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Episodic burial and exhumation in NE Brazil after opening of the South Atlantic

Peter Japsen[1,†], Johan M. Bonow[1], Paul F. Green[2], Peter R. Cobbold[3], Dario Chiossi[4], Ragnhild Lilletveit[5], Luciano P. Magnavita[6], and Augusto Pedreira[7]

[1]*Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, 1350 Copenhagen, Denmark*
[2]*Geotrack International, 37 Melville Road, Brunswick West, Victoria 3055, Australia*
[3]*Géosciences (UMR6118), Centre National de la Recherche Scientifique (CNRS) et Université de Rennes1, 35042 Rennes, France*
[4]*Statoil do Brasil, Praia de Botafoga 300, 22250-040 Rio de Janeiro, Brazil*
[5]*Statoil Angola Team, Grenseveien 21, 4035 Stavanger, Norway*
[6]*Petrobras, Avenida República do Chile 330, Rio de Janeiro, 20031-170, Brazil*
[7]*Geological Survey of Brazil (CPRM), Avenida Ulysses Guimaraes 2862, Salvador, 41213-000, Brazil*

ABSTRACT

It is a common assumption that elevated passive continental margins have remained high since rifting and breakup. Here, we show that the Atlantic margin of NE Brazil has undergone a more complex history. Our synthesis of geological data, landscape analysis, and paleothermal and paleoburial data reveals a four-stage history: (1) After Early Cretaceous breakup, the margin underwent burial beneath a thick sedimentary cover; (2) uplift episodes in the Campanian and Eocene led to almost complete removal of these deposits; (3) the resulting large-scale, low-relief erosion surface (peneplain) was deeply weathered and finally reburied at the Oligocene-Miocene transition; and (4) Miocene uplift and erosion produced a new, lower-level peneplain by incision of the uplifted and re-exposed Paleogene peneplain. Previous studies have identified aspects of this interpretation, but we have defined the absolute timing and magnitude of discrete events of burial and exhumation that followed Early Cretaceous rifting and Eocene–Oligocene peneplanation. We suggest that a late sedimentary cover protected Paleogene weathering profiles until the present day. The uplift phases in Brazil are synchronous with uplift phases in Africa and the Andes. The Andean phases coincided with rapid convergence on the western margin of South America, and the Campanian uplift coincided with a decline in spreading rate at the Mid-Atlantic Ridge. Consequently, we suggest that both vertical movements and lateral changes in the motion of the plates have a common cause, which is lateral resistance to plate motion.

[†]E-mail: pj@geus.dk

"Throughout the coast of Brazil, and certainly for a considerable space inland, from the Rio Plata to Cape St. Roque, lat. 5°S, a distance of more than 2,000 geographical miles, wherever solid rocks occurs, it belongs to a granitic formation. The circumstance of this enormous area being thus constituted of materials, which almost every geologist believes to have been crystallized by the action of heat under pressure, gives rise to many curious reflections. Was this effect produced beneath the depth of a profound ocean? Or did a covering of strata formerly extend over it, which has since been removed? Can we believe that any power, acting for a time short of infinity, could have denuded the granite over so many thousand square leagues?"

—Charles Darwin, Bahia or San Salvador, Brazil, 29 February 1832 (Darwin, 1839, p. 12)

INTRODUCTION

Landscapes along the Atlantic margin of NE Brazil are in many respects similar to those along other elevated passive continental margins (cf. Ollier and Pain, 1997; Japsen et al., 2009a, 2012) around the world, including West Greenland, Scandinavia, and SE Australia (Lidmar-Bergström et al., 2000; Bonow et al., 2006a, 2006b). Common characteristics are high-level, low-relief plateaus cut by deeply incised valleys, Mesozoic-Cenozoic rift systems along the coast, where erosional unconformities commonly truncate a tilted, postrift sequence, and a transition from continental to oceanic crust offshore. In NE Brazil, the plateaus reach more than 1 km above sea level (asl), and they are in many places separated by escarpments from low-level, low-relief surfaces below 500 m asl (Figs. 1A, 1B, 2, and 3).

It is a common assumption that elevated passive continental margins have remained high since the time of rifting and breakup, and the absence of postrift sediment on many elevated passive continental margins is taken as evidence for nondeposition (e.g., Ussami et al., 1986; Ollier and Pain, 1997; Karner and Driscoll, 1999; Watts, 2001). Such assumptions have far-reaching implications for understanding landscape development, hydrocarbon systems, and the properties of the lithosphere itself. However, studies of several elevated passive continental margins have challenged the assumption of permanent uplift, instead revealing histories of multiple episodes of postrift burial and subsequent uplift and erosion (e.g., Cobbold et al., 2001; Japsen et al., 2006, 2012; Burke and Gunnell, 2008; Turner et al., 2008).

Rifting of the Brazilian margin started in the Early Cretaceous and led to the formation of the Recôncavo-Tucano-Jatobá Rift, which reaches far into the continent (Figs. 1B and 2A) (Magnavita et al., 1994; Davison, 1999; Blaich et al., 2008). Continental breakup took place at the Albian-Aptian transition (Torsvik et al., 2009). Although there is evidence that the NE Brazilian margin underwent postrift thermal subsidence (McKenzie, 1978; White and McKenzie, 1988), there is also evidence for other events:

(1) On the basis of vitrinite reflectance data, Magnavita et al. (1994) inferred that up to 2 km of postrift section have been removed from the Recôncavo-Tucano-Jatobá Rift as a result of erosion. Consequently, the postrift section within the rift is thin (<400 m).

(2) Marine, postrift sediment of Albian age crops out at 800 m asl on the Planalto (plateau) do Araripe (Arai, 2000), and correlative deposits are at 600 m asl in the Recôncavo-Tucano-Jatobá Rift (Magnavita et al., 1994). The present elevation of these marine, postrift

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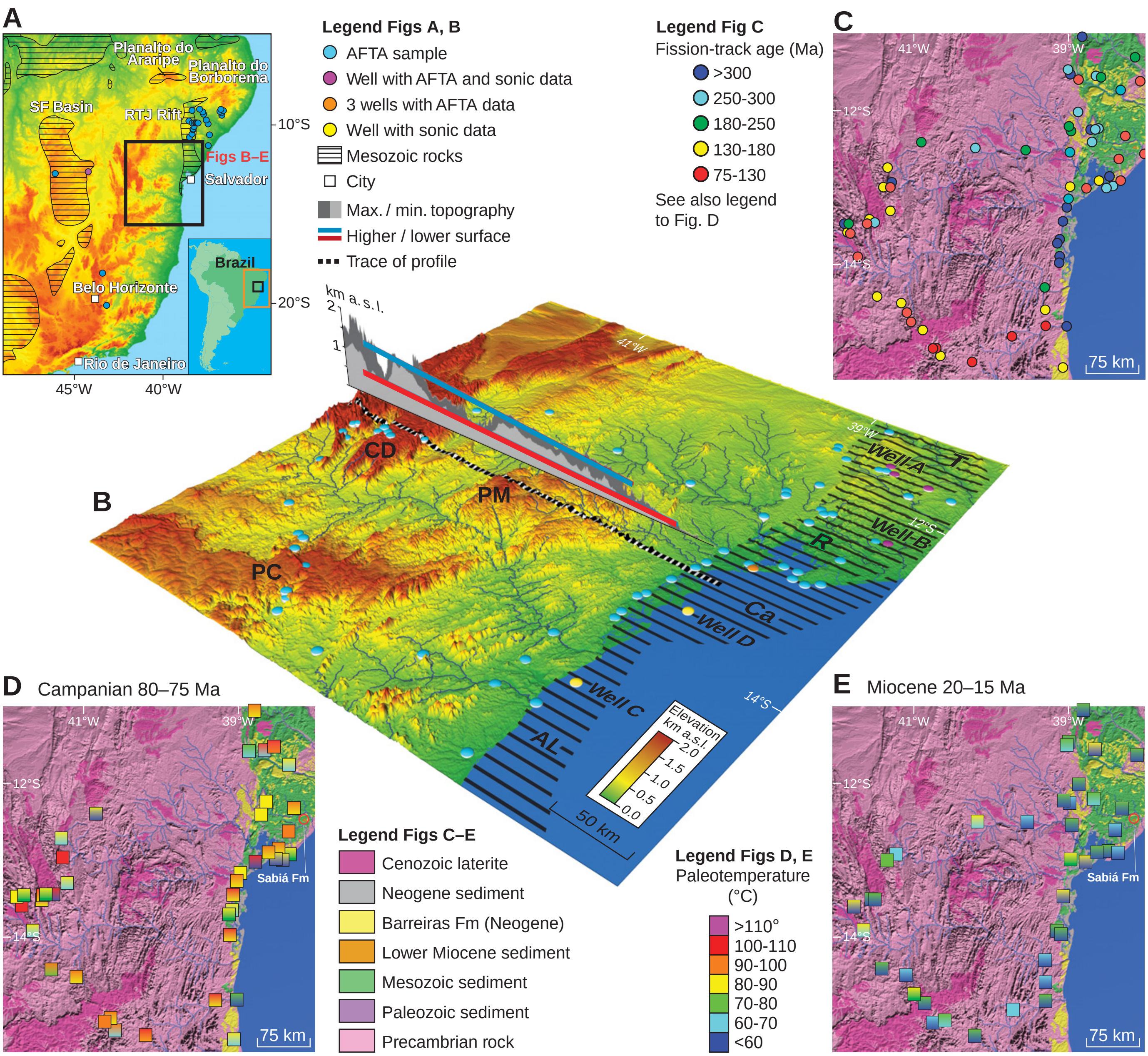

Figure 1. Maps of NE Brazil and of the main study area in eastern part of Bahia State. (A) Overview map (high grounds in yellow) (Amante and Eakins, 2008). RTJ—Recôncavo-Tucano-Jatobá Rift, SF—São Francisco. (B) Three-dimensional (3-D) map of altitude showing plateaus at ~1000 m above sea level (asl). CD—Chapada Diamantina, PM—Planalto de Maracás, PC—Planalto da Conquista. Early Cretaceous rift basins: Al—Almada, Ca—Camamu, R—Recôncavo, T—Tucano. (C) Map of fission-track ages in outcrop samples from this and previously published studies (Fig. 4). Young ages, postdating rifting, are not only in the coastal strip (as in conventional models of elevated passive continental margin development), but also occur hundreds of kilometers inland, suggesting profound denudation there. (D–E) Geological maps (CPRM, 2003) and paleotemperatures for Campanian and Miocene paleothermal episodes according to apatite fission-track analysis (AFTA) data from outcrop samples.

strata in the interior of Brazil thus testifies to postrift subsidence followed by significant uplift.

(3) The outlying Lower Miocene, marine Sabiá Formation rests on Early Cretaceous rift deposits within the Recôncavo Basin (Viana et al., 1971; Petri, 1972) (Fig. 2A). This observation indicates that the removal of the postrift section was completed prior to Miocene transgression and reburial of the margin.

(4) The plateau remnants are not easy to explain in the context of a rifted margin. Peulvast et al. (2008) suggested that the plateaus of Araripe and Borborema at 750–1100 m asl are remnants of a continuous and low-lying, Late Cretaceous

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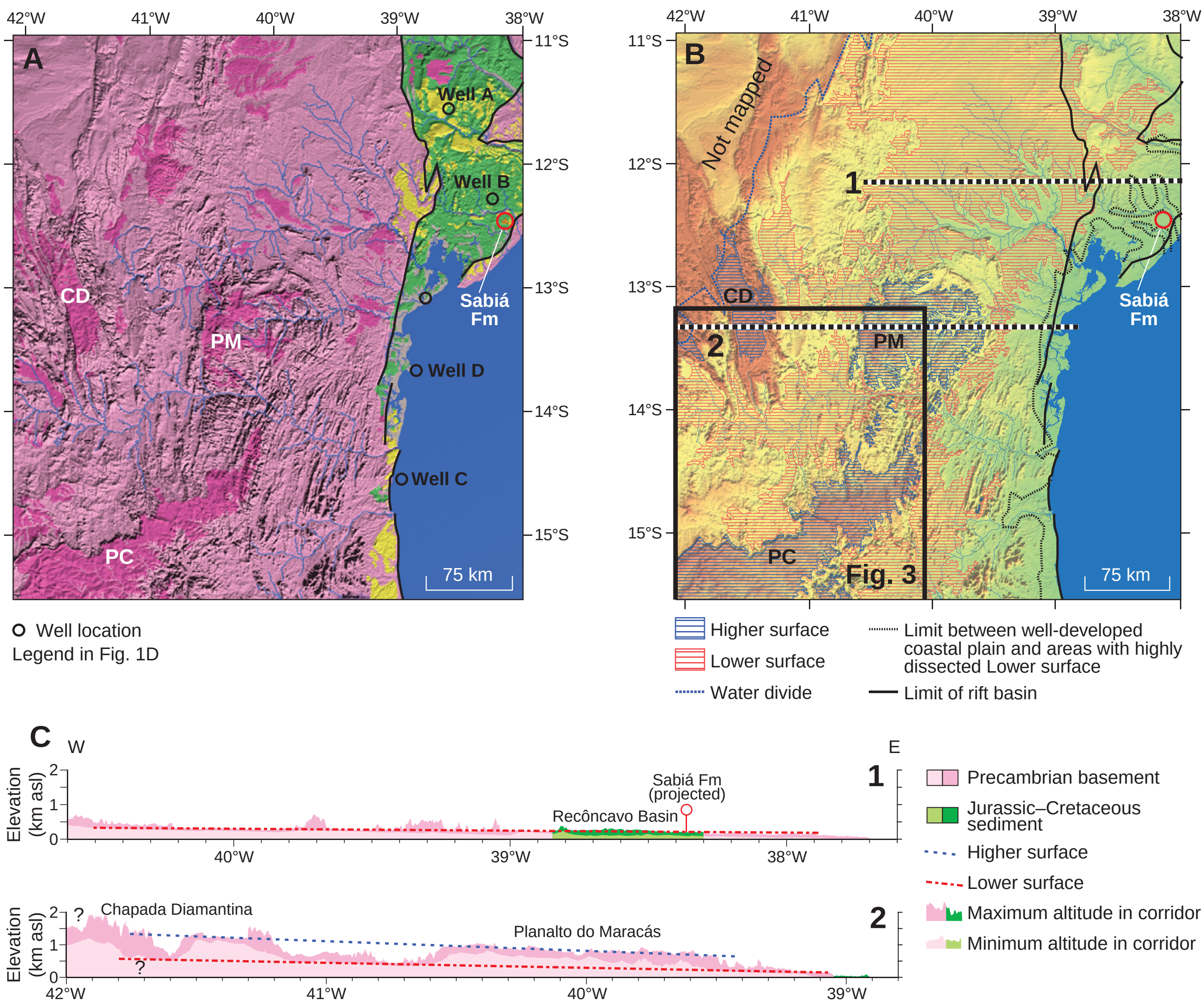

