic until Late Tertiary or Pleistocene dissection, and widely developed before the deposition of the Barreiras sediments in its distal parts, it may be considered as resulting from cyclic development of a "young" surface below remnants of poorly dated high surfaces (Peulvast et al., 2008).

To the south of the Chapada do Araripe, a low surface bevels the crystalline rocks of the basement and small sedimentary basins (Cedro, São José do Belmonte). Dissected and disconnected from the present base level, this surface extends 150–200 m below the late Albian unconformity and planation surface, locally exhumed in the southern escarpment from the sandstone cap of the Chapada. It reflects the post-Cenomanian formation of a large erosion surface, accompanied by vigorous stripping of the sandstone cap and by the formation of wide embayments into the Araripe plateau (Fig. 4A). Narrow NE–SW residual ridges of metamorphic rocks continuing the Borborema plateau to the south west, and wider sedimentary plateaus (Tucano-Jatobá basins) are preserved above this surface, the only one identified on this side of the Chapada. Its altitudes (530–400 m a.s.l.) are slightly higher than in the inner parts of the northern Sertaneja surface.

No clear connection between both low surfaces has been ascertained because of the presence of a sedimentary depression and of basement ridges between the east end of the Chapada do Araripe and the Borborema plateau, separating the Salgado River catchment from short NS tributaries of the São Francisco River. However, we suggest that the low plateaus that extend around the São Francisco bend and lower valley – including the transfer zone between the Tucano and Jatobá basins, where the river incised a deep canyon on its way to the South Atlantic Ocean – represent the same erosion level (Fig. 4B), developed on the south side of the topographic and drainage divide that links the Araripe and Borborema plateaus (Fig. 1). Both surfaces present altitudes of ~400–450 m close to the foot of these main highlands and bear residual mesas and ridges of sedimentary (post-rift sediments capped by remnants of Exu sandstones in Araripe outliers and the Jatobá basin) or igneous and metamorphic nature (basement areas).

3.2. Stratigraphic and palaeogeographic data

Some of the best clues on uplift and erosion patterns are given by the post-rift series preserved in Mesozoic basins close to the coast (Potiguar basin) and in the hinterland. In the center of the study area, the consistency of altitudes and stratigraphy between the Araripe and Tucano-Jatobá basins – where the post-rift cover remnants presently culminate above 900 m a.s.l. – gives indications on the conditions of sedimentation, uplift and geomorphic evolution west and southwest of the Borborema plateau. Although they now occur in the currently most elevated part of the study area, these basins lay at a palaeoelevation close to palaeosea level in Albian times.

To the north, the post-rift sediments of the Potiguar basin form the low-lying Chapada do Apodi (80–150 m a.s.l.). The onshore Potiguar basin is filled with a thick transgressive sequence whose lower layers, the 400–800 m thick Açu sandstones (Albian-Cenomanian) rest unconformably on syn-rift or transitional deposits and incompletely beveled basement highs and rift shoulders (see details and references in Peulvast and Bétard, 2015b). Upwards, these fluvial to estuarine sandstones are conformably covered by thick (up to 400 m) bioclastic calcarenites and calcilutites deposited in coastal and shallow marine environments from Turonian to Early Campanian (Jandaira Formation, 90-80 Ma). Their presence shows a decrease of the terrigenous input, as erosion on basement topography became limited to chemical weathering and removal of solutes, in a context of high sea levels and warm, humid climates (Haq et al., 1987; Arai, 2000; Miller et al., 2005; Huber et al., 2002). Apart from a few upstanding residual massifs, the landscape towards the end of this period was predominantly flat and low-lying.

In the Araripe basin, as well as in the Potiguar and RTJ basins (Magnavita et al., 1994), the pre-Late Aptian regional unconformity (a hiatus of *ca* 20 My) shows that widespread erosion of rift shoulders and syn-rift sediments had taken place soon after rifting or during its last

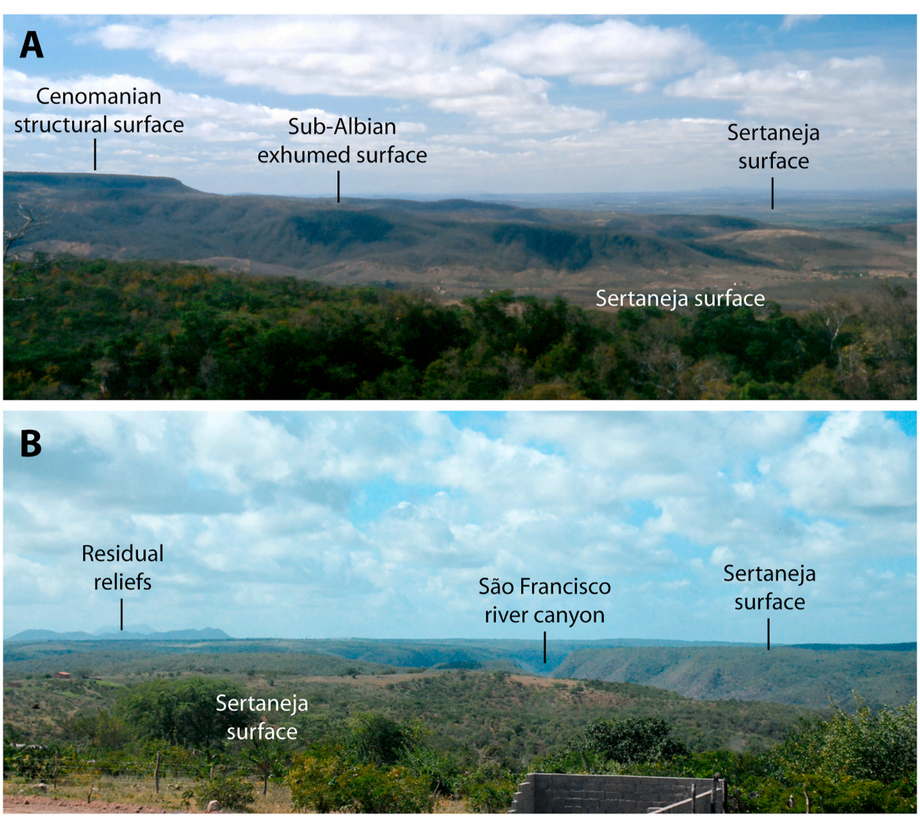
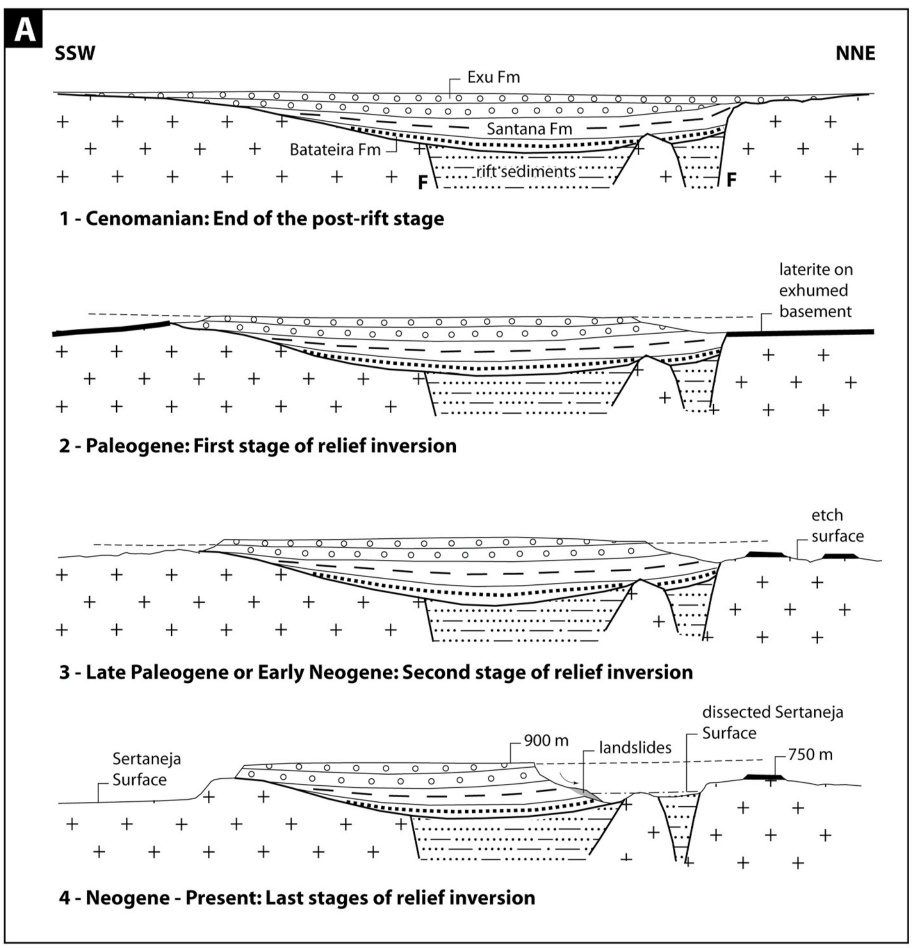


