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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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- 5 Jean-Pierre Peulvast\*, François Bétard\*\*
- 6 \* Sorbonne Université, Faculté des Lettres, Paris, France, jean-pierre.peulvast@wanadoo.fr
- 7 \*\* Université de Paris, UMR 8586 PRODIG, Paris, France, francois.betard@u-paris.fr
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#### 9 Abstract

10 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-11 like uplift post-dating Early Cretaceous intracontinental rifting and the formation of the Atlantic 12 13 passive margin in Aptian times. The post-Cenomanian uplift caused an inversion of Cretaceous basins 14 and generated a landscape in which the most elevated landforms correspond either to resistant post-rift 15 sedimentary cover, or to residuals of Cretaceous rift shoulders, above a low erosion surface. Since no 16 evidence of a former post-Cenomanian sedimentary cover of significant thickness was found outside 17 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 18 (apatite fission tracks analysis-AFTA), two slices of 1,000 m to 2,500 m would have been deposited 19 20 over the present pile in the south part of the study area, respectively in Campanian and Oligocene-21 Miocene times, before being totally removed. We examine here the diverging scenarios of geomorphic 22 evolution respectively based upon morphostratigraphy (our model) and upon low temperature thermochronology, submitting them to available evidence provided by an updated and geographically 23 24 extended review of geomorphological and sedimentological data, and trying to decipher some of the 25 reasons that might lead to disputable geomorphic interpretations. We stress the fundamental 26 importance of taking into account all the available results of geomorphological and geological 27 approaches in any interpretation of thermochronological and other analytic methods used for 28 reconstructing long-term landscape evolutions. This is one of the conditions for reinforcing the trust 29 one can have in their results, which may bring complementary or unique information, peculiarly in 30 places where sedimentary or volcanic markers are missing.

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32 **Keywords:** long-term landform evolution, morphostratigraphy, low temperature thermochronology, 32 Northeast Brazil, passive margin

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#### 36 **1. Introduction**

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38 Although covering a larger area, the present work is partly based upon some of our previous studies on 39 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 40 around the Cretaceous Cariri-Potiguar rift zone (Ceará State and surroundings). Its landforms were 41 42 studied by the means of extensive fieldwork and morphostructural mapping (Peulvast and Claudino 43 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 44 45 basin), fieldwork and DEM studies were completed by an updated review of regional studies on 46 sedimentary geology and long-term geomorphology.

47 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 48 in Aptian times (Peulvast et al., 2008). Limited post-Cenomanian uplift caused a shallow inversion of 49 Cretaceous basins and generated a landscape in which the most elevated landforms (1,000-1,200 m 50 a.s.l.) correspond either to resistant Mesozoic post-rift covers, or to residuals of syn-rift Cretaceous 51 52 footwall uplands. Low Cenozoic denudation depths favored a re-exposition of Palaeozoic and Mesozoic land surfaces (i.e. exhumation of stratigraphic unconformities) and created a low planation 53 surface below residual ridges and topographically inverted sedimentary basins. Crustal uplift and 54 55 denudation reached 600 m at most and did not exceed mean rates of 10 m/Ma.

56 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 57 58 (apatite fission tracks analysis-AFTA) reported for the Araripe basin (Morais Neto et al., 2005-2006), 59 with derived estimates implying burial by a considerable thickness of sedimentary rocks followed by 60 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 61 thermochronological results suggest that slices of 1,000 m to 2,500 m would have been deposited over 62 63 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 64 65 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 66 67 there. Therefore, either our morphostratigraphic results are wrong, or the published interpretations of 68 thermochronological data are disputable and deserve to be discussed.

69 Our aim is neither to criticize the interest of thermochronological methods and techniques 70 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 71 to discuss the arguments for diverging interpretations and evolution models. After a brief account of 72 73 the geomorphological features in the study area, we present a summary of diverging versions of the 74 geomorphic history, first those which are based upon morphostratigraphic constraints, and then the 75 thermochronological and geophysical data that were used by some authors to elaborate an alternative 76 model of regional geomorphic history, with much greater values of denudation depths and rates. 77 Recently published data on stratigraphy and sedimentology in Mesozoic basins are used to complete 78 our interpretations of such discrepancies. Discussing the opposite arguments and comparing both sets 79 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 80 questioned and that the most serious problems lie in the interpretation of thermochronological data in 81 82 terms of geomorphic evolution.