Figure 2. Geological map and interpretation of peneplains in the study area. (A) Geological map (CPRM, 2003) draped over a topographic model with limits of the Early Cretaceous rift basin (see Fig. 1B) after Magnavita et al. (1994) and Scotchman and Chiossi (2008). (B) Map of the higher surface and the lower surface in areas where they are well preserved. Edges of map coincide with black frame in Figure 1A; profile 1 continues 30 km east of this frame. Higher surface often coincides with presence of Cenozoic laterite. Lower surface extends across basement, rift sediment, and the Lower Miocene Sabiá Formation. (C) Two profiles to illustrate mapping of low-relief surfaces and interpreted peneplains, i.e., higher surface and lower surface (Bonow et al., 2009). Plateaus are part of one, seaward-dipping surface (profile 2). Locations of profiles are in Figure 2B. CD—Chapada Diamantina, PM—Planalto de Maracás, PC—Planalto da Conquista. Mapped, low-relief surfaces cut across basement (consisting of rocks that have different resistance to erosion) as well as the sedimentary sequence of the Recôncavo-Tucano-Jatobá Rift. Hence, surfaces are erosional features. According to our interpretation, the higher surface formed as a peneplain by fluvial erosion to near sea level during the Eocene–Oligocene. The higher surface was subsequently buried at the Oligocene-Miocene transition and then uplifted and re-exposed in the Miocene. Uplift caused rivers to incise, after which the lower surface formed below the higher surface.

rift flank that was uplifted in post-Cenomanian time, following deposition of the youngest rocks now on the plateau. However, apatite fission-track data from the region indicate that rocks now at the surface have cooled by at least 50 °C since the Campanian (Harman et al., 1998; Morais Neto et al., 2006, 2008, 2009), implying that kilometer-thick deposits once covered the present-day plateau surface but have been removed since the Late Cretaceous.

(5) Offshore, in the Camamu Basin (Fig. 1B), Late Cretaceous strata are thin or absent, and the Cenozoic succession is ~1 km thick, above a prominent Eocene unconformity (Cobbold et al., 2010). On the basis of vitrinite reflectance

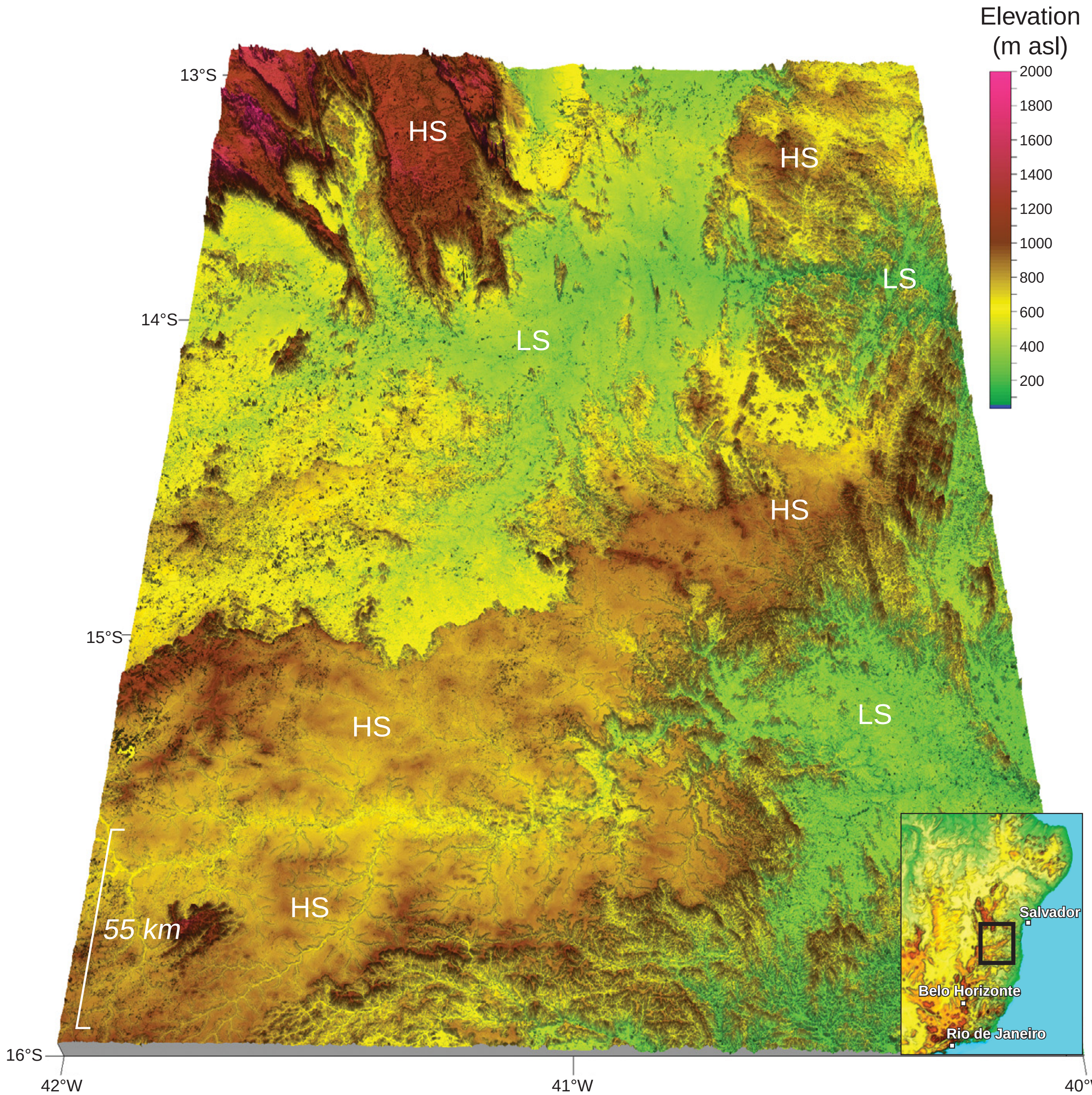

Figure 3. Altitude between Chapada Diamantina in the north and Planalto da Conquista in the south with interpretation of two peneplains, the higher surface (HS) and the lower surface (LS). The lower surface is between 300 and 400 m above sea level (asl) and dips slightly eastward. Sharp, erosional, winding escarpment separates the lower surface from higher surface. The higher surface is particularly well preserved on Planalto da Conquista (~900 m asl) where the surface covers an area of ~18,000 km^2 within the frame of Fig. 3; note the wide and shallow valley that trends toward east. The higher surface is also clearly defined on Chapada Diamantina (~1200 m asl).

data, Scotchman and Chiossi (2008) estimated that uplift and subsequent erosion have removed a kilometer-thick Cretaceous postrift section from the nearshore parts of this basin.

With this in mind, we report the outcome of an integrated study of landscape development and thermo-tectonic evolution of the elevated passive continental margin in NE Brazil, focusing on the Recôncavo-Tucano-Jatobá Rift and the extensive plateaus in the eastern part of the State of Bahia (Fig. 1A) (see also Bonow et al., 2009; Japsen et al., 2008a, 2008b, 2009b). We compare our results with those of similar studies on both sides of the South Atlantic and also with those in the North Atlantic domain, where breakup happened ~50 m.y. later than along the Brazilian margin.

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METHODS

We did field work in the main study area in 2007 and in the State of Minas Gerais in 2009 (near Belo Horizonte; Fig. 1A). The details of all analyses are available as supplementary information online.[1]

TECHNIQUE FOR MAPPING OF MAJOR LANDFORMS

We used a digital elevation model with 90 m grid (Jarvis et al., 2008) as input data for our landform analysis (Figs. 2 and 3). From the elevation data, we constructed a contour map, which is the primary input for the surface mapping. In the study area, we found that a 100 m contour gives a reasonable picture of the general landscape (cf. Bonow et al., 2006b). Furthermore, a contour map depicts the fully three-dimensional picture of the landscape, whereas the relief along a topographical profile depends on the location and azimuth of the transect (Figs. 2B and 2C). To support the mapping, we used profiles along a square grid with a spacing of 0.1°. Topographical profiles were plotted along the grid lines together with maximum and minimum heights, which we extracted every 100 m along the grid within a swath, 0.2° wide, centered along the topographical profile (Fig. 2C). The contour map and profiles were plotted on paper at a scale of 1:250,000. We analyzed 70 profiles with lengths of up to ~110 km.

We began the mapping of the surfaces in core areas that we defined from the contour map as areas of low relative relief and only minor fluvial valleys. In such areas, the maximum height along each swath coincides with the topographical profile. In this way (due to support from the profiles), we could map the same surface also in areas that are much more affected by fluvial erosion and thus more dissected. We determined the edge of a surface where there was a rapid change of inclination on the contour map. This method is also useful for identifying offsets within a surface, e.g., by faults (cf. Bonow et al., 2006b). We also identified surfaces incised below a higher plateau by aid of the minimum height along the profiles because such surfaces are guided by fluvial erosion to a base level. In summary, we identified the levels of the low-relief surfaces on the map and on the profiles. To ascertain that the interpretation was consistent, we checked that we could follow the surfaces from profile to profile. To distinguish erosion surfaces from structural surfaces, we compared our mapped surfaces with geological maps of the area (CPRM, 2003) and were thus able to identify lithological control on the mapped surfaces (cf. Fjellanger and Etzelmuller, 2003; Japsen et al., 2009a). We find that fluvial erosion down to the base level is the key to understanding the formation of extensive, low-relief surfaces such as those mapped here. Base level controls the fluvial erosion, and unless a local base level is present, represented, for example, by a resistant rock surface or an internal drainage basin, the ultimate base level is sea level, particularly for locations along continental margins after rifting and breakup. The process of valley widening by river erosion eventually results in a large-scale, low-relief erosion surface—a peneplain. Valley incision below such a surface is evidence for a lowering of base level (uplift of the landmass or drop in sea level), with subsequent formation of new valley floors grading to sea level and thus possibly resulting in the formation of a new peneplain. The height difference between the valley floor and the overlying surface therefore indicates the amount of uplift or fall in base level.

THERMOCHRONOLOGICAL ANALYSIS

We obtained apatite fission-track analysis (AFTA®) data from 83 outcrop samples from NE Brazil at elevations up to 1.6 km asl (locations shown in Fig. 1). Of these outcrop samples, 43 are of Precambrian basement, 13 are of Proterozoic sediment, and 27 are of Phanerozoic sediment. We also obtained AFTA data from 47 samples of Upper Jurassic–Lower Cretaceous sediment from seven boreholes down to 5.3 km below ground level in the Tucano and Recôncavo Basins and one sample of Proterozoic sediment from a well in the Sanfranciscana Basin (Fig. 1A). We also incorporated previously published AFTA data from 10 outcrop samples from Turner et al. (2008). Vitrinite reflectance data came from 144 samples of primarily Lower Cretaceous sediment, mainly from wells in the Tucano and Recôncavo Basins. Full details of all AFTA and vitrinite reflectance data, together with analytical details and technical background, are provided in the online data supplement (see footnote 1).

AFTA data in outcrop samples that have experienced different maximum paleotemperatures (e.g., reflecting different burial depths) prior to cooling in a single dominant episode show a well-defined relationship between mean track length and fission-track age (Green, 1986). Samples that have undergone only minor heating (say <60 °C) have old ages with relatively long mean track lengths (>13 µm), whereas samples heated above ~110 °C, in which all fission tracks were totally annealed prior to the onset of cooling, give much younger fission-track ages ("reset ages") and long mean lengths around ~14 µm or more. Between these two extremes, a decrease in fission-track age (representing increasing maximum paleotemperatures prior to the onset of cooling) is accompanied by a reduction in mean track length as tracks formed prior to the onset of cooling are progressively shortened. In the final stages of annealing, in samples heated to around 100 °C, the partially annealed tracks become so short that their contribution to the mean length is diminished. The mean length therefore increases with further reduction in fission-track age, trending upward toward the long mean length characterizing the reset ages and resulting in the characteristic "boomerang" trend. For further explanation, see Green (1986).

However, data from NE Brazil show a much more complex pattern of variation (Fig. 4), suggesting a more complex thermal-history framework involving a number of cooling episodes, and detailed assessment of data in individual samples is required before any rigorous conclusions can be reached. Nevertheless, the consistent trend shown by the data in Figure 4 suggests that a common style of thermal history affected the entire region, with different samples reaching differing paleotemperatures in the dominant regional cooling episodes. Since samples of sedimentary rock and basement plot together and define a common trend in Figure 4, the dominant, paleothermal events affected both basins and basement regions alike.

To investigate the details of the thermal history, we extracted thermal-history constraints from the AFTA and vitrinite reflectance data in each sample following the principles outlined by, e.g., Green et al. (2002, 2004) and Green and Duddy (2010). The process begins with construction of a default thermal history, assuming that the sample has never been any hotter than the present-day temperature. The default thermal history for an outcrop sample of sedimentary rock represents residence since deposition at the prevailing mean surface temperature, while for basement outcrop samples, a similar approach can be adopted using the age of the oldest overlying sedimentary unit. For downhole samples, the default thermal history is constructed from the burial history defined from the sedimentary section preserved in the well, combined with the present-day thermal gradient.

Note that this approach does not imply that the default thermal history is a realistic scenario; it simply allows an initial assessment of the data. If the default thermal history can

[1]GSA Data Repository item 2012051, full details of thermochronological analyses, landscape analysis, and analysis of sonic data, is available at http://www.geosociety.org/pubs/ft2012.htm or by request to editing@geosociety.org.