Fig. 4. Sertaneja and older surfaces south of the Chapada do Araripe and around the lower São Francisco valley. A: South rim of the Chapada do Araripe, east of Exu, looking west: the Cenomanian Exu sandstone overlooks a narrow and dissected granite step above the Sertaneja depression, eroded into the uplifted basement (foreground). This picture shows three of the surfaces described in the text, grouped in two main topographic levels. The Cenomanian structural surface, and the Albian surface on which the thin sandstone layer was deposited, belong to the highest level, whereas the Sertaneja surface is part of the lowest. B: The lower São Francisco valley downstream of the Xingo dam, inset in the Sertaneja surface developed on the basement near Piranhas (Alagoas); presence of residual ridges in the distance. Photos: J.P. Peulvast.

stages, before ~114 Ma (Fig. 5A). This phase was followed by thermal subsidence which allowed deposition of sediments in vast lake systems beyond the limits of the syn-rift deposition, especially to the south of the Araripe basin (Socorro, Cedro and São José de Belmonte outliers; Assine, 1994; Hegarty et al., 2002; Valença et al., 2003). During Albian to Cenomanian times, the basin was a landscape of lakes and lagoons surrounded by low hills, intermittently connected via shallow seaways to the Tucano–Jatobá basin (Petri, 1987; Assine et al., 2016).

The post-rift Araripe basin first formed in the northeast, where the Albian-Cenomanian series are more complete, and then extended to the south and the west, progressively lapping onto the basement. 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 are divided into several formations or members (Fig. 5B): the Barbalha, Crato, Ipubi and Romualdo Formations (Late Aptian-Early Albian), overlain by a mid-Cretaceous Araripe Group (Araripina and Exu Formations) according to Assine et al. (2014), or the Rio da Batateira and Santana Formations, the last one with the Crato, Ipubi and Romualdo members (Coimbra and Freire, 2021). According to recent works (Nascimento et al., 2016; Custódio et al., 2017; Varejão et al., 2021), well defined marine ingressions from the SSE, reaching the western extremity of the basin, occurred during the deposition of the Crato and Romualdo Formations or Members, in alternation with episodes of sedimentation in freshwater to hypersaline water bodies, under seasonal variations of water levels (carbonate successions of the Crato Formation, evaporates of the Ipubi Formation) (Fig. 6). The overlying clay-rich sandstone is the last deposit relevant to lacustrine to marine phases of sedimentation. It corresponds to the Arajara Formation (Ponte and Appi, 1990) or the terminal sequence of the Santana Formation (Assine, 2007).

The alluvial sediments of the 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), a slight erosional unconformity between the upper unit (Exu Formation, Late Albian-Cenomanian) and the lower one, restricted to the western part of the basin (Araripina Formation, middle Albian), suggests moderate syn-sedimentary deformation. Conglomerates to fine-grained sandstones displaying graded bedding occur in the western (distal) part of



B Ponte & Appi (1990)			Assine (2007)			Assine et al. (2014)		Sequence
Araripe Group	Exu Formation		Araripe Group	Exu Formation		Araripe Group	Exu Formation	Post-rift II
	Arajara Formation			Araripina Formation			Araripina Formation	
	Santana Formation	Romualdo Member		Santana Formation	Romualdo Member	Santana Group	Romualdo Formation	Post-rift I
		Ipubi Member			Ipubi Layers		Ipubi Formation	
		Crato Member			Crato Member		Crato Formation	
	Rio da Batateira Formation			Barbalha Formation			Barbalha Formation	

Fig. 5. Evolution of the Araripe basin. A: Morphostructural evolution of the Araripe basin (from Peulvast and Bétard, 2015a). B: Comparison among the most frequently used names for the lithostratigraphic units of the Post-rift Sequence of the Araripe Basin. From Coimbra and Freire, 2021.

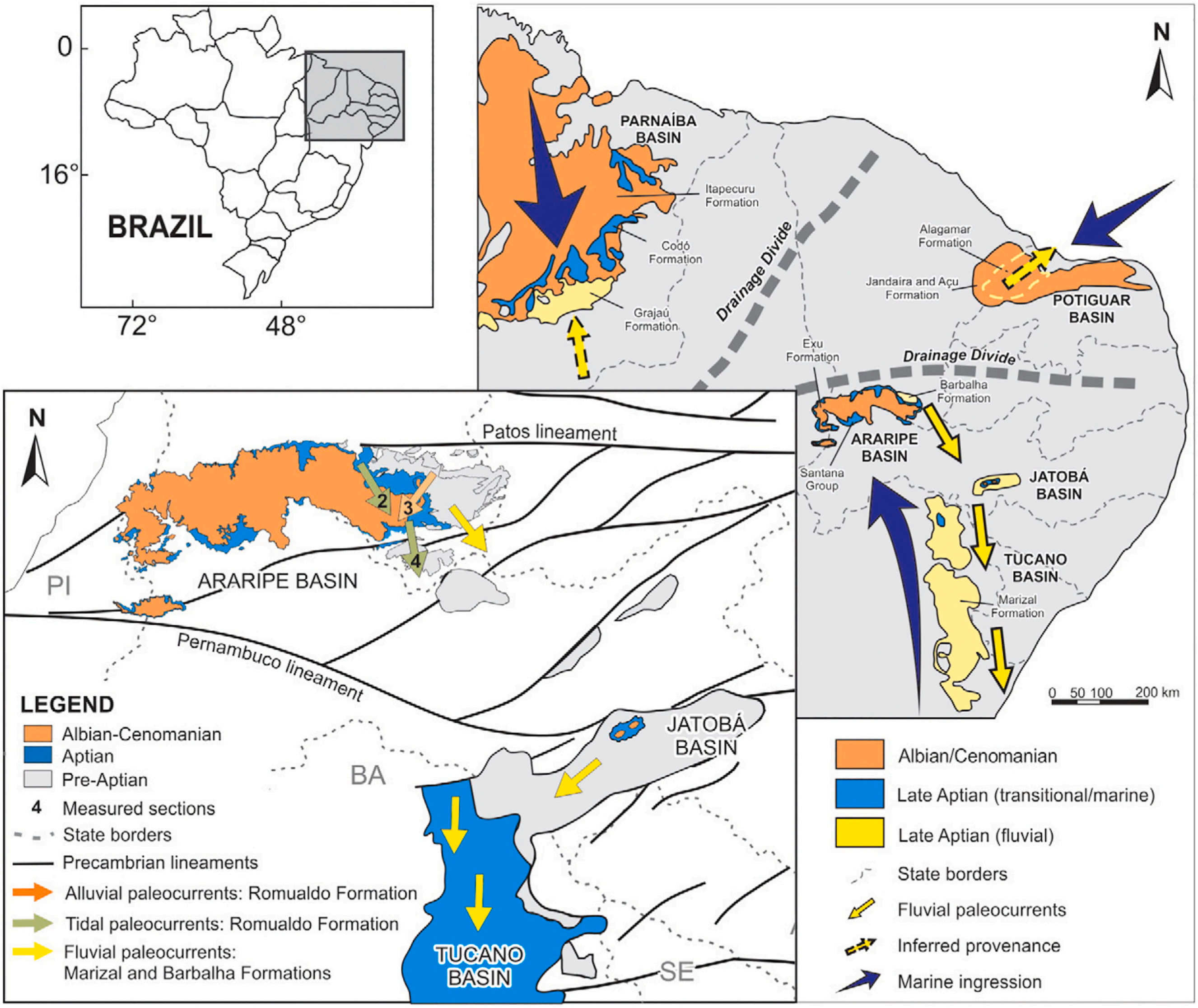


Fig. 6. Palaeogeographical map of northeastern Brazil during Aptian times (from Custódio et al., 2017).

the basin, where argillaceous layers indicate a floodplain environment (Assine, 2007). 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, with a rapid westward progradation through low-relief topography of a braid-plain dominated by flashy flow regimes in a dry palaeoclimate (Martill, 1993).