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#### 84 **2.** The study area

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86 2.1. Main topographic features

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88 Comprised between 3° and 10° S, and 36 and 41° W, the study area forms the northern part of the 89 Brazilian Northeast, or "Nordeste", and mainly belongs to the structural Borborema Province 90 (Almeida et al., 1981) (Fig. 1). To the north (Ceará and western parts of the Rio Grande do Norte and 91 Paraiba States), a 400 km wide hemicycle with a roughly concentric pattern of highlands, corridors 92 and low plains (Peulvast and Bétard, 2015b), is mainly drained by the Jaguaribe and Piranhas rivers 93 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 1,000 m a.s.l.) whereas it is

95 intersected to the north by two offset EW alignments of mountain slopes forming a very discontinuous96 escarpment along the Equatorial Atlantic margin.

To the southeast and the east, the Borborema massif (1,200 m a.s.l.) separates the JPH from 97 the lower São Francisco depression (Pernambuco and northern Bahia States) and from the stepped 98 plateaus and lowlands of the east coast (Pernambuco, Alagoas and Sergipe States: Monteiro and 99 100 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 101 through the low plateaus and ridges of a wide inland depression and more elevated tablelands and 102 mesas corresponding to the Tucano-Jatobá basin (600-1000 m a.s.l.). The whole region climatically 103 104 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. 105

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#### 107 2.2. Geological and morphostructural settings

109 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 110 described by Peulvast et al. (2008), comprise parts of the Mesozoic Cariri-Potiguar rift basins 111 (Araripe) as well as parts of their shoulders (Central Ceará highlands, Borborema). Interior lowlands 112 also extend both on rift basins and faulted basement (Fig. 2). These discrepancies, also represented to 113 the south (topographic inversion of the post-rift layers in the Jatobá and Tucano basins, epigeny of the 114 São Francisco River through the Jatobá basin) reflect various types of structural controls and show 115 116 interferences between tectonic and erosion histories (Peulvast and Bétard, 2015b).

117 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). 118 119 Onshore, the present structural pattern is organized around a discontinuous NE-SW set of basins and half grabens - the 500 km long intracratonic Cariri-Potiguar rift zone. Representing failed rift 120 structures of Early Cretaceous age with remnants of their post-rift sedimentary cover (Araripe and 121 122 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 123 124 sediments (the Barreiras Group) underlies the low-lying "tabuleiros" between the marginal escarpment 125 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 Reconcâvo-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-Reconcâvo) 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.

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# 150 3. Morphostratigraphic constraints for the reconstruction of landscape evolution since 151 Cretaceous rifting: An updated overview

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#### *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 163 164 Patos fault zone, this planation surface is widely developed at low altitudes along the oceanic front and 165 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 166 167 post-Cretaceous in age, but 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, 168 and widely developed before the deposition of the Barreiras sediments in its distal parts, it may be 169 170 considered as resulting from cyclic development of a "young" surface below remnants of poorly dated high surfaces (Peulvast et al., 2008). 171

172 To the south of the Chapada do Araripe, a low surface bevels the crystalline rocks of the 173 basement and small sedimentary basins (Cedro, São José do Belmonte). Dissected and disconnected 174 from the present base level, this surface extends 150-200 m below the late Albian unconformity and 175 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 176 stripping of the sandstone cap and by the formation of wide embayments into the Araripe plateau (Fig. 177 4A). Narrow NE–SW residual ridges of metamorphic rocks continuing the Borborema plateau to the 178 179 south east, 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 180 181 than in the inner parts of the northern Sertaneja surface.

182 No clear connection between both low surfaces has been ascertained because of the presence 183 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 184 São Francisco River. However, we suggest that the low plateaus that extend around the São Francisco 185 186 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 187 (Fig. 4B), developed on the south side of the topographic and drainage divide that links the Araripe 188 and Borborema plateaus (Fig. 1). Both surfaces present altitudes of ~400-450 m close to the foot of 189 190 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 metamorphicnature (basement areas).

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#### 194 *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.

203 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 204 whose lower layers, the 400-800 m thick Acu sandstones (Albian-Cenomanian) rest unconformably on 205 syn-rift or transitional deposits and incompletely bevelled basement highs and rift shoulders (see 206 207 details and references in Peulvast and Bétard, 2015b). Upwards, these fluvial to estuarine sandstones 208 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, 90-209 80 Ma). Their presence shows a decrease of the terrigenous input, as erosion on basement topography 210 became limited to chemical weathering and removal of solutes, in a context of high sea levels and 211 212 warm, humid climates (Haq et al., 1987; Arai, 2000; Miller et al., 2005; Huber et al., 2002). Apart 213 from a few upstanding residual massifs, the landscape towards the end of this period was predominantly flat and low-lying. 214

215 In the Araripe basin, as well as in the Potiguar and RTJ basins (Magnavita et al., 1994), the 216 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 stages, before ~114 217 218 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 219 220 basin (Socorro, Cedro and São José de Belmonte outliers; Assine, 1994; Hegarty et al., 2002; Valenca 221 et al., 2003). During Albian to Cenomanian times, the basin was a landscape of lakes and lagoons 222 surrounded by low hills, intermittently connected via shallow seaways to the Tucano-Jatobá basin 223 (Petri, 1987; Assine et al., 2016).