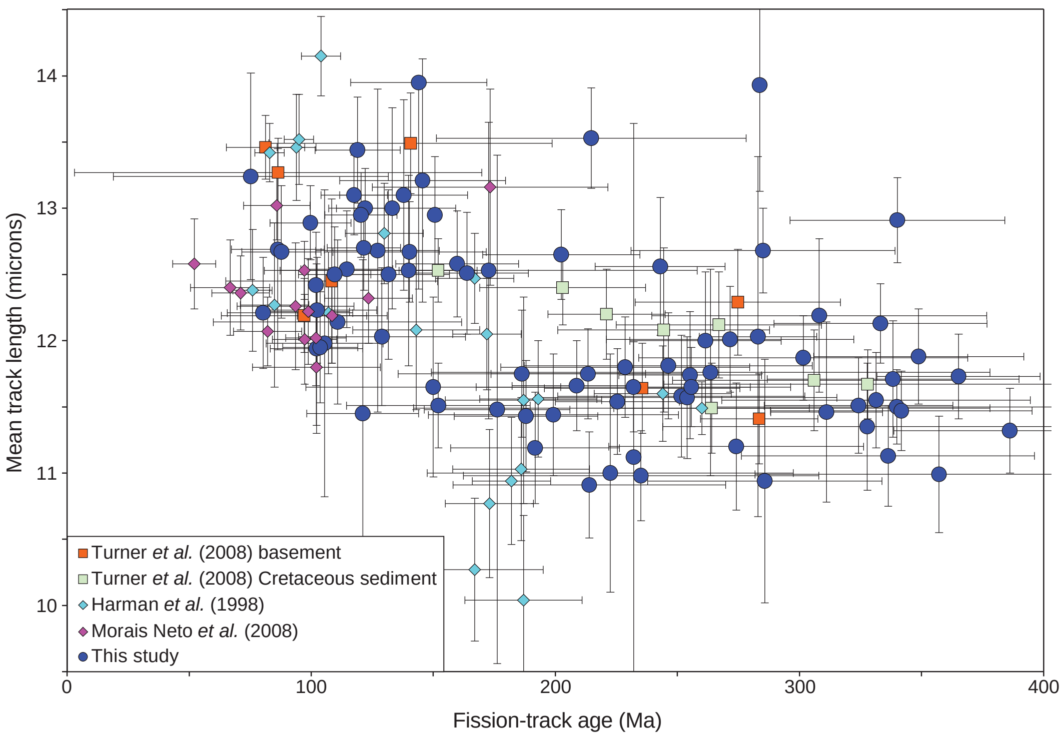

Figure 4. Mean track length versus fission-track age for outcrop samples from NE Brazil; data are from this study together with data from previously published studies (Harman et al., 1998; Morais Neto et al., 2008; Turner et al., 2008). The complex pattern revealed by the plot indicates that the thermal history involved more than just a single cooling episode. The different data sets define a consistent trend, although note that the Borborema data from Morais Neto et al. (2008) plot at the limit of the trend, suggesting a different history specific to those samples.

explain the AFTA data, possibly combined with the presence of shorter tracks inherited from sediment provenance regions, then it is not possible to extract further thermal-history information. Alternatively, if the AFTA data show a greater degree of postdepositional annealing (i.e., fission-track age and/or track-length reduction) than expected from the default thermal history, then the sample must have been hotter in the past, and information on the magnitude and timing of heating and cooling events can be extracted from the data. In this case, modeling AFTA parameters through likely thermal-history scenarios within a framework constrained as far as possible by geological data (through the default thermal history) allows definition of the range of conditions giving predictions that match the observed data within 95% confidence limits (i.e., ±2σ). In samples of sedimentary rock in which the AFTA data are dominated by tracks formed prior to deposition, it is often not possible to separate postdepositional effects from the influence of tracks formed prior to deposition, and only a limit to the magnitude of the maximum postdepositional temperature can be obtained.

We did not attempt to constrain the entire thermal history of each sample using AFTA, because the data are dominated by the effects of the maximum paleotemperature, which overprints the previous history. Instead, we focused on determining the key aspects of the thermal history that control the fission-track age and length distribution, i.e., maximum paleotemperature, and the time at which cooling began. Estimates of these parameters were extracted from the AFTA data using a kinetic model of fission-track annealing that takes full quantitative allowance of the influence of wt% Cl on annealing rates (Carlson et al., 1999; Barbarand et al., 2003). The process was explained by Green et al. (2002) and illustrated further by Green and Duddy (2010). Independent estimates of maximum paleotemperature were derived from vitrinite reflectance data using the kinetic model of Burnham and Sweeney (1989). We routinely found consistent interpretations from the two techniques using this approach (e.g., Japsen et al., 2007b; Green and Duddy, 2010).

AFTA data contain a high degree of redundancy, in the sense that many different histories can produce similar data that cannot be resolved (cf. Chalmers et al., 2010), and for this reason, integration of geological constraints is vital to extracting accurate thermal-history information. Thermochronology studies conventionally assume monotonic cooling histories, but preservation of even a thin veneer of sedimentary cover shows that underlying basement was at the surface when the sediment was deposited. Failure to take such constraints into account can result in misleading interpretations (cf. Persano et al., 2006, 2007; Brown, 2007; Gibson, 2007; Green and Duddy, 2007), since AFTA data can only define progressive cooling events and will not independently identify reheating.

Even where no sedimentary outliers are preserved, we favor an interpretation scenario involving a series of heating and cooling episodes. Such histories appear reasonable in NE Brazil, where outliers of Cretaceous sediment are widespread. AFTA data in individual samples allow resolution of multiple episodes through the distribution of track lengths, together with the fission-track age reduction. In favorable cases, three discrete episodes can be resolved from data in a single sample. Typically, the earliest event will reset the fission-track age. If the sample then cools and is reheated to 90 °C or 100 °C, tracks formed after the earlier cooling will be shortened to around 10 µm; renewed cooling followed by reheating to a lower peak paleotemperature, say 70 °C, will shorten those tracks formed after the second cooling event to around 13 µm. Quantitative modeling of the fission-track age and track-length data will show that all aspects of the data can only be explained by a scenario involving three discrete episodes of heating and cooling.

In regions that have undergone a number of cooling episodes, AFTA data will reveal only those events that dominate the data in individual samples. Synthesis of data from a large number of samples across a wide region then allows identification of the main, regional cooling episodes.

Where AFTA and/or vitrinite reflectance data are available through a vertical rock section, either from boreholes or from vertical transects in outcrop, the variation of paleotemperatures in key paleothermal episodes with depth/elevation allows the paleogeothermal gradient in each episode to be determined (Bray et al., 1992). Extrapolation of fitted paleogradients to an assumed paleosurface temperature then allows determination of the amount of section that has been removed since the onset of cooling in each episode. Paleotemperature profiles also allow identification of situations where heating is due to non-burial-related phenomena such as hot fluids (Duddy et al., 1994, 1998).

MAGNITUDE OF EXHUMATION FROM PALEOBURIAL (SONIC) DATA

We estimated the magnitude of exhumation for five well locations (four in the Recôncavo-Tucano-Jatobá Rift and one in the Camamu Basin; Figs. 1 and 5) by comparing sonic-log data for sandstone with normal velocity-depth trends (baselines). Japsen et al. (2007a) constructed baselines for sandstone based on the properties of sandstone with varying clay content, but they considered 4 km to be the maximum depth for practical purposes and thus chose anchor points at that depth to constrain the baselines in the form of modified, velocity-average equations:

$$V(z) = V_m - (V_m - V_c)e^{-z/b}, \tag{1}$$

where V_m is the matrix velocity of the sediment, V_c is the sonic velocity of the sediment at critical porosity (~1600 m/s for sand), z is depth below the surface of the sedimentary succession, and b is a decay parameter. These baselines predict velocities of around 4.5 km/s for pure sandstone (0%–5% clay) at a depth of 4 km and only a minor increase of velocity at greater depth. However, the sonic data for well D (Fig. 5C), for example, show a gradual increase of velocity from 4 to 5 km/s over a 2-km-thick sandstone interval. Consequently, we calibrated the baselines for pure sandstone to match the data from the study area (Figs. 5B and 5C) with the following parameters for the modified, velocity-average equation (Eq. 1):

$$\begin{aligned} &\text{BR00, 0\% clay: } V_m = 5400 \text{ m/s}, b = 2500 \text{ m}, \\ &\text{BR00, 5\% clay: } V_m = 5400 \text{ m/s}, b = 2800 \text{ m}. \end{aligned} \tag{2}$$

For velocities higher than ~4.5 km/s, the revised baselines plot at shallower depths than those of Japsen et al. (2007a), and thus result in smaller estimated amounts of exhumation (Fig. 5A). Figure 6C shows a comparison between the magnitude of exhumation (with estimated uncertainty) for wells A and B based on sonic data and the results based on paleothermal data. These figures show that the estimated amounts of removed section based on sonic data are 2–3 km for both wells, that the uncertainty is bigger for well A than for well B, and that the higher values of these estimates are in best agreement with the results based on the paleothermal data. The fluvial deposits with alternating sand and shale units penetrated by wells A and B only contain a few thick sand units with a uniform sonic-log pattern, and comparison with baselines is thus not straightforward.

DENUDATION CHRONOLOGY FROM LANDSCAPE ANALYSIS

Within the study area, we identified two surfaces of low relative relief and of regional extent, the higher surface and the lower surface (Figs. 1B, 2, and 3). There is also a coastal plain of limited extent, and above the level of the higher surface, there are distinct hills along ridges of particularly resistant rock (e.g., along the eastern escarpment along Chapada Diamantina; Fig. 2C). These ridges may or may not be remnants of a surface above the higher surface, but we do not address this issue in the present study. The topographic model in Figure 3 depicts the relation between the higher surface and lower surface in the central part of the study area, where a sharp, erosional, winding escarpment separates the two surfaces.

The higher surface is preserved on high ground and includes the plateaus of Chapada Diamantina (~1200 m asl) and Planalto da Conquista (~900 m asl). These plateaus define a coherent surface, dipping slightly seaward. The higher surface cuts across Proterozoic sediment and Precambrian basement that frequently is deeply weathered into a soft and disintegrated rock many tens of meters below the surface; these weathering profiles have been mapped as Cenozoic laterites by the Geological Survey of Brazil (CPRM, 2003) (e.g., Fig. 2). The higher surface and the laterites are preserved where the drainage system is unaffected by the fluvial system related to the younger, lower surface. The lower surface is well defined across wide areas in the interior (up to 500 m asl), but it can also be traced as a summit level across an intermediate zone along the coast, where it is highly dissected by the rivers that define the coastal plain. The lower surface cuts across Precambrian basement outside the rift and the postrift sediment of the Aptian Marizal Formation within the rift (Silva et al., 2007), but it also truncates the Lower Miocene, marine Sabiá Formation within the Recôncavo Basin (Viana et al., 1971; Petri, 1972).

Both the higher surface and the lower surface cut across rocks of different ages and resistances and are therefore erosional features (peneplains). They presumably formed by denudation to a nearly horizontal plain, because even slightly dipping surfaces would be incised by fluvial valleys and the relief would be rejuvenated (Rudberg, 1970) until a new and younger peneplain formed.

The higher surface must originally have extended across a larger area than that of the plateau remnants as the lower surface has developed at its expense. The higher surface is characterized by Cenozoic laterites over large areas, and both the higher surface and the laterites are currently subject to erosion along the escarpments that outline the plateaus. We consequently find that the laterites formed after fluvial erosion had graded the higher surface to base level during the Cenozoic, but prior to the uplift of the higher surface to its present elevation. The age of the lower surface is Neogene because it postdates the Lower Miocene Sabiá Formation. The older, higher surface must consequently have developed during the Paleogene prior to the early Miocene transgression. This implies that the Sabiá Formation accumulated on the higher surface (when it was near sea level), but the sediment has been found in meter-deep trenches (Petri, 1972) below the lower surface, presumably because it was thus preserved by some degree of down-faulting. The lower surface is rapidly being dissected by river incision into the soft sediment of the Recôncavo-Tucano-Jatobá Rift. We infer a change in base level that occurred recently, and this fits well with the estimate of Bigarella (1975), who suggested that this change took place since ca. 2 Ma. Both of these regional erosion surfaces developed during the Cenozoic and thus are post-breakup phenomena that formed along the Atlantic margin. Consequently, we find that sea level is the most likely base level to which the surfaces graded.

Similar plateaus outside the study area are also of Paleogene age (Fig. 1A). For example, in the Sanfranciscana Basin, a regional erosion surface truncates Maastrichtian sediment (Campos and Dardenne, 1997), and this surface correlates with the higher surface within the study area (Valadão, 1998). On the Planalto da Borborema, Paleogene sandstones and conglomerates of the continental Serra do Martins Formation cover the plateau surface (Morais Neto et al., 2008). This demonstrates that the surface was exposed in Paleogene times until the Serra do Martins Formation accumulated over it and preserved the surface to the present day. A Paleogene age for the higher surface across the highlands of Chapada Diamantina and Planalto da Conquista is also in agreement with the interpretation of King (1967), who mapped these plateaus as part of the Paleogene Sul-Americana surface. The highly dissected higher surface of

