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

Peter Japsen¹, Johan M. Bonow¹, Paul F. Green², Peter R. Cobbold³, Dario Chiossi⁴, Ragnhild Lilletveit⁵, Luciano P. Magnavita⁶, and Augusto Pedreira⁷

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

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 Albic 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...
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
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
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.

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 km² 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).
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 if 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...
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 paleoearth thermal 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. 1B 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:

\[ V(z) = V_m - (V_m - V_s)e^{bz} \]

where \( V_m \) is the matrix velocity of the sediment, \( V_s \) 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):

- BR00, 0% clay: \( V_m = 5400 \text{ m/s}, b = 2500 \text{ m} \)
- BR00, 5% clay: \( V_m = 5400 \text{ m/s}, b = 2800 \text{ m} \)

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 paleoeth-
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 Arraípe 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. Paleotemperature values 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 sediments 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 paleogeothermals 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 which we estimated from the AFTA data. The results therefore suggest a pattern of decreasing amounts of paleoburial from...
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.

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 non-fossiliferous, 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).

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 (Paraguacu). 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.

**EPISODIC 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 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.

**POSTSTRFT UPLIFT IN THE ATLANTIC DOMAIN**

West Greenland provides another example from the Atlantic domain of an elevated passive continental margin with high-level plateaus (Bonnor 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 penepalns 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 penepalns 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 penepalns and the formation of the present-day landscape by destruction of the penepalns 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 penepaln 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 penepalns 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...
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 peneplain surface (UPS) defines the plateau, whereas the lower peneplain 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 Sábiá 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 peneplain 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 the low relief was dominated by a low-laying, 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 paleo-burial 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 Sábiá 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 Sábiá 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 Sábiá 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 post rift 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 the vertical movements and lateral changes in the motion of the plates have a common cause, which is lateral resistance to plate motion.

ACKNOWLEDGMENTS

This study was supported financially by Statoil do Brasil and Petrobras. We thank Tony Doré for initiating the study, Lucy Sant’Anna and Claudio Riccomini for inspiring discussions and for providing us with sample material of the Fonseca Formation, Henrik Ingerman Petersen and Carsten Guvad for analyzing the organic content of the sample of the Fonseca Formation, and James A. Chalmers for commenting on the paper. The paper is published with permission of the Geological Survey of Denmark and Greenland, Petrobras, and Statoil do Brasil. AFTA® is the registered trademark of Georack International Pty Ltd.

REFERENCES CITED


Chalmers, J.A., Green, P., Japsen, P., and Rasmussen, E.S., 2010, The Scandianian basins have not persisted

Geological Society of America Bulletin, published online on 13 January 2012 as doi:10.1130/B30515.1
Episodic burial and exhumation in NE Brazil


SCIENCE EDITOR: CHRISTIAN KOEBERL
ASSOCIATE EDITOR: STEFANO MAZZOLI

MANUSCRIPT RECEIVED 25 MARCH 2011
REVISED MANUSCRIPT RECEIVED 29 JUNE 2011
MANUSCRIPT ACCEPTED 13 JULY 2011
Printed in the USA