The post-rift Araripe basin first formed in the northeast, where the Albian-Cenomanian series 224 are more complete, and then extended to the south and the west, progressively lapping onto the 225 basement. This stratigraphic transgressive-regressive sequence, known as the Araripe Group (Ponte 226 and Ponte Filho, 1996) is made of fluvial, lacustrine, lagoonal and marine sediments of Aptian to 227 Cenomanian age. They are divided into several formations or members (Fig. 5B): the Barbalha, Crato, 228 229 Ipubi and Romualdo Formations (Late Aptian-Early Albian), overlain by a mid-Cretaceous Araripe Group (Araripina and Exu Formations) according to Assine (2014), or the Rio da Batateira and 230 Santana Formations, the last one with the Crato, Ipubi and Romualdo members (Coimbra and Freire, 231 2021). According to recent works (Nascimento et al., 2016; Custódio et al., 2017; Varejão et al., 232 2020), well defined marine ingressions from the SSE, reaching the western extremity of the basin, 233 234 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 235 water levels (carbonate successions of the Crato Formation, evaporates of the Ipubi Formation) (Fig. 236 6). The overlying clay-rich sandstone is the last deposit relevant to lacustrine to marine phases of 237

sedimentation. It corresponds to the Arajara Formation (Ponte and Appi, 1990) or the terminal 238 239 sequence of the Santana Formation (Assine, 2007).

The alluvial sediments of the Exu Formation (150–250 m in thickness) unconformably cover 240 the older layers and, to the south, west and north-west, the basement (Fig. 5). According to Assine 241 (2007), a slight erosional unconformity between the upper unit (Exu Formation, Late Albian-242 243 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 244 sandstones displaying graded bedding occur in the western (distal) part of the basin, where 245 argillaceous layers indicate a floodplain environment (Assine, 2007). In the eastern (proximal) part of 246 247 the basin, the sandstones are coarser and more immature, with abundant conglomerate beds and crossbedding. These indicate sedimentation in braided channels, with a rapid westward progradation 248 249 through low-relief topography of a braid-plain dominated by flashy flow regimes in a dry 250 palaeoclimate (Martill, 1993).

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#### 3.3 Geomorphic history and morphostratigraphic constraints: evidence from inner Cretaceous basins 253

254 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 255 the Pernambuco lineament and a common post-rift history. Outliers containing the whole post-rift 256 sequence are located in the Socorro basin (Serra Vermelha) and the narrow Serra Negra-Serra do 257 Periquito buttes (northern border of the Jatobá basin), at similar altitudes, 400 m above the 258 259 surrounding basement surface (Fig. 7). In the northern Tucano basin, the upper part of the post-rift 260 series is mainly found in the 130 km<sup>2</sup> 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 261 thin intervals of interbedded shales and limestone, equivalent to the Barbalha Formation in the Araripe 262 263 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 264 265 continental paleodrainage, flowing to the south (Varejão et al., 2016).

While the other basins of the eastern margin of northeast Brazil were still experiencing 266 267 transgressive marine conditions until the late Cretaceous, the end of the sedimentary sequence in the 268 Araripe and Jatobá basins was continental. In the Araripina and Exu formations, paleoflow directions 269 suggest transport to the west (Assine, 2007). The source area is the Borborema region whose uplift, 270 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 271 the Albian sediments suggest that no significant overburden was ever removed by erosion from the 272 exposed upper surface of the Exu caprock (Baudin and Berthou, 1996; Arai, 2000), thus forming an 273 274 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 275 276 erosion of the seaward flank of a broad crustal upwarp that inverted the Araripe and other Cretaceous 277 basins. The drainage made inroads into the hinterland through older Cretaceous half-grabens and 278 Brasiliano shear zones (Peulvast et al., 2008; Fig. 8).

279 To the south, the corresponding low surface developed on the other side of the same upwarp 280 and of its continuation along the South Atlantic margin through the Tucano basin, towards the 281 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, 282 Jatobá and Tucano basins) and the Borborema plateau, crossing the Tucano-Jatobá basin through a 283 complex fracture zone (Fig. 2). This development was followed by the entrenchment of the São 284 285 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 286 287 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 288 289 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 290 291 escarpment of the Borborema highlands (Monteiro and Corrêa, 2020). Such an event would be 292 obviously post-Cretaceous in age, and is suggested to have occurred in the Eocene, according to maps 293 published by Macgregor (2013).

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#### 295 *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).