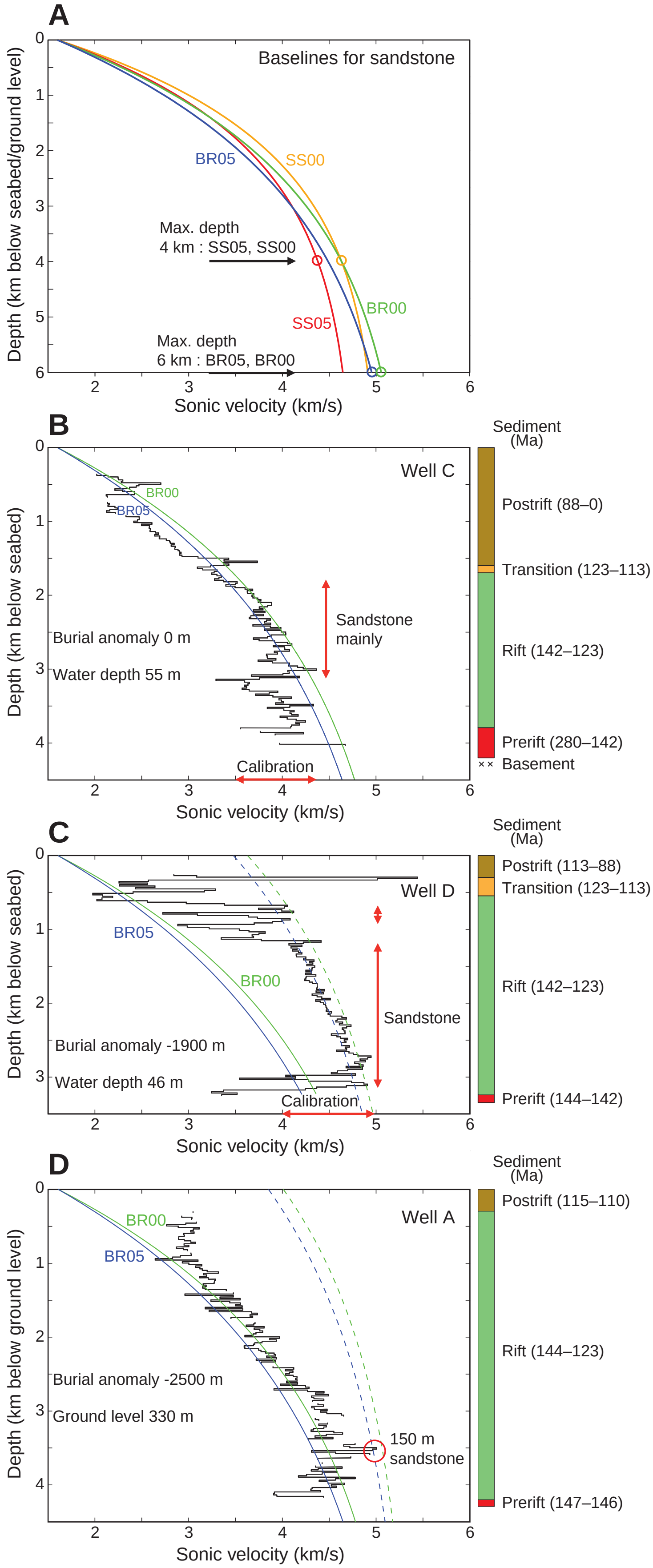

Figure 5. Plots of sonic log data compared to baselines for sandstone. (A) Baselines for sandstone. Models for 0% and 5% clay content are based on a prediction of porosity and sonic velocity of consolidated sandstone with data at 4 km depth as anchor point (SS00 and SS05; Japsen et al., 2007a). We revised baselines SS00 and SS05 by calibration to data from wells C and D that indicate 6 km as the practical maximum depth where sandstone reaches a sonic velocity of 5 km/s (BR00 and BR05: Eq. 2). (B) Plot of the sonic log for offshore well C (Almada Basin). According to the completion log, a more than 1-km-thick sedimentary sequence is dominated by sandstone. The upper bound for the sonic data in this interval shows velocities increasing from ~3.4 to 4.3 km/s, corresponding to the predictions of the SS00 and SS05 trends of Japsen et al. (2007a). Consequently, we interpreted these velocities to reflect pure sandstone at maximum burial depth and used the sonic data in this interval to calibrate the sandstone baselines. (C) Plot of the sonic log for offshore well D (Camamu Basin). According to the completion log, an ~2-km-thick interval consists of uniform sandstone, and the sonic data for this interval show a steady increase of velocity with depth from ~4 to 5 km/s. We interpreted these high velocities to be due to a greater burial of the sandstone by ~1900 m of section that has subsequently been removed, and we used the sonic data in this interval to calibrate the sandstone baselines. (D) Plot of the sonic log for onshore well A (Tucano Basin). Fluvial deposits with alternating sand and shale units dominate the drilled sequence, but a 150-m-thick sandstone unit at a depth of ~4.5 km has a sonic velocity of ~5 km/s. We compared the sonic velocity of this unit with the revised, sandstone baselines (Eq. 2) and estimated that an ~2.5-km-thick section covered the entire rift sequence (and the sandstone unit) before its removal by erosion. The sonic data were averaged over 10 m intervals after deletion of data points from borehole intervals with severe caving. The burial anomaly is the difference between present-day depth and estimated maximum burial depth (negative in case of erosion). Dashed lines are the BR00 and BR05 baselines shifted vertically by the burial anomaly to fit the sonic data for sandstone units. Location is given in Figure 1.

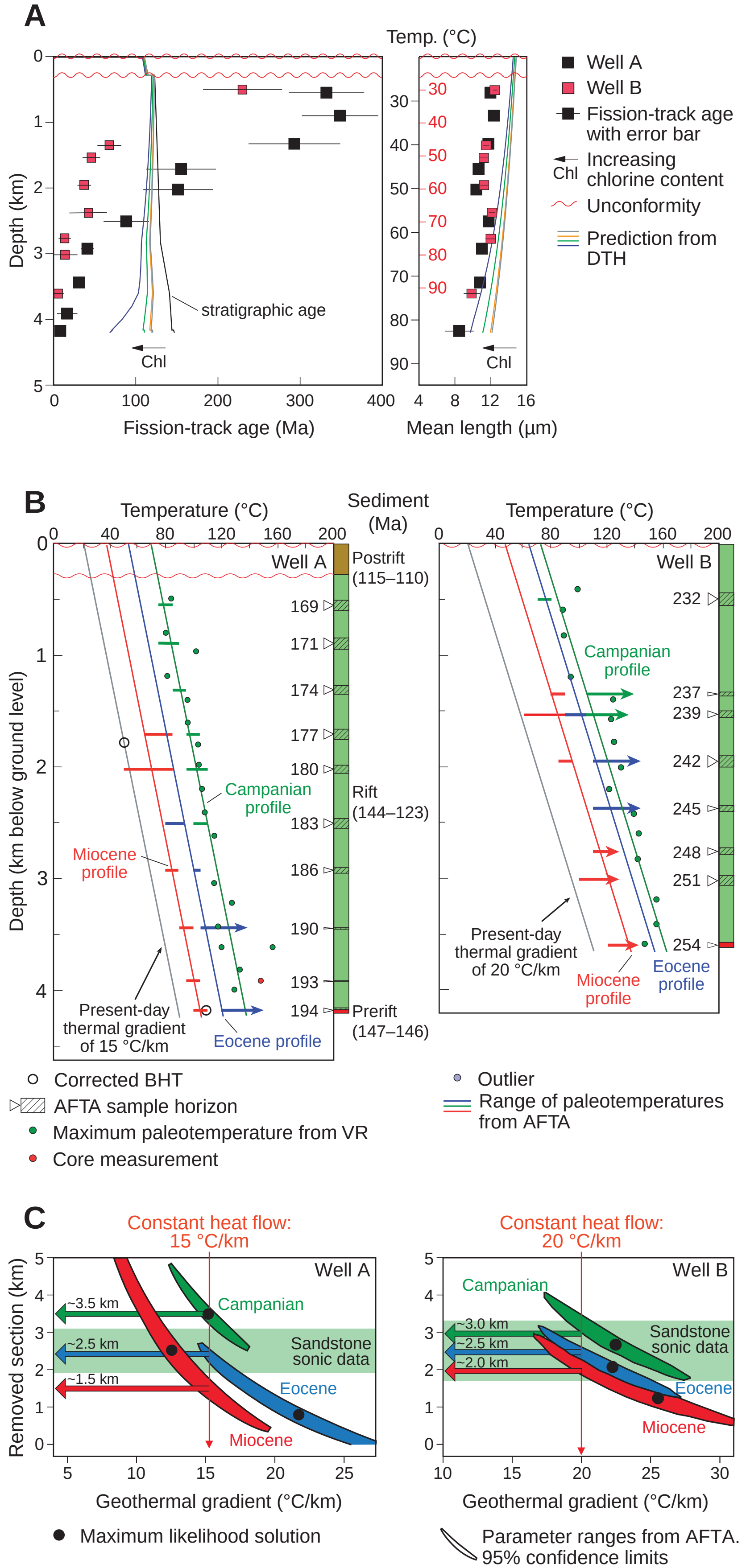

Figure 6. Paleothermal data from two wells defining burial and exhumation histories in the Recôncavo-Tucano-Jatobá Rift. (A) Apatite fission-track parameters for samples from wells A and B (drilled in the Tucano and Recôncavo Basins, respectively) plotted against depth and present-day temperature. The black line in the left panel shows the increasing stratigraphic age with depth, and the colored lines show the predicted patterns of fission-track age and mean track length for apatites containing <0.1, 0.5, 1.0, and 1.5 wt% Cl from the default thermal history (DTH). The default thermal history was derived from the preserved sedimentary section and the present-day thermal gradient calculated from corrected borehole temperatures (BHT) in each well. The fission-track ages decrease systematically with depth, and at depths greater than 2 km, they are much less than the values predicted from the default thermal history. This shows that the sampled units have been hotter in the past (Green et al., 2002). The pattern of decrease in fission-track age with depth is characteristic of a section that has undergone major cooling, with the "break in slope" at a depth of ~2.5 km representing the transition between partial and total annealing of fission tracks formed prior to the onset of cooling (cf. Green et al., 2002). The corresponding fission-track age of ca. 75 Ma represents the onset of exhumation. (B) Paleotemperature constraints versus depth in wells A and B for the Campanian, Eocene, and Miocene paleothermal episodes. Drilled stratigraphy for each well is shown to the right. Constraints for each episode in both wells define linear profiles, subparallel to the present-day temperature profile, characteristic of heating due predominantly to deeper burial. VR—vitrinite reflectance. (C) Ranges of amount of removed section and paleogeothermal gradients (banana-shaped areas) required to explain paleothermal profiles in wells A and B within 95% confidence limits. Limits on the amount of removed section were estimated from sonic data from sandstone units (rectangular areas). Interpretations based on constant geothermal gradients corresponding to present-day conditions are also indicated, with paleothermal and paleoburial (based on sonic data; Fig. 5) approaches giving highly consistent results in both wells. The present-day temperature profile for well B is based on corrected BHT data and temperatures revised on the basis of the apatite fission-track analysis (AFTA) data (see supplementary data online [see text footnote 1]).

Planalto de Maracás corresponds to the Velhas surface of King, whereas the lower surface and the coastal plain are equivalent to his Paraguaçu surface within our study area.

North of our study area (north of 8°S, east of 41°W), Peulvast et al. (2008) also identified two erosional levels of regional extent: a low plain between 0 and 300 m asl (the Sertaneja surface or Sertão), and the discontinuous remains of a high plain between 750 and 1100 m asl (including the Araripe and Borborema Plateaus). These two erosion surfaces are thus equivalent to the lower surface and higher surface, respectively, in this study. We conclude that there are two regional peneplains in NE Brazil, a lower surface (Paraguaçu/Sertaneja), and remnants of a higher surface (Sul-Americana), which were formed by erosion during Neogene and Paleogene time, respectively.

PALEOTHERMAL EVENTS DUE TO BURIAL AND EXHUMATION

We have defined nine regional cooling episodes from a synthesis of thermal history solutions derived from AFTA data in all samples (Table 1). The events date back to the Paleozoic, but here we focus on the (postrift) Cretaceous and Cenozoic development. The AFTA data define cooling episodes that began ca. 120 Ma and in the intervals 80–75, 48–45, and 18–15 Ma (Aptian, Campanian, Eocene, and Miocene cooling episodes; see Fig. 7). Note that these time intervals represent the ranges of 95% uncertainty for the onset of cooling in each episode. An Albian event that began between 110 and 105 Ma is only recognized outside the main study area (northeasternmost samples in Fig. 1A). This event correlates closely with the timing of breakup (Torsvik et al., 2009) as also recognized by Harman et al. (1998) and by Turner et al. (2008).

The Aptian cooling episode is dominant in AFTA data from most basement samples, and we interpret this event as reflecting exhumation, not only of the rift margins, but also of the hinterland (e.g., ~200 km west of the rift). Even though we did not detect it in samples from the basin fill, a major correlative unconformity is present between the synrift section and the postrift Marizal Formation of Aptian age (Silva et al., 2007), suggesting some degree of exhumation at this time.

AFTA and vitrinite reflectance data from wells in the Recôncavo-Tucano-Jatobá Rift show that the synrift sequences began to cool from their maximum, postdepositional paleotemperatures in the Campanian (Fig. 6). Variation of the Campanian paleotemperatures with depth suggests that heating was due to additional burial by 2–3 km of postrift section if the paleogeothermal gradient was similar to the present-day value, but slightly higher gradients (corresponding to lower amounts of additional burial) are also possible. Our analysis of paleoburial (sonic) data from deep wells also indicates that a 2–3-km-thick cover buried the rift sequence prior to uplift and erosion (Fig. 6C). This confirms that the geothermal gradient had remained fairly low since maximum burial and that the subsequent cooling was due primarily to exhumation. Campanian cooling dominates all AFTA data from the Recôncavo-Tucano-Jatobá Rift and the exposed parts of the Almada and Camamu Basins, and it is also important in the data from the surrounding basement regions (Fig. 1D). Heating to Campanian paleotemperatures must thus have been primarily due to deeper burial, with subsequent cooling due to exhumation. Paleotemperatures defined for outcrop samples in the interior highlands correspond to burial below a rock column of ~2 km. We consequently interpret the Campanian as a time of profound uplift and erosion across the entire area, following postrift subsidence and burial (Fig. 7).

AFTA data from some deep well samples also provide evidence for Eocene cooling. Eocene paleotemperatures were probably not of sufficient magnitude in shallower samples to be resolved from those of the Campanian and Miocene episodes, but it seems likely that Eocene cooling also affected much of the study area. Analysis of paleotemperature profiles in the wells suggests that Eocene paleotemperatures were due to additional burial by 2–2.5 km of postrift section under heat-flow conditions very close to those of the present day, and that cooling was due to renewed exhumation.

AFTA data from outcrop samples of both rift sediment and basement also consistently show Miocene cooling (Fig. 1E). Analysis of paleotemperature profiles in the wells again suggests that paleogeothermal gradients were close to present-day values, and that Miocene paleotemperatures reflect additional burial by ~1.5 km of section. Miocene paleotemperatures for samples from the highlands correspond to burial below a rock column of ~1 km. We interpret the Miocene cooling as representing regional uplift and erosion during the final phase of the exhumation history that began in the Campanian.

The postrift exhumation episodes that we have established from AFTA data correlate closely with major unconformities in the offshore Camamu and Almada Basins in the mid-Campanian, mid-Eocene, and mid-Miocene (see Table 1; Caixeta et al., 2007; Gontijo et al., 2007). The correlation is better for the Almada Basin, probably because the Camamu Basin was affected by a major, submarine slide (Cobbold et al., 2010), which has to some extent obscured the stratigraphic evidence.