3.3. Geomorphic history and morphostratigraphic constraints: evidence from inner Cretaceous basins

Outside the Araripe basin, outliers of lacustrine limestone, similar to those of the Crato Member, exist in the Jatobá and northern Tucano basins, indicating a continuation of the lake systems to the south of the Pernambuco lineament and a common post-rift history. Outliers containing the whole post-rift sequence are located in the Socorro basin (Serra Vermelha) and the narrow Serra Negra-Serra do Periquito buttes (northern border of the Jatobá basin), at similar altitudes, 400 m above the surrounding basement surface (Fig. 7). In the northern Tucano basin, the upper part of the post-rift series is mainly found in the 130 km^2 mesa called Serra do Tonã, which is 100 m higher than its surroundings. However, in this last case, over the Marizal Formation (fluvial sandstones, shales and thin intervals of interbedded shales and limestone, equivalent to the Barbalha Formation in the Araripe basin), the upper part of the sequence is limited to laminated limestones which correspond to the Crato Formation, with fluvial paleocurrent directions suggesting that both basins were part of the same continental paleodrainage, flowing to the south (Varejão et al., 2016).

While the 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 and Jatobá basins was continental. In the Araripina and Exu formations, paleoflow directions suggest transport to the west (Assine, 2007). The source area is the Borborema region whose uplift, more intense to the east, has begun as soon as the middle Albian (Assine, 1994). Subsidence in the Araripe basin ended after deposition of the Exu sediments. Analyses of organic matter maturation in the Albian sediments suggest that no significant overburden was ever removed by erosion from the exposed upper surface of the Exu caprock (Baudin and Berthou, 1996; Arai, 2000), thus forming an almost uneroded topographic surface for the last 90 Ma.

To the north, it is indisputable that the Sertaneja plain developed in post-Cenomanian times by erosion of the seaward flank of a broad crustal upwarp that inverted the Araripe and other Cretaceous basins. The drainage made inroads into the hinterland through older Cretaceous half-grabens and Brasiliano shear zones (Peulvast et al., 2008, Fig. 8).

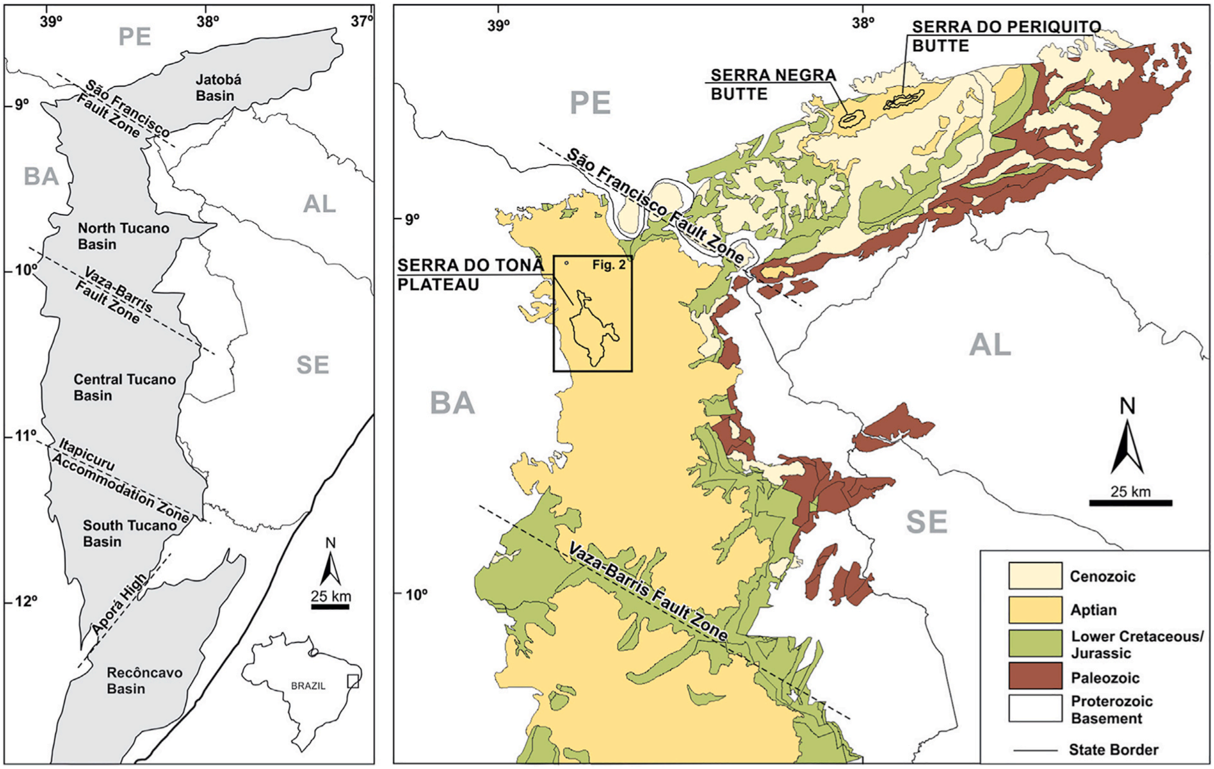


Fig. 7. Post-rift sediments in the northern Tucano and Jatobá basins (from Varejão et al., 2016).

To the south, the corresponding low surface developed on the other side of the same upwarp and of its continuation along the South Atlantic margin through the Tucano basin, towards the Diamantina plateaus (Fig. 1). Here, drainage and planation made their way to the "tabuleiros" and the ocean around the São Francisco River, between the inverted remnants of the post-rift cover (Araripe, Jatobá and Tucano basins) and the Borborema plateau, crossing the Tucano-Jatobá basin through a complex fracture zone (Fig. 2). This development was followed by the entrenchment of the São Francisco River in a narrow canyon during or after uplift and tilting of the margin. Probably involving an epigeny, this process remains to be explained (Potter, 1997). We suggest that it might correspond either to the capture of a former endoreic or northward flowing system in the mid-São Francisco basin (where the Late Cretaceous Urucuia Formation and the Plio-Pleistocene deposits are represented by eolian sands and sandstones according to Silva et al., 2003) or to retreat of the head of a river flowing oceanward to the southeast, a process which is observed to the north, on watersheds of the eastern escarpment of the Borborema highlands (Monteiro and Corrêa, 2020). Such an event would be obviously post-Cretaceous in age, and is suggested to have occurred in the Eocene, according to maps published by Macgregor (2013).

3.4. *Uplift, denudation depths and morphogenetic reconstruction*

To the north, in the Potiguar basin, the base of the Jandaira limestone (92 Ma) currently occurs between −500 m at the coastline near Tibau, and 60–120 m a.s.l. on the edge of the Chapada do Apodi. According to available curves, sea-level was at +140 or +80 m in early Turonian times (Haq et al., 1987; Miller et al., 2005); therefore, the deformation of this limestone layer records a post-Turonian subsidence of ~600 m at the coastline and 20 m at the landward periphery of the basin (or a slight uplift according to the curve by Miller et al., 2005).

In the remote hinterland, the current elevation of marine Albian layers up to 700 m above present sea level (Baudin and Berthou, 1996; Neumann, 1999), indicates that the Araripe basin was vigorously uplifted. Assuming that sea-level rose from +150 to +220 m in Albian times (Haq et al., 1987), this suggests a minimal post-Albian crustal uplift of 500–600 m, which is comparable to values proposed by Magnavita et al. (1994) in the Recôncavo–Tucano–Jatobá area. Because erosion has never been demonstrated to have significantly affected the bulk of the Exu sandstone caprock, except along a few hanging dry valleys (Baudin and Berthou, 1996; Arai, 1999; Peulvast and Bétard, 2015b), the ~600 m of post-Albian crustal uplift in the area now forming the continental divide ca. 300 km from the coast is also considered to be an estimate of long-term surface uplift of this part of the Brazilian shield. Maximum post-rift denudation depths are provided by the maximum value of topographic inversion observed along the eastern Chapada do Araripe, i.e. ~600 m near the cities of Crato and Porteiras. The corresponding mean erosion rate (7–10 m/Ma) is similar to that of vertical movements.