303 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 304 vigorously uplifted. Assuming that sea-level rose from +150 to +220 m in Albian times (Haq et al., 305 1987), this suggests a minimal post-Albian crustal uplift of 500–600 m, which is comparable to values 306 307 proposed by Magnavita et al. (1994) in the Recôncavo-Tucano-Jatobá area. Because erosion has 308 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), 309 310 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 311 Brazilian shield. Maximum post-rift denudation depths are provided by the maximum value of 312 313 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 to 10 m/Ma) is similar to that of vertical 314 315 movements.

316 In the northern part of the study area, we have previously established a good correspondence 317 between the volumes of the offshore sediments and the post-Cenomanian denudation depths integrated 318 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 319 mean thickness of the late Miocene and younger Barreiras and Tibau sediments deposited in the 320 Potiguar basin and along the coastal strip. Such moderate values, similar to that obtained on the whole 321 322 post-Cenomanian epoch, do not imply any Neogene acceleration of uplift and erosion (Peulvast and 323 Bétard, 2013).

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#### 325 *3.5. Geomorphic history at regional scale*

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327 During the Cenozoic, the regional landscape formed in response to moderate crustal uplift, in a context 328 of an episodically fluctuating but continuously falling base level (Peulvast et al., 2008; Peulvast and 329 Bétard, 2015b). After formation of the transform passive margin in Aptian times, the crustal uplift 330 caused an inversion of the Cretaceous basins by differential erosion. Denudation in the last 90 My 331 exhumed a number of Mesozoic palaeosurfaces at low elevations, including a palaeopiedmont of 332 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 340 could perhaps have been a flexural response of the low-rigidity lithosphere to sediment loads on the 341 342 margin, and thus a slowly ongoing process since the late Cretaceous. Lithospheric thinning (down to 343 60 km under the Borborema dome) is mentioned by Klöcking et al. (2020), who explain the Cenozoic 344 uplift by the emplacement of warm as then opphere beneath the plate combined with thermomechanical 345 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 346 347 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., 348 349 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 350 the specific evolution of the São Francisco drainage basin and of the eastern margin would justify a 351 more detailed study. 352

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

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356 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 357 landscape development (e.g., Gallagher et al., 1994; Gunnell et al., 2003). In the study area, Harman et 358 359 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 360 recently formed rift margin. In a more recent review of AFT ages measured along the eastern Brazilian 361 margin, Engelmann de Oliveira and Jelinek (2017) determined that the occurrence and distribution of 362 "young" AFT ages along the margin of the Borborema Province show a correlation with the 363 Cretaceous thermotectonic event related to the opening of the South Atlantic Ocean. The uplift should 364 have been caused by thermal imbalance, magmatism, and tectonic reactivations forming onshore 365 366 basins.

367 Other data obtained along transects through the Borborema plateau and in the eastern 368 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 369 370 of regional uplift along the Brazilian Atlantic margin and subsequent erosion. Combined with <sup>40</sup>Ar/<sup>39</sup>Ar dating of amphiboles, biotite, muscovite and K-feldspar, and thermal modeling of argon 371 diffusion in feldspar, low temperature thermochronology (AFT and U-Th/He on apatites) indicates 372 that post-rift exhumation to shallow crustal levels (<3 km) occurred from 100-90 Ma on. Younger 373 374 fission track ages (~75-50 Ma) correspond to an increase of denudation during the Late 375 Cretaceous/Early Paleocene transition. According to the same authors (Morais Neto and Vasconcelos, 376 2010), any later uplift (Miocene) must have been minor. AFT studies also indicate two cooling events 377 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 140 378 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 379

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 1,000 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 388 389 (Magnavita et al., 1994) suggests that post-rift thermal subsidence has taken place after a period of 390 erosion at the end of rifting (Aptian), until the end of the Oligocene, producing ~650 m of normally 391 compacted post-rift sediments. Later on, the basin and surroundings were uplifted by 600 m and then 392 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 393 394 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 395 396 would have taken place at the end of rifting, before post-rift subsidence and sedimentation. In this 397 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 398 crustal uplift due to flexural uplift and Oligocene magmatic underplating. 399

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):

407 (1) Following Early Cretaceous breakup, a kilometer-scale burial of the margin beneath a408 sedimentary cover, with maximum burial of the syn-rift sequence in the Campanian;

409 (2) Campanian and Eocene phases of uplift leading to almost complete removal of these
410 deposits by river erosion to base level and to formation of a peneplain (the higher surface) with a
411 deeply weathered surface;

412 (3) Oligocene–Miocene subsidence of the interior and of the coastal zone leading to reburial of413 the higher surface;

414 (4) Miocene uplift and erosion, producing a new peneplain (the lower surface) by river
415 incision below the uplifted and re-exposed higher surface. Minor uplift in the Quaternary would have
416 led to incision below the lower surface and to formation of the coastal plain.