The allowed range of paleogeothermal gradients for the Campanian episode in well A (Tucano Basin) is close to the present-day gradient of 15 °C/km that we derived from the AFTA data and published temperature data (Meister, 1973) (Fig. 6C), as are results for the later episodes. The range of allowed paleogradients for well B (Recôncavo Basin) is broader than that for well A, but the paleotemperatures in the three key episodes are consistent with paleogeothermal gradients in the range of 20–25 °C/km. This range overlaps with the present-day gradient in this well of ~20 °C/km that we estimated from the AFTA data. The results therefore suggest a pattern of decreasing amounts of paleoburial from

TABLE 1. INTERVALS DEFINING THE BEGINNING OF EPISODES OF REGIONAL COOLING BASED ON APATITE FISSION-TRACK ANALYSIS (AFTA) DATA IN 131 SAMPLES FROM OUTCROPS AND BOREHOLES IN NE BRAZIL

Onset of cooling (Ma)	Onset of cooling (chronostratigraphy)	Areas and rocks affected by cooling event	Equivalent hiatus (Ma)
450–410	Ordovician–Devonian	West flank of Camamu, SW hinterland*	530–440 (T)
320–300	Carboniferous	West flanks of Recôncavo and Camamu*	Ca. 300 (T)
230–220	Late Triassic	SW hinterland*	250–150 (R,T)
180–170	Middle Jurassic	Both flanks of Recôncavo, west flank of Almada, SW hinterland*	250–150 (R,T)
Ca. 120	Aptian	Most basement samples	124–116 (R,T)
110–105	Albian	Only NE samples (Fig. 1A)	–
80–75	Campanian	Sediment and basement samples	80–75 (A)
48–45	Eocene	Deep well samples	47–45 (A)
18–15	Miocene	Sediment and basement samples	16–12 (A)

Note: A—Almada Basin (Gontijo et al., 2007); R—Recôncavo Basin (Silva et al., 2007); T—North Tucano–Jatobá Basins (Costa et al., 2007).

*The earlier (pre-Cretaceous) episodes are recognized only in restricted areas where the effects of more recent events (particularly the Aptian episode) are low enough to preserve evidence of the earlier history. It seems likely that the early episodes affected a wider part of the region.

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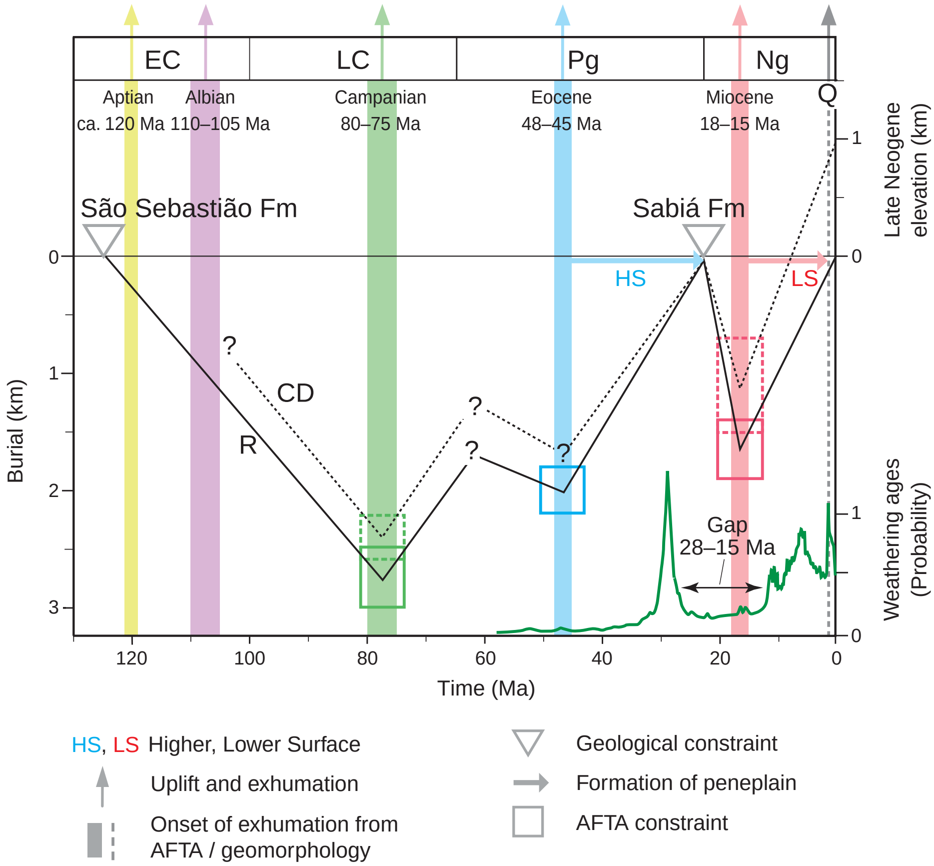

Figure 7. Burial and exhumation history of rocks now exposed on the higher and lower surfaces within the study area. CD—basement at the higher surface (HS) in Chapada Diamantina, shown by dashed line and boxes (cf. Figs. 1D and 1E). R—rift sediment close to the lower surface (LS) in the Recôncavo Basin, shown by full line and boxes (well B, Fig. 6C). Green curve—relative probability of weathering ages on the Borborema Plateau (Guia Lima, 2008) (location on Fig. 1A). The colored bands show the times of onset of cooling events defined from apatite fission-track analysis (AFTA) that are inferred to be due to episodes of uplift and exhumation, and their width indicates the uncertainty in the onset of cooling. Timing of the Quaternary event at ca. 2 Ma is according to Bigarella (1975). The Albian event is only recognized in samples east of the rift. EC—Early Cretaceous; LC—Late Cretaceous; Pg—Paleogene; Ng—Neogene; Q—Quaternary.

north (Tucano Basin) to south in each episode and a corresponding increase in basal heat flow.

Results of major apatite fission-track studies were reported from NE Brazil by Harman et al. (1998), Turner et al. (2008), and Morais Neto et al. (2008). Study areas in the first two studies partly overlap with ours, whereas the latter was focused on the Borborema Plateau (Fig. 1A). Harman et al. (1998) identified two main phases of cooling, the first in the Early Cretaceous (ca. 130 Ma) and the second in the Late Cretaceous (60–80 Ma). Harman et al. (1998) estimated a total cooling to the present day along the continental margin of ~100 °C since 130 Ma, and a cooling in the interior of their study area since 80 Ma of 50–70 °C. Turner et al. (2008) also identified two major cooling episodes that began in the intervals 110–100 Ma and 40–10 Ma. Morais-Neto et al. (2008) interpreted their data in terms of two dominant episodes of cooling that began in the intervals 100–90 Ma and 20–0 Ma, but they also reported evidence for an intermediate event in the interval 65–50 Ma. The dominant cooling episodes identified in this study correspond well with those identified by Turner et al. (2008). The Early Cretaceous cooling event of Harman et al. (1998) corresponds broadly with the Aptian event that we identified in the northeasternmost part of our study area, whereas their Late Cretaceous event corresponds to the Campanian event that we identified throughout our study area. The conclusions of the three studies are thus broadly compatible with our results, even though those studies did not resolve the full complexity of the variation in the thermal history across the region. The results of our study provide considerably more detail, in particular, because we also analyzed samples from deep wells in the rift.

INTEGRATED HISTORY OF BURIAL, UPLIFT, AND EXHUMATION

Our results show that prior to the Campanian, the present land surface was buried below a 2–3-km-thick rock column across both the rift and the interior highlands (curves “R” and “CD,” respectively, in Fig. 7), and it most likely included a continuous Cretaceous cover. The evidence from AFTA for Campanian exhumation in both the rift and the highlands suggests that sediment accumulated over both regions prior to the onset of exhumation. This seems plausible because the highlands are midway between the Cretaceous rift and the Sanfranciscana Basin, where an extensive cover of both Lower and Upper Cretaceous sediment is present (Campos and Dardenne, 1997) (Fig. 1A).

The Lower Miocene Sabiá Formation rests on Early Cretaceous rift deposits (Petri, 1972), and this indicates that the postrift section was removed during the Campanian and Eocene exhumation events within the Recôncavo Basin. An intervening phase of reburial is possible, and Campanian–Eocene sediment is present near the shore (Caixeta et al., 2007; Gontijo et al., 2007), but since such deposits are absent onshore within the study area, this scenario cannot be tested. The final removal of ~2 km of postrift sediment from within the rift occurred between the Eocene event and the early Miocene. Exhumation of similar magnitude may also have affected the interior highlands, because there is no structural evidence for major inversion of the rift and because the Eocene event correlates with tectonic activity across much of Brazil (Cobbold et al., 2001). We therefore find that the higher surface, which formed as an erosional surface during the Paleogene according to the geological and geomorphological evidence presented here, must have graded to base level after the Eocene event, which demonstrably removed 2 km within the rift.

The top of the rift sequence in the Recôncavo Basin was thus at the surface during the early Miocene transgression, but the AFTA data show that the entire sequence later was buried below an ~1.5-km-thick cover prior to Miocene exhumation (Fig. 7). The rift must consequently have been reburied below a Miocene cover with the Sabiá Formation as its basal part. Furthermore, rocks that are now exposed on the higher surface in the interior highlands were also buried below a kilometer-thick cover prior to the Miocene event. However, since the higher surface was formed by erosion to base level during the Paleogene, those rocks that are now on the higher surface were also near the surface prior to the Miocene. The higher surface was consequently reburied by sediment at the Oligocene-Miocene transition, also in the interior highlands. The younger lower surface thus formed after the Miocene event and after almost complete removal of the Miocene cover.

In summary, we conclude that the present landscape is due to multiple postrift episodes of burial, uplift, and exhumation:

(1) Following Early Cretaceous breakup, the margin underwent kilometer-scale burial beneath a sedimentary cover, with maximum burial of the synrift sequence in the Campanian (Fig. 8A).

(2) Campanian and Eocene phases of uplift led 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. 8B).

(3) Oligocene–Miocene subsidence of the interior and of the coastal zone led to reburial of the higher surface (Fig. 8C).

(4) Miocene uplift and erosion produced a new peneplain (the lower surface) by river incision below the uplifted and re-exposed higher surface. Minor uplift in the Quaternary led to incision below the lower surface and to formation of the coastal plain (Fig. 8D).

This four-stage model agrees with the results of previous studies, which found that the Recôncavo-Tucano-Jatobá Rift was buried below a kilometer-thick cover prior to exhumation (Magnavita et al., 1994), that the plateau surface (higher surface) in NE Brazil was fully developed by the end of the Paleogene (King, 1967; Bigarella, 1975; Valadão, 1998), that the Oligocene-Miocene transition was characterized by subsidence of the coastal regions throughout Brazil (Schobbenhaus and Brito Neves, 2003), and that uplift affected much of Brazil in the Miocene (King, 1967; Valadão, 1998; Cobbold et al., 2001; Bigarella et al., 2007). Aspects that have remained unrecognized in previous studies, however, are the absolute timing of the episodes of uplift and the magnitudes of the burial and exhumation episodes that followed Early Cretaceous rifting and Eocene–Oligocene peneplanation.

The outlier of the Sabiá Formation within the Recôncavo-Tucano-Jatobá Rift testifies to Miocene burial, but no remnants of such a cover have—to our knowledge—been reported from the plateaus in our study area. However, plateaus elsewhere in NE Brazil are covered with nonfossiliferous, continental sediment (Fig. 1A), e.g., the Paleogene Serra do Martins Formation (Morais Neto et al., 2008) (Planalto da Borborema), the Cenozoic Chapadão Formation (Campos and Dardenne, 1997) (the Sanfranciscana Basin), and the Chapada de Canga Formation (Sant'Anna et al., 1997) (near Belo Horizonte). Furthermore, post–30 Ma reburial of the Planalto da Borborema has been indicated by AFTA data from the Serra do Martins Formation and the underlying basement (Morais Neto et al., 2008, 2009). Along the Atlantic margin, the cover may have consisted of several formations, e.g., the Sabiá Formation, the lower part of the Neogene continental Barreiras Formation (Bigarella, 1975), and Neogene coastal deposits of the Rio Doce Formation (Gontijo et al., 2007).

Vasconcelos and Carmo (2008) found a distinct relation between Ar-Ar ages for lateritic weathering profiles and three main landscape

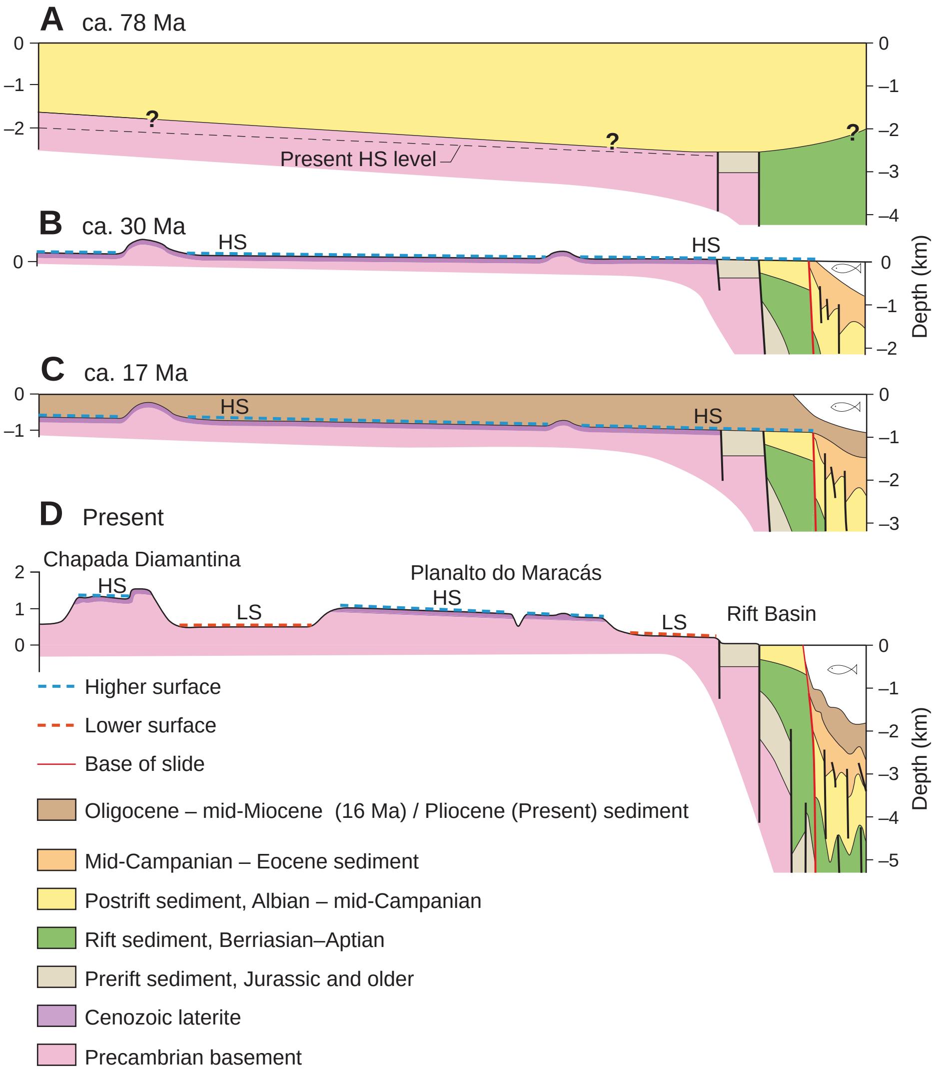

Figure 8. Burial and exhumation history along a profile across Chapada Diamantina and the rift basin, based on the topographic profile shown in Figure 1B and a geological cross section offshore (Menezes and da Silva Milhomen, 2008). (A) Ca. 78 Ma: Campanian maximum burial of the Lower Cretaceous synrift sequence below a Cretaceous cover that most likely extended over the interior highlands and into the Sanfranciscana basin (see Fig. 1A). (B) Ca. 30 Ma: Final formation of the higher surface (HS) by erosion to base level as a peneplain with deep weathering profiles and laterites after Campanian and Eocene phases of uplift and erosion. Major sliding offshore took place after the Campanian and Eocene uplift events (Cobbold et al., 2010). (C) Ca. 17 Ma: Oligocene–Miocene burial of the interior highlands and of the coastal zone. (D) Present: re-exposure of the higher surface and formation of the lower surface (LS) by river incision after Miocene uplift. Minor uplift in the Quaternary led to incision below the lower surface and to formation of the coastal plain.