In the northern part of the study area, we have previously established a good correspondence between the volumes of the offshore sediments and the post-Cenomanian denudation depths integrated across the Jaguaribe–Piranhas embayment, from the 600 m Araripe maximum to 0 m at the coastline (Fig. 9; see details in Peulvast et al., 2008). Erosion rates <10 m/Ma have also been deduced from mean thickness of the late Miocene and younger Barreiras and Tibau sediments deposited in the Potiguar basin and along the coastal strip. Such moderate values, similar to that obtained on the whole post-Cenomanian epoch, do not imply any Neogene acceleration of uplift and erosion (Peulvast and Bétard, 2013).

3.5. *Geomorphic history at regional scale*

During the Cenozoic, the regional landscape formed in response to moderate crustal uplift, in a context of an episodically fluctuating but continuously falling base level (Peulvast et al., 2008; Peulvast and Bétard, 2015b). After formation of the transform passive margin in Aptian times, the crustal uplift caused an inversion of the Cretaceous basins by differential erosion. Denudation in the last 90 My exhumed a number of Mesozoic palaeosurfaces at low elevations, including a

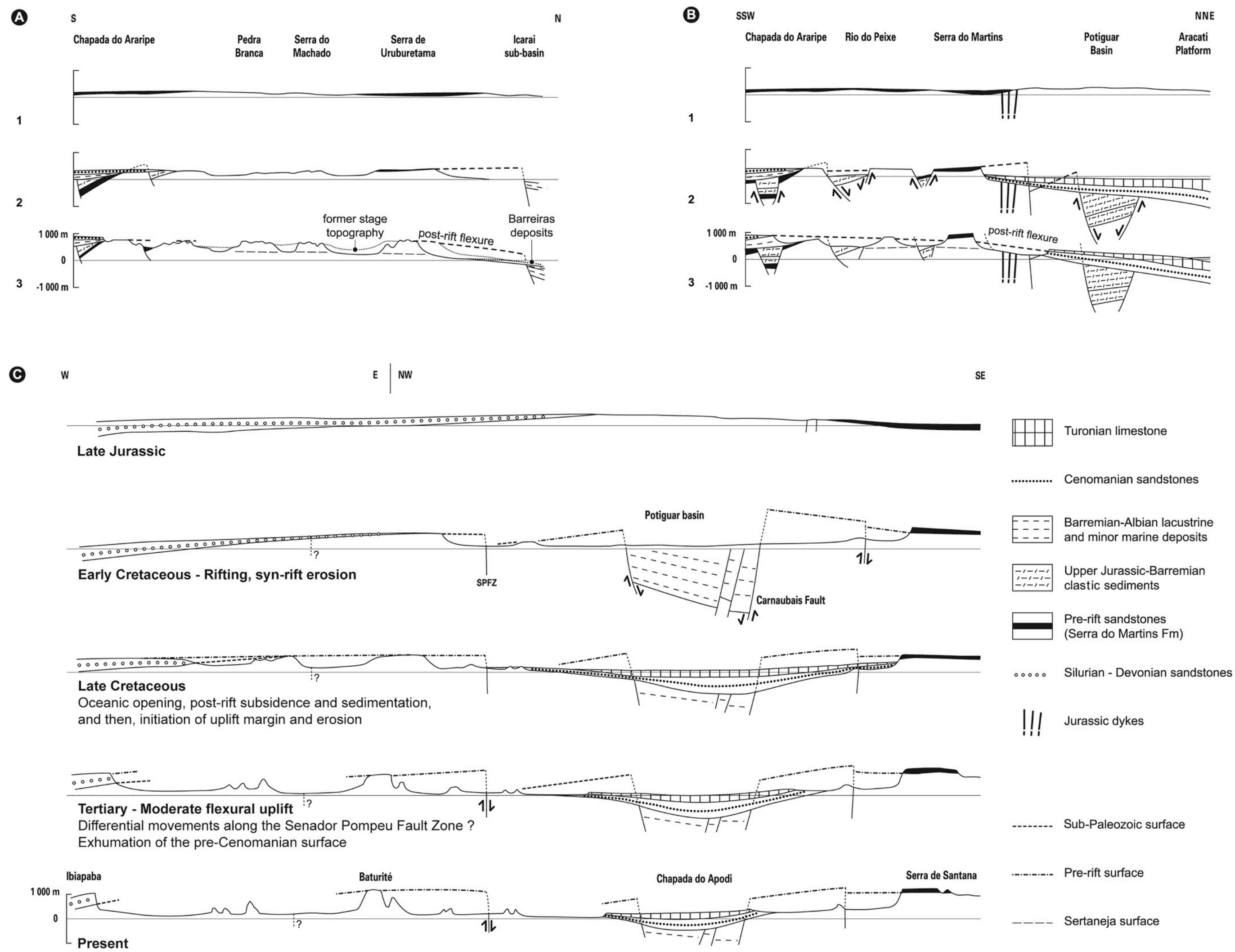


Fig. 8. Reconstruction of the morphotectonic evolution of the northern Brazilian "Nordeste" since pre-rift times (profiles from Peulvast et al., 2008).

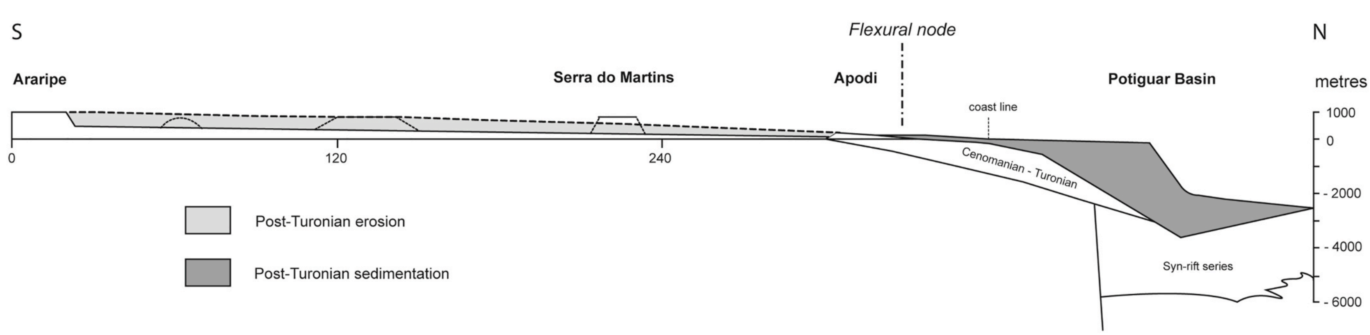


Fig. 9. Uplift, denudation and sedimentation along the Equatorial margin of northeast Brazil (profile from Peulvast et al., 2008).

palaeopiedmont of Cretaceous age at the northern tip of the Serra do Martins (Peulvast and Claudino Sales, 2004).

The stages of post-Cretaceous uplift and erosion remain less well constrained by stratigraphy than the earlier evolution, due to a ~50 My or more hiatus in onshore sedimentation between the Campanian and the Neogene. Post-Cenomanian basin inversion involved maximum surface uplift in the Chapada do Araripe area, with magnitudes steadily declining towards the coastline. The sedimentary record of denudation for that period is contained in offshore deposits and in the coastal belt of Barreiras sediments, suggesting a definitive shift of depocentres to the new Atlantic margin and a steadily buoyant and eroding hinterland (Peulvast et al., 2008).

The cause and exact timing of post-Cenomanian crustal upwarping are poorly constrained. It could perhaps have been a flexural response of the low-rigidity lithosphere to sediment loads on the margin, and thus a slowly ongoing process since the late Cretaceous. Lithospheric thinning (down to 60 km under the Borborema dome) is mentioned by Klöcking et al. (2020), who explain the Cenozoic uplift by the emplacement of warm asthenosphere beneath the plate combined with thermomechanical erosion. Uplift could instead be the consequence of a more discrete dynamic event related either to Oligocene magmatism in the region, or to continental-scale far-field stresses determined by Andean convergence, although a Neogene acceleration of uplift and denudation is not clearly recorded or may be the result of a transition from a tropical to a semi-arid climate (Peulvast et al., 2008; Jelinek et al., 2014). To the south, in the Tucano-Jatobá basin and around, the main lines of the geomorphic history seem to be roughly similar (Magnavita et al., 1994; Jelinek et al., 2014), although the relationship with the specific evolution of the São Francisco drainage basin and of the eastern margin would justify a more detailed study.