417 According to the authors, a small outlier of marine shales (Sabiá Formation) found on the 418 eastern margin of the Recôncavo basin would testify to regional Miocene burial. However, no 419 remnants of such a cover have been reported from the surrounding plateaus, where only sparse 420 outcrops of thin non fossiliferous, continental sediments are found far to the north, outside the basin, 421 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 422 423 Serra do Martins Formation and the underlying basement (Morais Neto et al., 2008, 2009). Reburial of 424 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 425 during the Miocene uplift event. The presence of an extensive Cretaceous cover prior to Campanian 426 427 uplift and exhumation might similarly explain the lack of pre-70 Ma weathering ages.

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#### 429 **5. Discussion**

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

#### 433 5.1.1. RTJ rift and basin

434 The discussion mainly bears on the "episodic burial and exhumation model", which was first 435 elaborated for the volcanic margin of West and southern East Greenland (Bonow et al., 2006; Japsen 436 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 437 438 reflectance) and sonic data from several wells in the Reconcâvo basin and on the Bahia margin show that the cover reached thicknesses of 2 to 3 km. The AFTA data from the wells give constraints on the 439 440 timing. The authors also assume that AFTA data from outcrop samples across NE Brazil, including the 441 Chapada Diamantina and surroundings (Bahia State), all show that the present-day basement areas 442 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 443 444 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 445 446 the interior of their study area of 50-70°C since 80 Ma.

447 Indeed, the data used in Japsen et al.'s work correspond to 4 wells located in the Reconcâvo 448 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 449 450 history of geothermal and on cross calibrations for the interpretation of sonic log data, cannot be fully 451 extrapolated for areas located up to 400 km from the coast, even taking into account older works based 452 on AFTA data. These data (e.g. Harman et al., 1998) do not fit with values of eroded basement or 453 post-rift cover rocks obtained from morphostratigraphic works on other regions of NE Brazil (Chapada do Araripe) and even exceed by 1,000 m at least values given by Morais Neto, who "only" 454 455 found 1,500 m of former burial in the Araripe basin.

456 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). 457 458 and as happened in the Potiguar basin (Peulvast et al., 2008). Such a geographically limited subsidence 459 would not imply deep burial of remote basement areas in the Chapada Diamantina and Maracas 460 regions. In our opinion, the high surfaces identified in the region rather were mainly formed during the 461 post-rift stage in relation with base-levels offered by moderately thick post-rift covers deposited in the 462 nearby post-rift subsidence areas - up to 600-700 m or slightly more -, as evidenced in the Ceará state 463 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 464 465 incipient basin inversion and uplift of the onshore regions of the margin (Borborema plateau).

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#### 467 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.

474 Morais Neto et al. (2005–2006) indicate maximum heating to 93 °C after the deposition of the
475 Batateira or Barbalha layers (maximal burial of 2.2 km, but before 100 Ma, i.e. before the deposition

476 of the Exu sandstone, which therefore does not seem to have been followed by later burial). The pre-477 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 478 sandstone rests unconformably over the older formations, including basement highs, to the south and 479 close to Crato. Some denudation in response to uplift occurred locally before its deposition on the 480 481 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 482 the post-rift period (Baudin and Berthou, 1996), interpretations of the thermal histories of each sample 483 are non-unique and probably insufficient for reconstructing a regional history of sedimentation, uplift 484 485 and erosion.

486 The apatite cooling histories presented by Morais Neto et al. (2005-2006) all report 487 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 488 numerous recognized discrepancies between AFTA results and morphostratigraphic evidence (French 489 Massif Central: Ricordel-Prognon et al., 2010; NW England, SW Scotland: Luszczak et al., 2014; 490 central West Greenland: Jess et al., 2019; central Finland: Hall et al., 2020) and discussed in various 491 492 publications (Gunnell, 2003; Peulvast et al., 2008, 2009; Wildman et al., 2014; Jess et al., 2019), these 493 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 494 exhumation or denudation values and rates, but generally remain unknown. This is the case in the 495 496 Eocene to Miocene epoch, which is also the time of magmatism in surrounding regions (mainly the 497 north and northeast of the Borborema plateau, which until now record the highest internal levels of 498 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., 2012) but vary 499 500 in other studies on the continental margin between 18-20 and 30°C/km, with surface temperatures of 501 25°C (Jelinek et al., 2014).