types in Brazil. Weathering ages are 70–30 Ma for the main plateau surfaces (Sul-Americana), 15–6 Ma for intermediate surfaces (Velhas), and less than 4 Ma for lower surfaces (Paraguaçu). Notably, the authors highlighted the major gaps in the record, pre–70 Ma and 30–15 Ma. Reburial of the higher surface by an Oligocene–Miocene cover provides a straightforward explanation for the gap in the weathering record between 30 and 15 Ma (see Fig. 7; Guia Lima, 2008), 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 may similarly explain the lack of pre–70 Ma weathering ages.

BURIAL AND EXHUMATION OF THE EOCENE FONSECA FORMATION IN THE HIGHLANDS OF MINAS GERAIS

A rare insight into the Cenozoic development of the highlands in the interior of Brazil is possible due to an outlier of the Eocene Fonseca Formation near Belo Horizonte in the State of Minas Gerais, ~500 km southwest of the study area (Fig. 1A). This sediment is preserved in a small, graben-like basement structure ~800 m asl, and it is unconformably overlain by the undated, ironstone conglomerate of the Chapada de Canga Formation (Sant'Anna et al., 1997).

Abundant organic material from a sample of the Fonseca Formation was analyzed in the source-rock laboratory at the Geological Survey of Denmark and Greenland (GEUS) and yielded a reliable T_{max} value of 427 °C, which is equivalent to a vitrinite reflectance of 0.4%–0.5% (Tissot and Welte, 1984), corresponding to a paleotemperature between 66 and 83 °C (cf. Green et al., 2002). This result is highly consistent with AFTA data from a basement sample collected near the Fonseca outcrop (fission-track age 126.9 ± 14.5 Ma; mean track length 12.1 ± 0.2 µm). The thermal history extracted from these data involves cooling from >110 °C around 150 Ma, followed by subsequent cooling from 100 °C to 85 °C, which began in the interval 145–70 Ma, and finally between 80 °C and 60 °C in the interval 50–10 Ma. The two earlier cooling events correlate with the Jurassic and Campanian events identified in the main study area (Table 1). The similarity between the paleotemperatures in the most recent event defined from AFTA and those indicated by the T_{max} value confirms that this event postdates deposition of the Fonseca Formation. The timing defined by AFTA spans both the Eocene and Miocene events identified from regional data, and it remains uncertain whether maximum burial of the Fonseca Formation occurred in late Paleogene or Neogene times.

Whatever the timing, these post-Fonseca paleotemperatures are equivalent to burial under 1.5–2.0 km of cover for a paleogeothermal gradient of 25 °C/km or a cover of 0.7–1.0 km for a gradient of 60 °C/km. Because the Fonseca Formation was deposited by a meandering river system (Sant'Anna et al., 1997), more extensive areas must have been covered by these kilometer-thick deposits of Eocene and younger sediment. A likely scenario is thus that even the highest summit in the area, Pico do Sol (2.1 km asl), was buried under this cover. Furthermore, the predominantly early Eocene ages (Spier et al., 2006) for the formation of deep weathering profiles, less than 100 km from the outcrop of the Fonseca Formation, most likely reflect exposure prior to the deposition of (and burial by) the Fonseca Formation. The weathering profiles thus remained immune to erosion for tens of millions of years because they were protected by a sedimentary cover, not because of low erosion rates since Eocene time (e.g., Spier et al., 2006).

In summary, these observations lead us to suggest that the area was low-lying during the deposition of the Fonseca Formation, and that it subsided until the rocks now exposed at present-day surface were buried under fluvial deposits in post-Fonseca times. The present landscape thus formed much later, i.e., after kilometer-scale uplift and removal of the now-lost overburden to the Fonseca Formation.

POSTRIFT UPLIFT IN THE ATLANTIC DOMAIN

West Greenland provides another example from the Atlantic domain of an elevated passive continental margin with high-level plateaus (Bonow et al., 2006a, 2006b). Major differences relative to the evolution of the Brazilian margin (apart from the present climate) are that breakup happened much later west of Greenland (mid-Paleocene; Chalmers and Pulvertaft, 2001) and that seafloor spreading there has ceased (end-Eocene; Chalmers and Pulvertaft, 2001). In both West Greenland (Japsen et al., 2006) and NE Brazil, maximum burial of the rift took place tens of millions of years after breakup and was followed by several phases of uplift and exhumation, eventually leading to formation of the present-day landscape, which is characterized by elevated plateaus in various stages of dissection (Figs. 9A and 9B). The regional peneplains were formed by erosion after uplift that started between 48 and 45 Ma in NE Brazil and between 36 and 30 Ma in West Greenland; the subsequent uplift of the peneplains started between 18 and 15 Ma and between 11 and 10 Ma in the two areas, respectively. The plateau surfaces in NE Brazil were thus graded to base level during Eocene–Oligocene times, whereas those in West Greenland formed during Oligocene–Miocene times. The uplift of the peneplains and the formation of the present-day landscape by destruction of the peneplains began in the mid-Miocene in NE Brazil, but in the late Miocene in West Greenland. The dominant uplift events in Greenland thus happened ~10 m.y. later than in Brazil.

Japsen et al. (2012) suggested that landscapes typical of elevated passive continental margins around the world, characterized by elevated plateaus and coastal plains (cf. Ollier and Pain, 1997; Lidmar-Bergström et al., 2000), are generally independent of the processes of rifting and continental breakup. In addition to West Greenland (Japsen et al., 2006, 2009a) and NE Brazil (this study), this hypothesis also appears to apply to other margins, e.g., South Africa (King, 1967; Burke and Gunnell, 2008), SE Australia (Holdgate et al., 2008), and West Africa (Turner et al., 2008). We consequently suggest that the assumption, common to many previous studies, that rift margins remain permanently elevated after breakup is not reasonable. Japsen et al. (2012) thus argued that the present elevation of passive continental margins is due, not to the formation of the margin, but rather to its presence. Elevated passive continental margins occur close to abrupt boundaries between stretched and nonstretched lithosphere along the margin, and this is also the case in NE Brazil (Blaich et al., 2008).

Our results show that an interval of 20 m.y. is sufficient to form a regional peneplain by erosion to base level, after rejuvenation of relief during an initial uplift event (Figs. 9A and 9B). In NE Brazil, the plateau surfaces are defined by the higher surface, whereas they are defined by the upper planation surface in West Greenland. The time available for the formation of these regional peneplains was around 20 m.y. (~15–18 and 19–26 m.y., respectively). The lower surface forms an extensive surface below the plateaus in Brazil, whereas the lower planation surface in Greenland is a generation of paleovalleys incised below the upper planation surface. There was more time available for the formation of the lower surface in Brazil than for the lower planation surface in Greenland (~16–13 and 7–3 m.y., respectively), which seems reasonable given that the lower surface (Brazil) is more extensive than the lower planation surface (Greenland). On a geological time scale, there is evidence that relief disappears relatively quickly (e.g., Casas-Sainz and Cortes-Gracia, 2002; Japsen et al., 2009a).

Pronounced events of uplift and erosion in the Campanian (e.g., Walford et al., 2005; Turner

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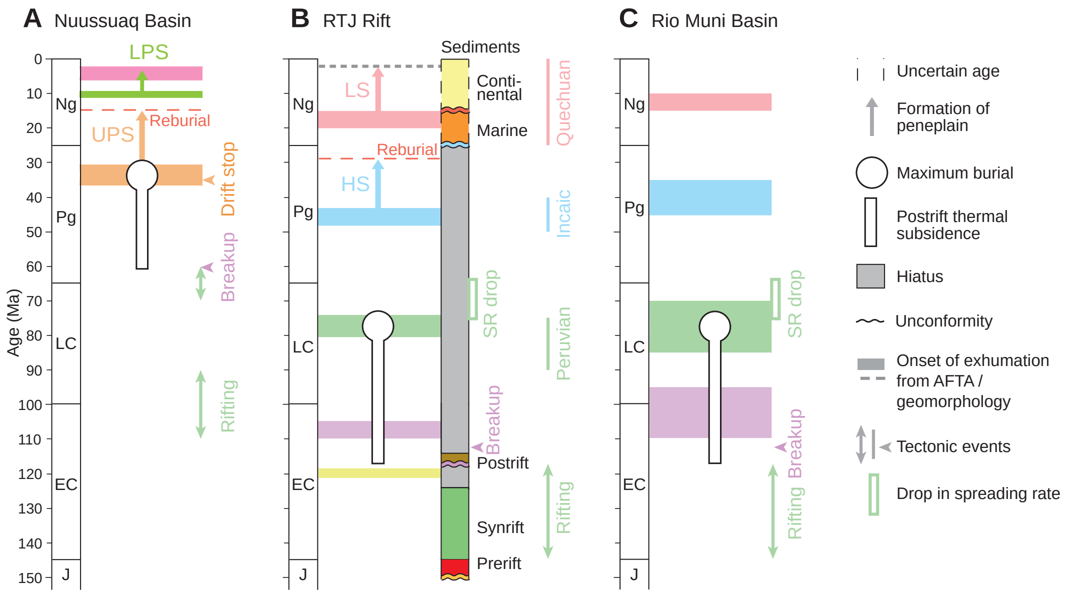

Figure 9. Comparison among timing of uplift events, formation of peneplains, and tectonic episodes along margins in the Atlantic domain. (A) Nuussuaq Basin (~70°N), West Greenland (Japsen et al., 2006). The upper planation surface (UPS) defines the plateau, whereas the lower planation surface (LPS) is a system of paleovalleys (Bonow et al., 2006a, 2006b). (B) Recôncavo-Tucano-Jatobá Rift (RTJ; ~12°S), NE Brazil (this study). Stratigraphy is after Viana et al. (1971) and Silva et al. (2007) (postrift sediment: Aptian Marizal Formation; marine sediment: Lower Miocene Sabiá Formation; continental sediment: Neogene Barreiras Formation). Main phases of Andean orogeny: Peruvian, Incaic, and Quechuan (Pardo-Casas and Molnar, 1987; Cobbold et al., 2001, 2007). (C) Rio Muni Basin (~2°N), West Africa (Turner et al., 2008) (conjugate margin to NE Brazil). The colors of the vertical bands indicate onset of uplift events and the interpreted correlation between events on the conjugate margins in NE Brazil and West Africa. The present-day landscapes in NE Brazil and West Greenland were formed millions of years after breakup when regional peneplains (higher surface and upper planation surface, respectively) were uplifted and dissected during the Neogene. Changes in plate motion are after Chalmers and Pulvertaft (2001) and Torsvik et al. (2009). SR—spreading rate; AFTA—apatite fission-track analysis; J—Jurassic; EC—Early Cretaceous; LC—Late Cretaceous; Pg—Paleogene; Ng—Neogene. See also caption to Figure 7.

et al., 2008; Rouby et al., 2009) and in the Eocene and Miocene (e.g., Walford et al., 2005; Turner et al., 2008) have also been documented from western and southwestern Africa. Evidence for several, broadly synchronous, trans-Atlantic uplift phases that postdate breakup of the South Atlantic (cf. Figs. 9B and 9C) is, however, presented here for the first time, although Harman et al. (1998) noted the symmetry between intracontinental deformation in Brazil and central Africa in the Late Cretaceous. In agreement with this trans-Atlantic synchronicity, Burke and Gunnell (2008) showed that many aspects of the postrift development of Africa are similar to NE Brazil. They presented both onshore and offshore evidence that southern Africa was low-lying by Santonian times (84 Ma), and that Afro-Arabia was dominated by a low-lying, low-relief land surface mantled by deeply weathered rock by mid-Oligocene times. However, Burke and Gunnell (2008) failed to produce an integrated model of burial and exhumation capable of explaining young fission-track ages in Africa postdating rifting by many million years far into the continental interior (a similar pattern to NE Brazil; Fig. 1C).

The Campanian, Eocene, and Miocene uplift phases in NE Brazil also coincide with three main phases of Andean orogeny, which occurred during periods of relatively rapid convergence at the Andean margin of South America (Pardo-Casas and Molnar, 1987; Cobbold et al., 2001, 2007): Peruvian (90–75 Ma), Incaic (50–40 Ma), and Quechuan (25–0 Ma). Since the Campanian uplift event in NE Brazil coincided with rapid convergence on the Andean margin of South America and with a decline in the Atlantic spreading rate (Torsvik et al., 2009) (and thus presumably not with increased ridge push), we suggest that all these uplift events have a common cause, which is lateral resistance to plate motion. Because the uplift phases in NE Brazil and SW Africa are common to the margins of two diverging plates, we also suggest that the driving forces can transmit across the spreading axis, probably at great depth, e.g., in the asthenosphere. The interaction between the differential opening of the Central and South Atlantic Oceans and Late Cretaceous continental tectonics in Brazil and central Africa also agrees with previous observations (e.g., Fairhead and Binks, 1991; Harman et al., 1998). Similarly, a phase of uplift and erosion at the Eocene-Oligocene transition (ca. 35 Ma), which affected margins around the North Atlantic (Green and Duddy, 2010; Japsen et al., 2010), correlates with a major plate reorganization there (Gaina et al., 2009).