4. Geomorphic history derived from thermochronological and geophysical data and models

For a few decades, low temperature thermochronology, especially by apatite fission track (AFT) analysis, has been used to provide constraints on erosion rates and to help reconstructing long-term landscape development (e.g., Gallagher et al., 1994; Gunnell et al., 2003). In the study area, Harman et al. (1998) identified an increase in average denudation rates occurring at 60–80 Ma over much of this region and tentatively explained it by a drop in base level and the generation of local relief along the recently formed rift margin. In a more recent review of AFT ages measured along the eastern Brazilian margin, Engelmann de Oliveira and Jelinek (2017) determined that the occurrence and distribution of "young" AFT ages along the margin of the Borborema Province show a correlation with the Cretaceous thermotectonic event related to the opening of the South Atlantic Ocean. The uplift should have been caused by thermal imbalance, magmatism, and tectonic reactivations forming onshore basins.

Other data obtained along transects through the Borborema plateau and in the eastern Borborema Province (Morais Neto et al., 2000; Mojzeszowicz, 2009; Morais Neto and Vasconcelos, 2010, Fig. 1) are consistent with mid or late Cretaceous cooling beginning around 100 Ma as a result of regional uplift along the Brazilian Atlantic margin and subsequent erosion. Combined with $^{40}Ar/^{39}Ar$ dating of amphiboles, biotite, muscovite and K-feldspar, and thermal modeling of argon diffusion in feldspar, low temperature thermochronology (AFT and U-Th/He on apatites) indicates that post-rift exhumation to shallow crustal levels (<3 km) occurred from 100 to 90 Ma on. Younger fission track ages (~75-50 Ma) correspond to an increase of denudation during the Late Cretaceous/Early Paleocene transition. According to the same authors (Morais Neto and Vasconcelos, 2010), any later uplift (Miocene) must have been minor. AFT studies also indicate two cooling events related to uplift and up to 3–4 km of erosion east of the reactivated Precambrian Portalegre Shear Zone (PSZ), south of the Potiguar basin (Fig. 1). The intervening heating event was recorded between 140 and 45 Ma on the block west of the PSZ and 55 and 15 Ma on the block to the east, and is believed to reflect burial in the first case and Oligocene ('Macau') volcanism in the second (Nóbrega et al., 2005). A similar study along the Senador Pompeu Shear Zone (SPSZ), in central Ceará, indicates two main cooling events, related to regional uplift, entre 130 and 90 Ma, and from 30 Ma (Cavalcante, 2006).

In the Araripe basin, according to interpretations of thermochronological results, a slice of 1000 m or more would have existed over the present pile (Morais Neto et al., 2005–2006; Japsen et al., 2012b), before being totally removed (Fig. 10). The AFT-derived estimates reported by Morais Neto et al. (2005–2006) from Palaeozoic and Jurassic sandstones of the Araripe basin would indicate palaeotemperatures of 70–85 °C during the Cenozoic, implying 1.5 km of post-rift denudation.

In the north Tucano basin, modeling from a flexural cantilever model on a transverse profile (Magnavita et al., 1994) suggests that post-rift thermal subsidence has taken place after a period of erosion at the end of rifting (Aptian), until the end of the Oligocene, producing ~650 m of normally compacted post-rift sediments. Later on, the basin and surroundings were uplifted by 600 m and then eroded down to 550 m a.s.l. (the present-day altitude of the Tucano basin), with preservation of a relatively thin veneer (400 m) of post-rift sediments and a slight onlap of the footwall. In this geophysical model, within the basin, maximum erosion reaches 1.5 km adjacent to the main boundary fault (west side), consistent with vitrinite reflectance data in the Reconcâvo basin. Most of this erosion would have taken place at the end of rifting, before post-rift subsidence and sedimentation. In this study, the Jatobá and north Tucano basin are suggested to have shared the evolution of the Araripe basin, with uplift of marine Albian sediments up to 800 m, accounting for 600 m of post-Albian crustal uplift due to flexural uplift and Oligocene magmatic underplating.

According to more recent studies by Japsen et al. (2012a) and Green et al. (2018), prior to the Campanian, the present land surface in the RTJ rift would have been buried below a 2–3-km-thick rock column across both the rift and the interior highlands, which would have included a continuous Cretaceous cover. The interpretation from AFTA for Campanian exhumation in both the rift and the highlands suggests that sediments accumulated over both regions prior to the onset of exhumation. In this model, the present landscape would be due to multiple post-rift episodes of burial, uplift, and exhumation (Fig. 11):

(1) Following Early Cretaceous breakup, a kilometer-scale burial of the margin beneath a sedimentary cover, with maximum burial of the syn-rift sequence in the Campanian;
(2) Campanian and Eocene phases of uplift leading to almost complete removal of these deposits by river erosion to base level and to formation of a peneplain (the higher surface) with a deeply weathered surface;

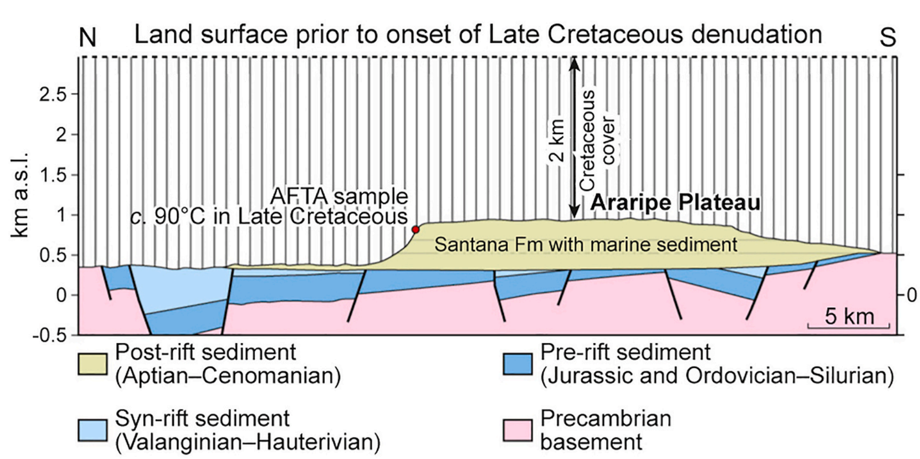


Fig. 10. The sedimentary pile over the Araripe basin according to Japsen et al. (2014) and Green et al. (2018).

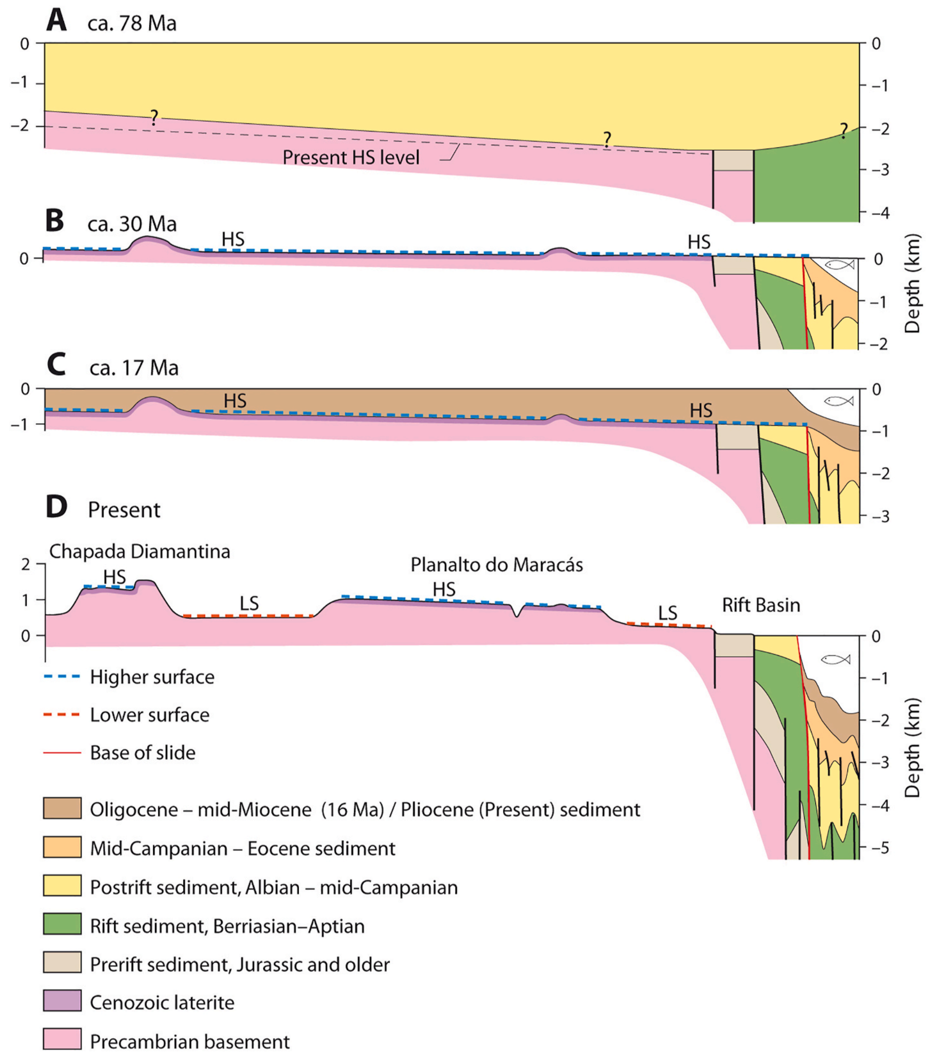


Fig. 11. Episodic burial and exhumation in northeast Brazil, according to Japsen et al. (2012a).