According to sedimentological studies of the Ipubi Formation, in the Araripe basin 502 503 (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 504 505 of gypsum in these evaporitic sediments, is considered as evidence for mesodiagenesis, yet 506 maintaining the original crystalline shape of gypsum. This occurrence was mentioned by Silva (1988), 507 who called it "sparse laths of anhydrite" among the gypsum. According to the author, the formation of 508 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. 509 Murray (1964) and Silva (1988) affirm that at least 900 m of burial would be necessary to transform 510 the whole primary gypsum into anhydrite. Since 250-350 m of the overlying strata (Romualdo, Arajara 511 512 or Araripina, Exu Formations) outcrop in the preserved remnants of the post-rift cover, it appears that at most 100 to 200 m of the last deposits were eroded, in relation with degradation and weathering 513 514 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 10-30% 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.

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#### 526 *5.2. Palaeosurfaces, weathering signatures and associated soil covers*

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528 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 529 reconstructing possible "episodic burial and exhumation" scenarios (Ricordel-Prognon et al., 2010). 530 531 Indeed, remnants of old lateritic crusts are recognized in a few areas, on small mesas capped by the 532 Serra do Martins sandstones, on the Serra do Pereiro (Peulvast and Claudino Sales, 2004; Bétard, 533 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 534 piedmont of the Chapada do Araripe (Fig. 5). Based on a systematic study of weathering profiles in 535 Northeast Brazil combining <sup>40</sup>Ar/<sup>39</sup>Ar and U-Th/He dating of supergene minerals, Lima (2008) 536 obtained radiometric ages ranging from  $43.2 \pm 4.3$  Ma to  $0.8 \pm 0.1$  Ma, indicating that weathering 537 538 processes last from the Eocene to the Pleistocene. These data suggest a long-lasting exposition of these 539 areas to surface conditions, excluding any recent (i.e. Oligocene-Miocene) burial below a now 540 vanished sedimentary cover.

541 The first cited occurrence corresponds to remnants of a high structural surface (650-700 m), 542 the others are recognized at lower altitude on various tabular or beveled structures. Some previous 543 interpretations had proposed age and origin similarities between the Serra do Martins Formation, the 544 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 545 uniform ages for underlying sediments and surfaces (see Lima, 2008), and morphostratigraphic 546 547 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 548 549 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 550 551 low altitude. However, in more humid coastal areas, lateritic soil formation has been recognized in the 552 Barreiras sediments for the mid-Miocene to late Quaternary period (Lima, 2008; Rossetti et al., 2013). 553 In most other regions, rather thin soils and saprolites prevail, appropriate to the present semi-arid 554 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 555 slopes, where thicker tropical soils (lixisols, acrisols) and red or yellow ferralsols occur. 556

The regional distribution of soils is highly reflective of the stepped pattern of landforms and 557 associated denudation rates (Bétard and Peulvast, 2013). Whereas only non-lateritic soils developed 558 from shallow, grus-type weathering mantles are found on the Sertaneja surface marked by semi-arid 559 560 conditions since the Miocene, relict laterites inherited from older (Paleogene) paleoclimates remain 561 currently scarce in the landscape and are essentially confined to ancient summit surfaces and/or in 562 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 563 denudation rates, with higher rates on the low-altitude Sertaneja surface steering the landscape towards 564 the stripping of most of the paleoweathering mantle, and favoring the development of a primary (non-565 lateritic) fersiallitic pedogenesis under the newly established semi-arid conditions, in existence at least 566 since the last 13 My (Harris and Mix, 2002; Bétard, 2012). 567

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

570 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 571 gravels of fluvial to colluvial origins are found either on high basement surfaces (southwest Ceará), or 572 on slightly dissected pediplains at low altitudes. Though the authors of the geological map include 573 Holocene deposits among these sediments, the most of them probably represent older formations, even 574 575 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; 576 577 Peulvast and Bétard, 2013).

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#### 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 588 589 critical questions which arise face to the "episodic burial and exhumation model" developed by Japsen 590 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 591 592 would  $\sim 1,000$  m of additional sediment have been provided in a landscape which is shown by several 593 authors (see Martill, 1993) to have remained surrounded by low hills? (iii) Could the erosion of the 594 Borborema highlands, to the east (the source area: Assine, 1994), might have fed such a sediment 595 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 596 sedimentation rates in most basins of Brazil (Macgregor, 2013)? (iv) How would such sediments, of 597 598 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 599 600 offshore)? (v). What could have been the topographic limits of the basin? (vi) To where would the 601 waste generated by post-depositional stripping of the sediment mass have been conveyed during the 602 later Cenozoic? Finally (vii) how would be explained the approximate but remarkable persistence of 603 the hydrographic divide close to the Patos Lineament and the Chapada do Araripe between the 604 Jaguaribe and São Francisco basin (Fig. 1, Fig. 6) through such a complex history of burial and 605 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 606 607 geological constraints.