CONCLUSIONS

We have presented paleothermal and paleoburial evidence that the Recôncavo-Tucano-Jatobá Rift as well as the proximal parts of the Camamu and Almada Basins along the Brazilian margin were buried below a thick, postrift section (<3.5 km) in agreement with the classical theory of continental stretching that predicts postrift thermal subsidence (e.g., McKenzie, 1978; White and McKenzie, 1988). However, our results contrast with other predictions of this theory because even though postrift subsidence lasted for a considerable time (~35 m.y.), the rift and margin were subject to uplift and exhumation, which started in the Campanian between 80 and 75 Ma. We thus explain the small remaining amount of postrift sequence within the Recôncavo-Tucano-Jatobá Rift through the removal of most of these deposits by forces that were unrelated to rifting and continental breakup, rather than by recourse to special conditions during rifting. The presence of marine, postrift sediment of mid-Cretaceous age at considerable elevation within the Recôncavo-Tucano-Jatobá Rift and in the interior of NE Brazil provides further evidence for postrift subsidence and subsequent uplift of both the margin and its hinterland.

We find that the elevated plateaus, which are dominant features in the study area, are remnants of an erosion surface that formed as a consequence of the uplift movements that affected the margin long after rifting. AFTA data from well samples provide evidence for the final removal of ~2 km of postrift sediment during an Eocene uplift event (that began between 48 and 45 Ma), and the presence of the Lower Miocene Sabiá outlier within the rift shows that this removal was completed in the Paleogene. Since there is no evidence for major inversion of the rift, we find that the peneplain that defines the plateaus (the higher surface) was graded to base level after the Eocene event. The relict weathering profiles that occur below the higher surface formed after fluvial erosion had graded the higher surface to base level, whereas the marine Sabiá Formation accumulated on this peneplain during the early Miocene transgression that affected much of the Brazilian margin.

The formation of the present relief is not the result of continuous uplift since the Campanian. The integration of thermochronological data with the results of the landscape analysis and the geological record shows that the higher surface was reburied at the Oligocene-Miocene transition below a cover (<1.5 km) prior to uplift and exhumation that started in the Miocene between 18 and 15 Ma. We interpret the Sabiá outlier to be a remnant of this cover, and sediment of equivalent age is present along the coast of Brazil, both onshore and offshore. Furthermore, plateaus elsewhere in NE Brazil are covered with nonfossiliferous, continental sediment, e.g., the Paleogene Serra do Martins Formation on the Planalto da Borborema. The lower surface was formed after the Miocene event by river incision below the uplifted and re-exposed higher surface, whereas minor uplift in the Quaternary led to incision below the lower surface and to formation of the coastal plain. This sequence of postrift events agrees with the results of many previous studies, but here we have been able to define the magnitude and timing of the burial and exhumation episodes that followed Early Cretaceous rifting and Eocene–Oligocene peneplanation.

A phase of Campanian–Eocene reburial is possible, but such deposits are absent within the study area. They are, however, present close offshore and in the highlands in the interior of Brazil, where the Eocene Fonseca Formation was deposited by a meandering river system. Paleothermal data for this unit and for the underlying basement indicate that an extensive area was covered by kilometer-thick deposits of Eocene and younger sediment. This implies that the predominantly early Eocene formation of weathering profiles in the area reflects exposure prior to the deposition of the Fonseca Formation, and that the present landscape formed after the removal of the now-lost overburden to the Fonseca Formation. We therefore suggest that the late sedimentary cover protected the Paleogene weathering profiles from erosion for millions of years. Burial of Paleogene weathering profiles elsewhere in Brazil may also explain why there is a general gap in the weathering record between 30 and 15 Ma as reported by Vasconcelos and Carmo (2008).

Elevated plateaus in various stages of dissection characterize the landscape along the Atlantic margin of NE Brazil. We have shown that this landscape, typical of elevated passive continental margins around the world, formed long after rifting and breakup. In the west part of Greenland, breakup happened ~50 m.y. later than along the Brazilian margin, but elevated plateaus in Greenland are also the result of several phases of postrift burial and exhumation (Japsen et al., 2006). The results from these diverse areas show that an interval of 20 m.y. is sufficient to form a regional peneplain by erosion to base level, after rejuvenation of relief during an initial uplift event. We find that the assumption in many previous studies that rift margins remain high cannot be supported.

The postrift uplift phases in NE Brazil were synchronous with uplift phases in Africa and the Andes. Because the uplift phases in NE Brazil and SW Africa are common to the margins of diverging plates, we suggest that the driving forces can transmit across the spreading axis, probably at great depth. The Campanian event coincided with a decline in the Atlantic spreading rate that was related to major changes in the relative plate motions in the South Atlantic. We conclude that both vertical movements and lateral changes in the motion of the plates have a common cause, which is lateral resistance to plate motion.

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REFERENCES CITED

Amante, C., and Eakins, B.W., 2008, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis: Boulder, Colorado, National Geophysical Data Center, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, http://www.ngdc.noaa.gov/mgg/global/global.html (accessed November 2011).

Arai, M., 2000, Chapadas: Relicts of mid-Cretaceous interior seas in Brazil: Revista Brasileira de Geociencias, v. 30, p. 436–438.

Barbarand, J., Carter, A., Wood, I., and Hurford, A.J., 2003, Compositional and structural control of fission track annealing in apatite: Chemical Geology, v. 198, p. 107–137, doi:10.1016/S0009-2541(02)00424-2.

Bigarella, J.J., 1975, The Barreiras Group in northeast Brazil: Anais da Academia Brasileira de Ciencias, v. 47, p. 365–393.

Bigarella, J.J., Becker, R.D., and Passos, E., 2007, Processos Erosivos, Vertentes Movimentos de Massa, Atividade Endógena, Superfícies de Erosão: Florianópolis, Brazil, Universidade Federal de Santa Catarina, 1436 p.

Blaich, O.A., Tsikalas, F., and Faleide, J.I., 2008, Northeastern Brazilian margin: Regional tectonic evolution based on integrated analysis of seismic reflection and potential field data and modelling: Tectonophysics, v. 458, p. 51–67, doi:10.1016/j.tecto.2008.02.011.

Bonow, J.M., Japsen, P., Lidmar-Bergström, K., Chalmers, J.A., and Pedersen, A.K., 2006a, Cenozoic uplift of Nuussuaq and Disko, West Greenland—Elevated erosion surfaces as uplift markers of a passive margin: Geomorphology, v. 80, p. 325–337, doi:10.1016/j.geomorph.2006.03.006.

Bonow, J.M., Lidmar-Bergström, K., and Japsen, P., 2006b, Paleosurfaces in central West Greenland as reference for identification of tectonic movements and estimation of erosion: Global and Planetary Change, v. 50, p. 161–183, doi:10.1016/j.gloplacha.2005.12.011.

Bonow, J.M., Japsen, P., Green, P.F., Cobbold, P.R., Pedreira, A.J., Lilletveit, R., and Chiossi, D., 2009, Post-rift landscape development of north-east Brazil: Geological Survey of Denmark and Greenland Bulletin, v. 17, p. 81–84.

Bray, R.J., Green, P.F., and Duddy, I.R., 1992, Thermal history reconstruction using apatite fission track analysis and vitrinite reflectance; a case study from the UK East Midlands and southern North Sea, *in* Hardman, R.F.P., ed., Exploration Britain: Geological Insights for the Next Decade: Geological Society of London Special Publication 67, p. 2–25.

Brown, M.C., 2007, Discussions and Reply—Apatite (U-Th)/He age constraints on the Mesozoic and Cenozoic evolution of the Bathurst region, New South Wales: Evidence for antiquity of the continental drainage divide along a passive margin: Australian Journal of Earth Sciences, v. 54, p. 1011–1012.

Burke, K., and Gunnell, Y., 2008, The African Erosion Surface: A Continental-Scale Synthesis of Geomorphology, Tectonics, and Environmental Change over the Past 180 Million Years: Boulder, Colorado, Geological Society of America, 66 p.

Burnham, A.K., and Sweeney, J.J., 1989, A chemical kinetic model of vitrinite reflectance maturation: Geochimica et Cosmochimica Acta, v. 53, p. 2649–2657, doi:10.1016/0016-7037(89)90136-1.

Caixeta, J.M., da Silva Milhomen, P., Witzke, R.E., Dupuy, I.S.S., and Gontijo, G.A., 2007, Bacia de Camamu: Boletim de Geociencias da Petrobras, v. 15, p. 455–461.

Campos, J.E.G., and Dardenne, M.A., 1997, Origem e evolução tectônica da bacia Sanfranciscana: Revista Brasileira de Geociencias, v. 27, p. 283–294.

Carlson, W.D., Donelick, R.A., and Ketcham, R.A., 1999, Variability of apatite fission-track annealing kinetics: I. Experimental results: The American Mineralogist, v. 84, p. 1213–1223.

Casas-Sainz, A.M., and Cortes-Gracia, A.L., 2002, Cenozoic landscape development within the Central Iberian Chain, Spain: Geomorphology, v. 44, p. 19–46, doi:10.1016/S0169-555X(01)00129-5.

Chalmers, J.A., and Pulvertaft, T.C.R., 2001, Development of the continental margins of the Labrador Sea: A review, *in* Wilson, R.C.L., Withmarsh, R.B., Taylor, B., and Froitzheim, N., eds., Non-Volcanic Rifting of Continental Margins: A Comparison of Evidence from Land and Sea: Geological Society of London Special Publication 187, p. 77–105.

Chalmers, J.A., Green, P., Japsen, P., and Rasmussen, E.S., 2010, The Scandinavian mountains have not persisted since the Caledonian orogeny. A comment on Nielsen et al. (2009a): Journal of Geodynamics, v. 50, p. 94–101, doi:10.1016/j.jog.2010.02.001.

Cobbold, P.R., Meisling, K.E., and Mount, V.S., 2001, Reactivation of an obliquely rifted margin, Campos and Santos Basins, southeastern Brazil: The American Association of Petroleum Geologists Bulletin, v. 85, p. 1925–1944.

Cobbold, P.R., Rossello, E.A., Roperch, P., Arriagada, C., Gómez, L.A., and Lima, C., 2007, Distribution, timing, and causes of Andean deformation across South America, *in* Ries, A.C., Butler, R.W.H., and Graham, R.H., eds., Deformation of the Continental Crust: The Legacy of Mike Coward: Geological Society of London Special Publication 272, p. 583–592.

Cobbold, P.R., Gilchrist, G., Scotchman, I.C., Chiossi, D., Fonseca Chaves, F., Gomes de Souza, F., and Lilletveit, R., 2010, Large submarine slides on a steep continental margin (Camamu Basin, NE Brazil): Journal of the Geological Society of London, v. 167, p. 583–592, doi:10.1144/0016-76492009-033.

Costa, I.P., Bueno, G.V., Milhomem, P.S., Lima e Silva, H.S.R., and Kosin, M., 2007, Sub-bacia de Tucano Norte e Bacia de Jatobá: Boletim de Geociencias da Petrobras, v. 15, p. 445–453.

CPRM (Geological Survey of Brazil), 2003, Mapa Geológico Região Centro Oriental da Bahia: Brasilia, Brazil, CPRM, scale 1:1,000,000, CD-ROM.

Darwin, C., 1839, Journal and remarks.1832–1836, *in* Fitzroy, R., and Darwin, C., eds., Narrative of the Surveying Voyages of His Majestie's Ships *Adventure* and *Beagle*: Between the Years of 1826 and 1836 Describing Their Examination of the Southern Shores of South America and the *Beagles* Circumnavigation of the Globe: London, Henry Colburn, 615 p.

Davison, I., 1999, Tectonics and hydrocarbon distribution along the Brazilian South Atlantic margin, *in* Cameron, N.R., Bate, R.H., and Clure, V.S., eds., The Oil and Gas Habitats of the South Atlantic: Geological Society of London Special Publication 153, p. 133–151.

Duddy, I.R., Green, P.F., Bray, R.J., and Hegarty, K.A., 1994, Recognition of the thermal effects of fluid flow in sedimentary basins, *in* Parnell, M., ed., Geofluids: Origin, Migration and Evolution of Fluids in Sedimentary Basins: Geological Society of London Special Publication 78, p. 325–345.

Duddy, I.R., Green, P.F., Hegarty, K.A., Bray, R.J., and O'Brien, G.W., 1998, Dating and duration of hot fluid flow events determined using AFTA® and vitrinite reflectance–based thermal history reconstruction, *in* Parnell, J., ed., Dating and Duration of Hot Fluid Flow and Fluid-Rock Interaction: Geological Society of London Special Publication 144, p. 41–51.

Fairhead, J.D., and Binks, R.M., 1991, Differential opening of the Central and South Atlantic Oceans and the opening of the West African rift system: Tectonophysics, v. 187, p. 191–203, doi:10.1016/0040-1951(91)90419-S.

Fjellanger, J., and Etzelmuller, B., 2003, Stepped paleosurfaces in southern Norway—Interpretation of DEM-derived topographic profiles: Norsk Geologisk Tidsskrift (Norwegian Journal of Geology), v. 57, p. 102–110.

Gaina, C., Gernigon, L., and Ball, P., 2009, Paleocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent: Journal of the Geological Society of London, v. 166, p. 601–616, doi:10.1144/0016-76492008-112.

Gibson, D.L., 2007, Discussions and Reply—Apatite (U-Th)/He age constraints on the Mesozoic and Cenozoic evolution of the Bathurst region, New South Wales: Evidence for antiquity of the continental drainage divide along a passive margin: Australian Journal of Earth Sciences, v. 54, p. 1012–1015.

Gontijo, G.A., da Silva Milhomen, P., Caixeta, J.M., Dupuy, I.S.S., and Menezes, P.E.L., 2007, Bacia de Almada: Boletim de Geociencias da Petrobras, v. 15, p. 463–473.