(3) Oligocene–Miocene subsidence of the interior and of the coastal zone leading to reburial of the higher surface;
(4) Miocene uplift and erosion, producing a new peneplain (the lower surface) by river incision below the uplifted and re-exposed higher surface. Minor uplift in the Quaternary would have led to incision below the lower surface and to formation of the coastal plain.

According to the authors, a small outlier of marine shales (Sabiá Formation) found on the eastern margin of the Recôncavo basin would testify to regional Miocene burial. However, no remnants of such a cover have been reported from the surrounding plateaus, where only sparse outcrops of thin non fossiliferous, continental sediments are found far to the north, outside the basin, e.g., the Serra do Martins Formation (Morais Neto et al., 2008), around the Borborema plateau. A post–30 Ma reburial of the Planalto da Borborema is reported as indicated by AFTA data from the Serra do Martins Formation and the underlying basement (Morais Neto et al., 2008, 2009). Reburial of the higher surface by an Oligocene–Miocene cover is also suggested to provide a straightforward explanation for a gap in weathering records between 30 and 15 Ma, prior to the removal of this cover during the Miocene uplift event. The presence of an extensive Cretaceous cover prior to Campanian uplift and exhumation might similarly explain the lack of pre–70 Ma weathering ages.

5. Discussion

5.1. *Reinterpreting the thermochronological data from the morphostratigraphic constraints*

5.1.1. *RTJ rift and basin*

The discussion mainly bears on the "episodic burial and exhumation model", which was first elaborated for the volcanic margin of West and southern East Greenland (Bonow et al., 2006; Japsen et al., 2010) and extended by Japsen et al. (2012b) to part of the northeast Brazil, as it is now on many other passive continental margins (Green et al., 2018). According to the authors, AFTA, VT (vitrinite reflectance) and sonic data from several wells in the Reconcâvo basin and on the Bahia margin show that the cover reached thicknesses of 2–3 km. The AFTA data from the wells give constraints on the timing. The authors also assume that AFTA data from outcrop samples across NE Brazil, including the Chapada Diamantina and surroundings (Bahia State), all show that the present-day basement areas were also buried below a thick rock column in the Campanian. A substantial part of the column would correspond to post-rift sediments as the 3-km column within the rift would have extended beyond the rift. Other AFT studies also show major mid to late Cretaceous cooling (Harman et al., 1998; Turner et al., 2008; Morais Neto et al., 2008, 2009). For example, Harman et al. (1998) estimated a cooling in the interior of their study area of 50–70 °C since 80 Ma.

Indeed, the data used in Japsen et al.'s work correspond to 4 wells located in the Reconcâvo rift, offshore or close to the sea (except one which is located more than 200 km east of the Chapada Diamantina). What happened here, with estimated burial depths strongly dependent of the inferred history of geothermal and on cross calibrations for the interpretation of sonic log data, cannot be fully extrapolated for areas located up to 400 km from the coast, even taking into account older works based on AFTA data. These data (e.g. Harman et al., 1998) do not fit with values of eroded basement or post-rift cover rocks obtained from morphostratigraphic works on other regions of NE Brazil (Chapada do Araripe) and even exceed by 1000 m at least values given by Morais Neto, who "only" found 1500 m of former burial in the Araripe basin.

Therefore, it would seem reasonable to take into account a flexural post-rift subsidence which would not have affected a very wide zone around the RTJ, as suggested by Magnavita et al. (1994), and as happened in the Potiguar basin (Peulvast et al., 2008). Such a geographically limited subsidence would not imply deep burial of remote basement areas in the Chapada Diamantina and Maracas regions. In our opinion, the high surfaces identified in the region rather were mainly formed during the post-rift stage in relation with base-levels offered by moderately thick post-rift covers deposited in the nearby post-rift subsidence areas – up to 600–700 m or slightly more -, as evidenced in the Ceará state and in the Araripe region, or even locally correspond to exhumed older surfaces (Peulvast et al., 2008). The Late-Cretaceous cooling inferred from AFT data probably corresponds to erosion induced by incipient basin inversion and uplift of the onshore regions of the margin (Borborema plateau).

5.1.2. Araripe basin: no geological evidence for post-Exu burial

In the Araripe basin, a previous discussion of the results of AFT analyses (Peulvast and Bétard, 2015a and b) led us to consider the hypothesis of post-Cenomanian deposition incompatible 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 at end of 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.

Morais Neto et al. (2005–2006) indicate maximum heating to 93 °C after the deposition of the Batateira or Barbalha 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 later burial). The pre-Exu evolution must be taken into consideration in order to understand the significance of these thermochronological data obtained on samples taken at various altitudes, in various layers. The Exu sandstone rests unconformably over the older formations, including basement highs, to the south and close to Crato. 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 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 (with caution) as reflecting a denudation of 1.5 km of sediments. However, as shown by increasingly numerous recognized discrepancies between AFTA results and morphostratigraphic evidence (French Massif Central: Ricordel-Prognon et al., 2010; NW England, SW Scotland: Luszczak et al., 2014; central West Greenland: Jess et al., 2019; central Finland: Hall et al., 2020) and discussed in various publications (Gunnell, 2003; Peulvast et al., 2008, 2009; Wildman et al., 2014; Jess et al., 2019), these results seem to remain in the uncertainty domain of the method. They may also reflect spatial and temporal changes in the paleogeothermal gradients. These are crucial factors for the calculation of exhumation or denudation values and rates, but generally remain unknown. This is the case in the Eocene to Miocene epoch, which is also the time of magmatism in surrounding regions (mainly the north and northeast of the Borborema plateau, which until now record the highest internal levels of thermal flux; Carneiro et al., 1989; Oliveira and Medeiros, 2012). The mean paleogeothermal gradients retained in most published studies correspond to the present-day gradient (Japsen et al., 2012a, b) but vary in other studies on the continental margin between 18 and 30 °C/km, with surface temperatures of 25 °C (Jelinek et al., 2014).

According to sedimentological studies of the Ipubi Formation, in the Araripe basin (Nascimento et al., 2016), only past burial of the Ipubi Formation below a few hundred meters of sediments at most may be admitted. The pervasive presence of fibrous anhydrite formed at the expense of gypsum in these evaporitic sediments, is considered as evidence for mesodiagenesis, yet maintaining the original crystalline shape of gypsum. This occurrence was mentioned by Silva (1988), who called it "sparse laths of anhydrite" among the gypsum. According to the author, the formation of fibrous anhydrite was incipient because the burial would have reached a mere 350–380 m, under pressures that still allow existence of primary (depositional) gypsum, with no sign of transformation. Murray (1964) and Silva (1988) affirm that at least 900 m of burial would be necessary to transform the whole primary gypsum into anhydrite. Since 250–350 m of the overlying strata (Romualdo, Arajara or Araripina, Exu Formations) outcrop in the preserved remnants of the post-rift cover, it appears that at most 100–200 m of the last deposits were eroded, in relation with degradation and weathering processes of the near-structural surface of Exu sandstone.