The same questions about hypothetic additional covers (origin, removal, final destination of 608 609 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 610 611 continental platform is particularly narrow, and the volume of the post-rift sedimentary wedge is much 612 smaller than the one which would correspond to the deposition of the huge quantity of waste produced 613 by the erosion of the supposed covers and of the basement (Macgregor, 2013). Even in front of the mouths of the São Francisco and Paraguacu rivers, the main ways along which the erosion products 614 might have been transported, there is no significant widening of the margin, neither any submarine fan 615 616 that could have formed at the foot of the continental slope (like the Niger, Congo or Amazon submarine fans, for example). 617

In our reconstruction of the regional geomorphic evolution based on the study of existing 618 sedimentary vestiges and outliers, we indicate a discontinuous and thin post-rift cover in large parts of 619 Ceará and its surrounding regions (Peulvast et al., 2008) which is also suggested by Assine et al. 620 (2016) and Custódio et al. (2017) (Fig. 6). Onshore, reconstructed geological sections indicate 621 maximum thicknesses of up to 600–700 m for this cover close to the coast (Potiguar basin) and in the 622 623 Araripe basin. These values are compatible with the volumes of material that the erosion of the 624 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-625 Cenomanian times and the volumes of sediments accumulated in the offshore basins (Fig. 9). No 626 627 morphological or sedimentological evidence of deep post-Cenomanian burial was detected, except for 628 the Turonian limestones of the Potiguar basin, which were deposited in shallow marine conditions. 629 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 630 Formation, preserved on isolated mesas at the northern and eastern periphery of the Borborema plateau 631 632 (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 633 634 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 635 reached the rest of the RTJ basin and surrounding areas. Moreover, there is no clear evidence of 636 accelerated offshore sedimentation that might reflect the later erosion of thick post-rift, Late 637 Cretaceous and/or Cenozoic sediments (see compilation of stratigraphic logs on the equatorial margin 638 639 in Peulvast et al., 2008).

640 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, 641 followed by very strong and quick uplift phases, and then by a new subsidence and burial phase, 642 643 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 644 645 (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 646 works if the "episodic burial and exhumation" model had to be maintained (see also Green et al., 647 648 2018; Jess et al., 2020). Such a scenario should be compared to that, somewhat similar but probably 649 involving much thinner and more discontinuous rock slices, that was proposed for the Armorican 650 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 651 buried during marine transgression in the Mid-Jurassic before being exhumed and eroded in the Early 652 Cretaceous (beginning of the opening of the Golfe de Gascogne) and then buried a second time due to 653 654 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 655 656 and vertical movements were always much lower in this region than in northeast Brazil. In their 657 explanations, the authors pay more attention to marine transgressions and regressions than to strong 658 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 659 reconstruction somewhat speculative. 660

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#### 662 *5.4. Denudation rates*

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The episodic burial and exhumation model proposed by Japsen et al. (2012a,b) for northeast Brazil implies very high sedimentation and erosion rates: 2,000 m of sedimentation between the Cenomanian and the Campanian (14 Ma: 142 m/Ma), 2,000 m of erosion in the Paleocene-Eocene (~35 Ma: 57 m/Ma), 1,000 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 lowenergy passive margin and platform environments.

Our estimates obtained north of the Borborema and in Ceará roughly match with the AFTA 670 671 results published by Jelinek et al. (2014) in more southern parts of northeast Brazil, from the 672 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 673 than ours (10-30 m/Ma in the Borborema region during their post-rift stage I: see discussion in 674 675 Peulvast and Bétard, 2015b). In a later publication, Jelinek et al. (2020) report slightly lower rates (15 676 m/Ma) in and around the RTJ rift for the denudation episode initiated in Early Cenozoic, with a 1,400 677 m thick eroded slice. Denudation rates of 6.8 to 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 678 a deeper dissection of the plateaus located on the eastern margin of northeast Brazil in comparison 679 with the northern one. In both regions, some distal parts of the low Sertaneja surface were already 680 formed during rifting and the transitional phase, between residual rift shoulder stumps, and then 681 682 weakly uplifted and eroded as the least uplifted parts of a broad monocline.

683 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 684 in Africa (Bierman and Caffee, 2001; van der Wateren and Dunai, 2001; Gunnell, 2003; Chardon et 685 al., 2013), Australia (Stone and Vasconcelos, 1999) or in the very stable cratonic region of central 686 687 Finland (2.5 m/Ma: Hall et al., 2020). Denudation rates were higher during the Cretaceous rifting and 688 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 689 690 Sales, 2004).