Green, P.F., 1986, On the thermo-tectonic evolution of northern England: Evidence from fission track analysis: Geological Magazine, v. 123, p. 493–506, doi:10.1017/S0016756800035081.

Green, P.F., and Duddy, I.R., 2007, Discussions and Reply—Apatite (U-Th)/He age constraints on the Mesozoic and Cenozoic evolution of the Bathurst region, New South Wales: Evidence for antiquity of the continental drainage divide along a passive margin: Australian Journal of Earth Sciences, v. 54, p. 1009–1020, doi:10.1080/08120090701488339.

Green, P.F., and Duddy, I.R., 2010, Synchronous exhumation events around the Arctic including examples from the Barents Sea and Alaska North Slope, *in* Vining, B.A., and Pickering, S.C., eds., Petroleum Geology: From Mature Basins to New Frontiers—Proceedings of the 7th Petroleum Geology Conference: London, Geological Society, p. 633–644.

Green, P.F., Duddy, I.R., and Hegarty, K.A., 2002, Quantifying exhumation from apatite fission-track analysis and vitrinite reflectance data: Precision, accuracy and latest results from the Atlantic margin of NW Europe, *in* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P., and White, N., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration: Geological Society of London Special Publication 196, p. 331–354.

Green, P.F., Crowhurst, P.V., and Duddy, I.R., 2004, Integration of AFTA and (U-Th)/He thermochronology to enhance the resolution and precision of thermal history reconstruction in the Anglesea-1 well, Otway Basin, SE Australia, *in* Boult, P.J., Johns, D.R., and Lang, S.C., eds., Eastern Australian Basins Symposium II (Adelaide, 19–22 September): Petroleum Exploration Society of Australia Special Publication, p. 117–131.

Guia Lima, M.D., 2008, A História do Intemperismo na Província Borborema Oriental, Nordeste do Brasil: Implicações Paleoclimáticas e Tectônicas [Ph.D. thesis]: Natal, Brazil, Universidade Federal do Rio Grande do Norte, 251 p.

Harman, R., Gallagher, K., Brown, R., Raza, A., and Bizzi, L., 1998, Accelerated denudation and tectonic/geomorphic reactivation of the cratons of northeastern Brazil during the Late Cretaceous: Journal of Geophysical Research–Solid Earth, v. 103, p. 27,091–27,105, doi:10.1029/98JB02524.

Holdgate, G.R., Wallace, M.W., Gallagher, S.J., Wagstaff, B.E., and Moore, D., 2008, No mountains to snow on: Major post-Eocene uplift of the East Victoria Highlands; evidence from Cenozoic deposits: Australian Journal of Earth Sciences, v. 55, p. 211–234, doi:10.1080/08120090701689373.

Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A., and Lidmar-Bergström, K., 2006, Elevated, passive continental margins: Long-term highs or Neogene uplifts? New evidence from West Greenland: Earth and Planetary Science Letters, v. 248, p. 330–339, doi:10.1016/j.epsl.2006.05.036.

Japsen, P., Mukerji, T., and Mavko, G., 2007a, Constraints on velocity-depth trends from rock physics models: Geophysical Prospecting, v. 55, p. 135–154, doi:10.1111/j.1365-2478.2007.00607.x.

Japsen, P., Green, P.F., Nielsen, L.H., Rasmussen, E.S., and Bidstrup, T., 2007b, Mesozoic-Cenozoic exhumation events in the eastern North Sea Basin: A multi-disciplinary study based on palaeothermal, palaeoburial, stratigraphic and seismic data: Basin Research, v. 19, p. 451–490, doi:10.1111/j.1365-2117.2007.00329.x.

Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A., and Lidmar-Bergström, K., 2008a, Cenozoic uplift around the North and South Atlantic, *in* The 33rd International Geological Conference, Abstract CD-ROM: Oslo, Norway, 1 p.

Japsen, P., Bonow, J.M., Green, P.F., Cobbold, P.R., Pedreira, A.J., Lilletveit, R., and Chiossi, D., 2008b, Burial and exhumation history of NE Brazil: Preliminary results based on apatite fission-track analysis, landscape analysis and the stratigraphic record, *in* American Association of Petroleum Geologists International Conference and Exhibition: Cape Town, South Africa, American Association of Petroleum Geologists, Abstracts CD, 1 p.

Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A., and Lidmar-Bergström, K., 2009a, Formation, uplift and dissection of planation surfaces at passive continental margins—A new approach: Earth Surface Processes and Landforms, v. 34, p. 683–699, doi:10.1002/esp.1766.

Japsen, P., Bonow, J.M., Green, P.F., Cobbold, P.R., Chiossi, D., and Lilletveit, R., 2009b, Burial, uplift and exhumation history of the Atlantic margin of NE Brazil, *in* American Association of Petroleum Geologists International Conference and Exhibition, 15–18 November 2009: Rio de Janeiro, Brazil, American Association of Petroleum Geologists, Abstracts volume CD, 4 p.

Japsen, P., Green, P.F., Bonow, J.M., Rasmussen, E.S., Chalmers, J.A., and Kjennerud, T., 2010, Episodic uplift and exhumation along North Atlantic passive margins: Implications for hydrocarbon prospectivity, *in* Vining, B.A., and Pickering, S.C., eds., Petroleum Geology: From Mature Basins to New Frontiers—Proceedings of the 7th Petroleum Geology Conference: London, Geological Society, p. 979–1004.

Japsen, P., Chalmers, J.A., Green, P.F., and Bonow, J.M., 2012, Elevated, passive continental margins: Not rift shoulders but expressions of episodic, post-rift burial and exhumation: Global and Planetary Change (in press), doi:10.1016/j.gloplacha.2011.05.004.

Jarvis, A., Reuter, H.I., Nelson, A., and Guevara, E., 2008, Hole-Filled Seamless SRTM Data v. 4: International Centre for Tropical Agriculture (CIAT), http://srtm.csi.cgiar.org (accessed November 2011).

Karner, G.D., and Driscoll, N.W., 1999, Tectonic and stratigraphic development of the West African and eastern Brazilian margins; insights from quantitative basin modelling, *in* Cameron, N.R., Bate, R.H., and Clure, V.S., eds., The Oil and Gas Habitat of the South Atlantic: Geological Society of London Special Publication 153, p. 11–40.

King, L.C., 1967, The Morphology of the Earth: Edinburgh, UK, Oliver and Boyd, 699 p.

Lidmar-Bergström, K., Ollier, C.D., and Sulebak, J.C., 2000, Landforms and uplift history of southern Norway: Global and Planetary Change, v. 24, p. 211–231, doi:10.1016/S0921-8181(00)00009-6.

Magnavita, L.P., Davison, I., and Kusznir, N.J., 1994, Rifting, erosion, and uplift history of the Recôncavo-Tucano-Jatobá Rift, northeast Brazil: Tectonics, v. 13, p. 367–388, doi:10.1029/93TC02941.

McKenzie, D.P., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32, doi:10.1016/0012-821X(78)90071-7.

Meister, E.M., 1973, Gradientes geotérmicos nas bacias sedimentares brasileiras: Boletim Técnico Petrobras, v. 16, p. 221–232.

Menezes, P.E.L., and da Silva Milhomen, P., 2008, Tectônica de sal nas bacias de Cumuruxatiba, do Almada e de Camamu, *in* Mohriak, W., Szatmari, P., and Couto Anjos, S.M., eds., Geologia e Tectônica. Exemplos nas Bacias Brasileiras: Rio de Janeiro, Ediçoes Beca Ltd., p. 251–270.

Morais Neto, J.M., Hegarty, K.A., and Karner, G.D., 2006, Preliminary constraints on paleotemperature and landscape evolution in and around Araripe Basin, northeastern Brazil, using apatite fission track analysis: Boletim de Geociencias da Petrobras, v. 14, p. 113–119.

Morais Neto, J.M., Green, P.F., Karner, G.D., and Alkmim, F.F., 2008, Age of the Serra do Martins Formation, Borborema Plateau, northeastern Brazil: Constraints from apatite and zircon fission track analysis: Boletim de Geociencias da Petrobras, v. 16, p. 23–52.

Morais Neto, J.M., Hegarty, K.A., Karner, G.D., and Alkmim, F.F., 2009, Timing and mechanisms for the generation and modification of the anomalous topography of the Borborema Province, northeastern Brazil: Marine and Petroleum Geology, v. 26, p. 1070–1086, doi:10.1016/j.marpetgeo.2008.07.002.

Ollier, C.D., and Pain, C.F., 1997, Equating the basal unconformity with the paleoplain: A model for passive margins: Geomorphology, v. 19, p. 1–15, doi:10.1016/S0169-555X(96)00048-7.

Pardo-Casas, F., and Molnar, P., 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time: Tectonics, v. 6, p. 233–248, doi:10.1029/TC006i003p00233.

Persano, C., Bishop, P., and Stuart, F.M., 2006, Apatite (U-Th)/He age constraints on the Mesozoic and Cenozoic evolution of the Bathurst region, New South Wales: Evidence for antiquity of the continental drainage divide along a passive margin: Australian Journal of Earth Sciences, v. 53, p. 1041–1050, doi:10.1080/08120090600923303.

Persano, C., Bishop, P., and Stuart, F.M., 2007, Discussions and Reply—Apatite (U-Th)/He age constraints on the Mesozoic and Cenozoic evolution of the Bathurst region, New South Wales: Evidence for antiquity of the continental drainage divide along a passive margin: Australian Journal of Earth Sciences, v. 54, p. 1005–1020.

Petri, S., 1972, Foraminíferos e o ambiente de deposição dos sedimentos do Mioceno do Recôncavo Baiano: Revista Brasileira de Geociencias, v. 2, p. 51–67.

Peulvast, J.P., Sales, V.C., Bétard, F., and Gunnell, Y., 2008, Low post-Cenomanian denudation depths across the Brazilian northeast: Implications for long-term landscape evolution at a transform continental margin: Global and Planetary Change, v. 62, p. 39–60, doi:10.1016/j.gloplacha.2007.11.005.

Rouby, D., Bonnet, S., Guillocheau, F., Gallagher, K., Robin, C., Biancotto, F., Dauteuil, O., and Braun, J., 2009, Sediment supply to the Orange sedimentary system over the last 150 My: An evaluation from sedimentation/denudation balance: Marine and Petroleum Geology, v. 26, p. 782–794, doi:10.1016/j.marpetgeo.2008.08.004.

Rudberg, S., 1970, The sub-Cambrian peneplain in Sweden and its slope gradient: Zeitschrift für Geomorphologie, Supplementband, v. 9, p. 157–167.

Sant'Anna, L.G., Schorscher, H.D., and Riccomini, C., 1997, Cenozoic tectonics of the Fonseca Basin region, eastern Quadrilatero Ferrifero, MG, Brazil: Journal of South American Earth Sciences, v. 10, p. 275–284, doi:10.1016/S0895-9811(97)00016-3.

Schobbenhaus, C., and Brito Neves, B.B., 2003, A geologia do Brasil no contexto da plataforma Sul-Americana, *in* Bizzi, L., Schobbenhaus, C., Vidotti, R.M., and Goncalves, J.H., eds., Geologia, Tectônica e Recursos Minerais do Brasil: Brasília, Brazil, CPRM (Geological Survey of Brazil), p. 1–54.

Scotchman, I.C., and Chiossi, D., 2008, Kilometre-scale uplift of the Early Cretaceous rift section, Camamu Basin, offshore north-east Brazil, *in* American Association of Petroleum Geologists International Conference and Exhibition: Cape Town, South Africa, American Association of Petroleum Geologists, 26 p (American Association of Petroleum Geologists Search and Discovery article 50183, http://www.searchanddiscovery.com).

Silva, O.B., Caixeta, J.M., da Silva Milhomen, P., and Kosin, M., 2007, Bacia de Recôncavo: Boletim de Geociencias da Petrobras, v. 15, p. 423–431.

Spier, C.A., Vasconcelos, P.M., and Oliveira, S.M.B., 2006, Ar-40/Ar-39 geochronological constraints on the evolution of lateritic iron deposits in the Quadrilatero Ferrifero, Minas Gerais, Brazil: Chemical Geology, v. 234, p. 79–104, doi:10.1016/j.chemgeo.2006.04.006.

Tissot, B.P., and Welte, D.H., 1984, Petroleum Formation and Occurrence: Berlin, Springer Verlag, 699 p.

Torsvik, T.H., Rousse, S., Labails, C., and Smethurst, M.A., 2009, A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin: Geophysical Journal International, v. 177, p. 1315–1333, doi:10.1111/j.1365-246X.2009.04137.x.

Turner, J.P., Green, P.F., Holford, S.P., and Lawrence, S.R., 2008, Thermal history of the Rio Muni (West Africa)–NE Brazil margins during continental breakup: Earth and Planetary Science Letters, v. 270, p. 354–367, doi:10.1016/j.epsl.2008.04.002.

Ussami, N., Karner, G.D., and Bott, M.H.P., 1986, Crustal detachment during South Atlantic rifting and deformation of Tucano-Gabon basin system: Nature, v. 322, p. 629–632, doi:10.1038/322629a0.

Valadão, R.C., 1998, Evolução de Longo-termo do Relevo do Brasil Oriental [Ph.D. thesis]: Salvador, Brazil, Universidade Federal da Bahia, 243 p.

Vasconcelos, P., and Carmo, I.D., 2008, Calibrating denudation chronology through ^{40}Ar/^{39}Ar weathering geochronology, *in* 33rd International Geological Conference, Abstract CD-ROM: Oslo, 1 p.

Viana, C.F., da Gama Junior, E., da Araújo Simöes, I., Moura, J.A., dos Reis Fonseca, J., and Alves, R.J., 1971, Revisão estratigráfica da bacia Recôncavo/Tucano: Boletim Técnico Petrobras, v. 14, p. 157–192.

Walford, H.L., White, N.J., and Sydow, J.C., 2005, Solid sediment load history of the Zambezi Delta: Earth and Planetary Science Letters, v. 238, p. 49–63, doi:10.1016/j.epsl.2005.07.014.

Watts, A.B., 2001, Isostasy and Flexure of the Lithosphere: Cambridge, UK, Cambridge University Press, 458 p.

White, N., and McKenzie, D., 1988, Formation of the steers head geometry of sedimentary basins by differential stretching of the crust and mantle: Geology, v. 16, p. 250–253, doi:10.1130/0091-7613(1988)016<0250:FOTSSH>2.3.CO;2.

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