Moreover, X-ray diffraction analysis of clay minerals in pyrobitumen shale samples taken in five gypsum mines in the Araripe basin (Souza Neto et al., 2013a) reveals expansive and interlayered clays with illite/smectite (I/S) values ranging from between 10 and 30% of illite layers. Recent models indicate that "Smectite illitization occurs very early … at shallow burial depth …" (Lanson et al., 2009). The presence of I/S interlayered clays might also be interpreted as a result of intercalation of smectite with clastic clay minerals (Souza Neto et al., 2013b), which would also indicate shallow burying and long-lasting conditions of low temperatures.

Such contradictory interpretations lead us to favor those given by Arai (2000) and Baudin and Berthou (1996), according to whom the sands and conglomerates of the Exu Formation which fill the depression mark the end of the sedimentary history in the Araripe basin.

5.2. Palaeosurfaces, weathering signatures and associated soil covers

Most surfaces lack well dated superficial deposits or weathering crusts, the formation of which is considered as corresponding to periods of surface exposition which must be taken into account in reconstructing possible "episodic burial and exhumation" scenarios (Ricordel-Prognon et al., 2010). Indeed, remnants of old lateritic crusts are recognized in a few areas, on small mesas capped by the Serra do Martins sandstones, on the Serra do Pereiro (Peulvast and Claudino Sales, 2004; Bétard, 2007; Gurgel et al., 2013), on the Chapada do Apodi (Ponta Grossa-Peroba sea cliffs), on palaeosurfaces of the Campos Sales-Araripe area (Bétard et al., 2005), and on parts of the south piedmont of the Chapada do Araripe (Fig. 5). Based on a systematic study of weathering profiles in Northeast Brazil combining $^{40}Ar/^{39}Ar$ and U-Th/He dating of supergene minerals, Lima (2008) obtained radiometric ages ranging from 43.2 ± 4.3 Ma to 0.8 ± 0.1 Ma, indicating that weathering processes last from the Eocene to the Pleistocene. These data suggest a long-lasting exposition of these areas to surface conditions, excluding any recent (i.e. Oligocene-Miocene) burial below a now vanished sedimentary cover.

The first cited occurrence corresponds to remnants of a high structural surface (650–700 m), the others are recognized at lower altitude on various tabular or beveled structures. Some previous interpretations had proposed age and origin similarities between the Serra do Martins Formation, the post-Campanian sediments of Peroba-Ponta Grossa

(Potiguar basin), and the Miocene Barreiras Formation (Sousa et al., 1999). In fact, similarities between weathering formations do not imply uniform ages for underlying sediments and surfaces (see Lima, 2008), and morphostratigraphic relationships do not favor this interpretation. According to available palaeogeographical maps (Tardy and Roquin, 1998), conditions favorable to laterite formation might have occurred in inner Northeast Brazil only during Early Tertiary (Eocene), whereas later and drier periods (Neogene: Thiry et al., 1999) would have only allowed sporadic formation of carapaces and ferruginous gravels in lixisols at low altitude. However, in more humid coastal areas, lateritic soil formation has been recognized in the Barreiras sediments for the mid-Miocene to late Quaternary period (Lima, 2008; Rossetti et al., 2013). In most other regions, rather thin soils and saprolites prevail, appropriate to the present semi-arid climatic conditions (leptosols, luvisols and cambisols), except on sand or sandstone surfaces of high or low altitudes (lixisols and arenosols: Bétard, 2007) and in the more humid coastal strip and mountain slopes, where thicker tropical soils (lixisols, acrisols) and red or yellow ferralsols occur.

The regional distribution of soils is highly reflective of the stepped pattern of landforms and associated denudation rates (Bétard and Peulvast, 2013). Whereas only non-lateritic soils developed from shallow, grus-type weathering mantles are found on the Sertaneja surface marked by semi-arid conditions since the Miocene, relict laterites inherited from older (Paleogene) paleoclimates remain currently scarce in the landscape and are essentially confined to ancient summit surfaces and/or in positions of major drainage divides which do not seem to have ever been buried in more recent times (Serra do Pereiro, Araripe surroundings). This organization of soil covers is symptomatic of contrasted denudation rates, with higher rates on the low-altitude Sertaneja surface steering the landscape towards the stripping of most of the paleoweathering mantle, and favoring the development of a primary (non--lateritic) fersiallitic pedogenesis under the newly established semi-arid conditions, in existence at least since the last 13 My (Harris and Mix, 2002; Bétard, 2012).

Remnants of waste deposits identified on parts of these surfaces – alluvial fans, terraces, pediment covers – are more readily interpretable and also give indications on a long-lasting and continuous landscape evolution (i.e. without burial episodes of wide extent). According to the geological map of Ceará (CPRM, 2003), such deposits of argillaceous, often ferruginous, sands and gravels of fluvial to colluvial origins are found either on high basement surfaces (southwest Ceará), or on slightly dissected pediplains at low altitudes. Though the authors of the geological map include Holocene deposits among these sediments, the most of them probably represent older formations, even on low surfaces, since a slight entrenchment of valleys now cuts them from their source areas, scarps and inselberg slopes located up to 20 or 30 km away (Baturité and Quixadá areas: Bétard, 2007; Peulvast and Bétard, 2013).

5.3. Discussing the validity of "episodic burial and exhumation models" in northeast Brazil

According to Jelinek et al. (2014), and as discussed higher, although the timing of the main exhumation events based on thermochronology is consistent with that published by Japsen et al. (2012b), the intervening periods of widespread sedimentation are not required by the data. Similarly, the data obtained from calibrated drainage analysis in order to reconstruct the spatial and temporal uplift of South America (with particular emphasis on the Borborema, Altiplano and Patagonia plateau; Rodriguez Tribaldos et al., 2017) do not record any subsidence and sedimentation event during the Cenozoic.

However, as stressed in previous publications (e.g. Peulvast and Bétard, 2015b), the most critical questions which arise face to the "episodic burial and exhumation model" developed by Japsen et al. (2012b) for the post-rift evolution of the Brazilian Northeast may be listed as follows: (i) What should be the nature and origin of the additional overburden inferred from AFT analysis? (ii) How would ~1000 m of additional sediment have been provided in a landscape which is shown by several authors (see Martill, 1993) to have remained surrounded by low hills? (iii) Could 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, in a relatively short period, between the Cenomanian and the Campanian (less than 10 My), which is a period of moderately high sedimentation rates in most basins of Brazil (Macgregor, 2013)? (iv) How would such sediments, of unknown nature (clastic or marine?), have been spread over the back slope of an uplifting continental passive margin rather than on its oceanic side (where no such sedimentary record has been detected offshore)? (v). What could have been the topographic limits of the basin? (vi) To where would the waste generated by post-depositional stripping of the sediment mass have been conveyed during the later Cenozoic? Finally (vii) how would be explained the approximate but remarkable persistence of the hydrographic divide close to the Patos Lineament and the Chapada do Araripe between the Jaguaribe and São Francisco basin (Figs. 1 and 6) through such a complex history of burial and exhumation, which would have created a completely different landform and drainage organization? Clearly, most of these questions do not easily find positive answers corresponding to available geological constraints.

The same questions about hypothetic additional covers (origin, removal, final destination of the waste products) arise for the kilometer-thick cover of Oligocene-Miocene age which is also supposed to have buried the whole region, after the Campanian-Eocene phase of erosion. The Bahia continental platform is particularly narrow, and the volume of the post-rift sedimentary wedge is much smaller than the one which would correspond to the deposition of the huge quantity of waste produced by the erosion of the supposed covers and of the basement (Macgregor, 2013). Even in front of the mouths of the São Francisco and Paraguaçu rivers, the main ways along which the erosion products might have been transported, there is no significant widening of the margin, neither any submarine fan that could have formed at the foot of the continental slope (like the Niger, Congo or Amazon submarine fans, for example).

In our reconstruction of the regional geomorphic evolution based on the study of existing sedimentary vestiges and outliers, we indicate a discontinuous and thin post-rift cover in large parts of Ceará and its surrounding regions (Peulvast et al., 2008) which is also suggested by Assine et al. (2016) and Custódio et al. (2017) (Fig. 6). Onshore, reconstructed geological sections indicate maximum thicknesses of up to 600–700 m for this cover 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 (Fig. 9). 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. The accumulations of Cenozoic clastic sediments (Barreiras Group) only reached a few tens of meters along the north and east coasts. Even the Paleocene 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 meters in thickness and cannot be considered as remnants of a thick and continuous post-rift cover. The same may be suggested for the very small occurrence of Miocene sediments (Sábia Formation) close to the coast in the Reconcâvo basin, which does not seem sufficient to allow extrapolation to a corresponding transgression which would have reached the rest of the RTJ basin and surrounding areas. Moreover, there is no clear evidence of accelerated offshore sedimentation that might reflect the later erosion of thick post-rift, Late Cretaceous and/or Cenozoic sediments (see compilation of stratigraphic logs on the equatorial margin in Peulvast et al., 2008).