Confirmed by <sup>10</sup>Be cosmogenic analyses made on surface samples, soil profiles and river 691 692 sediments of distinct geomorphic domains in the eastern Borborema province (Morais Neto et al. 693 2010,a,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, 694 695 2013): (i) the low magnitude of crustal uplift deduced from the current elevation of marine Albian 696 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 favourable to a phenomenon 697 defined as 'morphological resistance' (Brunsden, 1993a,b); (iii) the lithological resistance of 698 basements rocks (e.g., granite, orthogneiss) and sedimentary covers (e.g. sandstone, limestone) 699 700 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 701 Middle Miocene at least (Harris and Mix, 2002). 702

703 According to the results of <sup>10</sup>Be cosmogenic analyses, very low erosion rates (0.1 to 13 m/Ma) 704 are observed on sedimentary mesas and crystalline plateaus of the Borborema highlands, with slightly 705 higher mean rates (1 to 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 706 707 1.5 Ma of geomorphic evolution in alternate dry to more or less humid conditions (Wang et al., 2004), 708 these data are in good agreement with our model of stepped surfaces preserving old features and thin 709 sedimentary covers at the top of the plateaus (Serra do Martins Formation) without important changes, 710 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 711 712 the development of this low surface and of the surrounding scarps and ridges (Morais Neto et al., 713 2010b).

714

#### 715 6. Conclusion

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717 Our review of publications based upon thermochronological data in northeast Brazil, in the light of 718 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 719 et al. (2018) claim that "these (our) simple models cannot explain the constraints provided by low 720 721 temperature chronology", we show that thermochronological methods, which often overestimate 722 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 723 724 denudation. In the study area, we conclude that the most serious problems lie in the interpretation of 725 thermochronological data (see Morais Neto et al., 2008, for example), in particular because of the lack 726 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 727 728 Mesozoic post-rift cover should be reconsidered. As was shown in central West Greenland by Jess et 729 al. (2019, 2020), the geological and geomorphological constraints retained and interpreted by the 730 promoters of the "episodic burial and exhumation model" (e.g. Green et al., 2018, 2020) must be 731 embedded within thermal history, even though other, non-retained facts seriously contradict the 732 proposed model.

733 More generally, we stress the fundamental importance of taking into account the available morphostratigraphic constraints and geomorphological reasoning in any interpretation of 734 thermochronological and other analytic methods used for reconstructing long-term landscape 735 736 evolutions. In our opinion, elaborating models that insufficiently take into account the reality of 737 landforms and geological structures, the stratigraphic evidence or the distribution of soil covers leads 738 to shaky assumptions that weaken any attempt to understanding the regional landscape patterns. As a 739 return, elaborating more realistic models of long-term landform evolution including denudation rates 740 and modalities based upon both types of methods, when possible, will bring elements for a better 741 calibration of the physical methods. This is one of the conditions for reinforcing the trust one can have 742 in their results, which bring useful, complementary or unique information, peculiarly in places where 743 sedimentary, volcanic or pedological markers are missing.

744 745

#### 746 **Declaration of interests**

747

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

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#### 1044 Figure captions

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1046 Fig. 1. Topography and drainage of the study area, and location of AFT samples from previous1047 thermochronological studies (Late Aptian divide from Assine et al., 2016).

Fig. 2. Simplified geological map of the study area (from Neves, 2014). 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.

1051 Fig. 3. Stepped planation surfaces in the northern part of the study area: synthetic profiles (from1052 Peulvast et al., 2008).

1053 Fig. 4. Sertaneja and older surfaces south of the Chapada do Araripe and around the lower São 1054 Francisco valley. A: South rim of the Chapada do Araripe, east of Exu, looking west: the Cenomanian 1055 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, 1056 1057 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 1058 1059 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 1060 in the distance. Photos: J.P. Peulvast. 1061

- 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
- 1065 Fig. 6. Palaeogeographical map of northeastern Brazil during Aptian times (from Custódio et al., 2017).
- 1067 Fig. 7. Post-rift sediments in the northern Tucano and Jatobá basins (from Varejão et al., 2016).
- 1068 Fig. 8. Reconstruction of the morphotectonic evolution of the northern Brazilian "Nordeste" since pre-1069 rift times (profiles from Peulvast et al., 2008).
- 1070 Fig. 9. Uplift, denudation and sedimentation along the Equatorial margin of northeast Brazil (profile1071 from Peulvast et al., 2008).
- 1072 Fig. 10. The sedimentary pile over the Araripe basin according to Japsen et al. (2014) and Green et al.1073 (2018).
- **Fig. 11.** Episodic burial and exhumation in northeast Brazil, according to Japsen et al. (2012a).



40°W

38°W







East of the Senador Pompeu Fault Zone (Jaguaribe-Potiguar compartment)



West of the Senador Pompeu Fault Zone (Baturité-Irauçuba compartment)



B

Residual reliefs

São Francisco river canyon Sertaneja surface

Sertaneja surface