At last, it would be necessary to explain which geophysical mechanisms would induce deep post-rift subsidence on so wide surfaces, exaggerated by isostatic reaction to these overburdens, followed by very strong and quick uplift phases, and then by a new subsidence and burial phase, finally concluded by a new uplift and erosion period, far inland from the continental margin. Outside volcanic passive margins such as those of west and east Greenland where this model was elaborated (with thick overburdens of Paleocene lavas: Bonow et al., 2006; Japsen et al., 2010), explaining such a behavior in platform environment is a serious issue, which would have to be addressed in further works if the "episodic burial and exhumation" model had to be maintained (see also Green et al., 2018; Jess et al., 2020). Such a scenario should be compared to that, somewhat similar but probably involving much thinner and more discontinuous rock slices, that was proposed for the Armorican Massif (western France) by Bessin and Guillocheau (2017). In their reconstruction of the geomorphic evolution, these authors suggest that parts of this Variscan massif should have been beveled and then buried during marine transgression in the Mid-Jurassic before being exhumed and eroded in the Early Cretaceous (beginning of the opening of the Golfe de Gascogne) and then buried a second time due to the Late-Cretaceous marine transgression. A second exhumation would have occurred during the Paleocene, followed by limited transgressions during the Cenozoic. However, we remark that relief and vertical movements were always much lower in this region than in northeast Brazil. In their explanations, the authors pay more attention to marine transgressions and regressions than to strong vertical crustal movements such as those that are suggested in northeast Brazil. At last, they recognize that no remnant of Mesozoic cover is preserved outside the eastern margins of the massif, making this reconstruction somewhat speculative.

5.4. Denudation rates

The episodic burial and exhumation model proposed by Japsen et al. (2012a,b) for northeast Brazil implies very high sedimentation and erosion rates: 2000 m of sedimentation between the Cenomanian and the Campanian (14 Ma: 142 m/Ma), 2000 m of erosion in the Paleocene-Eocene (~35 Ma: 57 m/Ma), 1000 m of sedimentation in the Oligocene-Miocene (~15 Ma: 66 m/Ma), and comparable erosion rates until the Present. Such rates are much higher than those usually reported in similar low-energy passive margin and platform environments.

Our estimates obtained north of the Borborema and in Ceará roughly match with the AFTA results published by Jelinek et al. (2014) in more southern parts of northeast Brazil, from the Borborema plateau to the Conquista and Jetiquinhonha plateaus through the Sertaneja Depression, the RTJ Rift and the Chapada Diamantina (Bahia State), although the rates are generally somewhat higher than ours (10–30 m/Ma in the Borborema region during their post-rift stage I: see discussion in Peulvast and Bétard, 2015b). In a later publication, Jelinek et al. (2020) report slightly lower rates (15 m/Ma) in and around the RTJ rift for the denudation episode initiated in Early Cenozoic, with a 1400 m thick eroded slice. Denudation rates of 6.8–10 m/Ma are reported for the flexured shoulders of the Tucano basin. The systematic differences in rates might reflect a different, more abrupt uplift style and a deeper dissection of the plateaus located on the eastern margin of northeast Brazil in comparison with the northern one. In both regions, some distal parts of the low Sertaneja surface were already formed during rifting and the transitional phase, between residual rift shoulder stumps, and then weakly uplifted and eroded as the least uplifted parts of a broad monocline.

Long-term denudation rates obtained in the study area from morphostratigraphic constraints were <10 m/Ma and similar to values reported from the Appalachians (Gardner et al., 1993) or cratons in Africa (Bierman and Caffee, 2001; Van der Wateren and Dunai, 2001; Gunnell, 2003; Beauvais and Chardon, 2013; Grimaud et al., 2018), Australia (Stone and Vasconcelos, 1999) or in the very stable cratonic region of central Finland (2.5 m/Ma: Hall et al., 2020). Denudation rates were higher during the Cretaceous rifting and transitional stages, as indicated in the stratigraphic record by the rapid pre-Cenomanian erosion of large parts of the Potiguar footwall uplands, over a period of 20–30 Ma or less (Peulvast and Claudino Sales, 2004).

Confirmed by ^{10}Be cosmogenic analyses made on surface samples, soil profiles and river sediments of distinct geomorphic domains in the eastern Borborema province (Morais Neto et al., 2010a,b), the low post-rift denudation rates in NE Brazil are explained by a conjunction of four factors that also influence the conditions of scarp formation and evolution (Peulvast and Bétard, 2013): (i) the low magnitude of crustal uplift deduced from the current elevation of marine Albian layers (Araripe, Apodi and RTJ basins); (ii) the low amplitude and long wavelength of crustal deformation of an initially low-relief topographic surface, which is favorable to a phenomenon defined as 'morphological resistance' (Brunsden, 1993a,b); (iii) the lithological resistance of basements rocks (e.g., granite, orthogneiss) and sedimentary covers (e.g. sandstone, limestone) explaining the widespread preservation of residual topography and high surfaces above the Sertaneja erosional plain; (iv) the long-term semiarid climate in NE Brazil, probably in existence since the Middle Miocene at least (Harris and Mix, 2002).

According to the results of ^{10}Be cosmogenic analyses, very low erosion rates (0.1–13 m/Ma) are observed on sedimentary mesas and crystalline plateaus of the Borborema highlands, with slighlty higher mean rates (1–11 m/Ma) in the Serteneja surface (Morais Neto et al., 2010a). The same was observed on the Diamantina Plateau (~5 m/Ma; Barreto et al., 2013). Even only representing the last 1.5 Ma of geomorphic evolution in alternate dry to more or less humid conditions (Wang et al., 2004), these data are in good agreement with our model of stepped surfaces preserving old features and thin sedimentary covers at the top of the plateaus (Serra do Martins Formation) without important changes, whereas faster erosion occurs at low levels, shaping the inner parts of the Sertaneja surface, close to the escarpments. They also confirm the importance of lithological controls and differential erosion in the development of this low surface and of the surrounding scarps and ridges (Morais Neto et al., 2010b).

6. Conclusion

Our review of publications based upon thermochronological data in northeast Brazil, in the light of morphostratigraphic constraints leads us to the conclusion that both methods exposed here gave diverging results, and that such a contradiction must receive appropriate explanations. Whereas Green et al. (2018) claim that "these (our) simple models cannot explain the constraints provided by low temperature chronology", we show that thermochronological methods, which often overestimate overburden thicknesses by factors of at least 2–4 (Hall et al., 2020) may be weakly appropriate for the study of geomorphic evolution in low-elevation passive margins, which involves too shallow levels of denudation. In the study area, we conclude that the most serious problems lie in the interpretation of thermochronological data (see Morais Neto et al., 2008, for example), in particular because of the lack of reliable data on variations of paleogeothermal gradients, and that the conclusions about the past existence of thick post-Cenomanian sediments outside the RTJ rift and over the preserved remnants of Mesozoic post-rift cover should be reconsidered. As was shown in central West Greenland by Jess et al. (2019, 2020), the geological and geomorphological constraints retained and interpreted by the promoters of the "episodic burial and exhumation model" (e.g. Green et al., 2018, 2020) must be embedded within thermal history, even though other, non-retained facts seriously contradict the proposed model.

More generally, we stress the fundamental importance of taking into account the available morphostratigraphic constraints and geomorphological reasoning in any interpretation of thermochronological and other analytic methods used for reconstructing long-term landscape evolutions. In our opinion, elaborating models that insufficiently take into account the reality of landforms and geological structures, the stratigraphic evidence or the distribution of soil covers leads to shaky assumptions that weaken any attempt to understanding the regional landscape patterns. As a return, elaborating more realistic models of long-term landform evolution including denudation rates and modalities based upon both types of methods, when possible, will bring elements for a better calibration of the physical methods. This is one of the conditions for reinforcing the trust one can have in their results, which bring useful, complementary or unique information, peculiarly in places where sedimentary, volcanic or pedological markers are missing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2021.103464.

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