Post-rift landscape development of north-east Brazil

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The evolution of the landscape of north-east Brazil in relation to the burial and exhumation history of both onshore and offshore areas is the focus of a research project carried out for StatoilHydro do Brasil and Petrobras from 2007 to 2009 by the Geological Survey of Denmark and Greenland in collaboration with Geotrack International. In hydrocarbon exploration it is important to understand the regional tectonic framework and thus also to consider the volumes of rocks that may have been present and then removed during the geological past. For example, the timing of hydrocarbon generation and changes in migration routes can be assessed when the timing and magnitude of uplift and erosion is known. Studies in West Greenland have demonstrated the usefulness of large-scale, low-relief, high-level landscapes as markers of uplift events, and in particular the strength of combining the denudation history from landscape analysis with the cooling history from apatite fission-track analysis (AFTA) data and the stratigraphic record (Bonow *et al.* 2006, 2007; Japsen *et al.* 2006, 2009). In the study area, there are two plateaux with elevations up to *c.* 1300 m above sea level (a.s.l.). The plateaux are currently being dissected by deeply incised fluvial valleys, and escarpments separate the two plateaux. The lowlands cut across Early Cretaceous rift systems along the Atlantic margin, including the intracontinental Recôncavo–Tucano–Jatobá (RTJ) Rift and also the Camamu Basin, of which the western margin is exposed onshore (Fig. 1). The RTJ Rift is a mature hydrocarbon province, whereas the deep-water parts of the Camamu Basin are the target of frontier exploration (e.g. Magnavita *et al.* 1994; Davison 1999; Cobbold *et al.* 2008). The post-rift sequence in the RTJ Rift and the inshore Camamu Basin is thin or absent. However, it has been estimated that up to 2000 m of sedimentary cover once was present, but has now been removed (Magnavita *et al.* 1994).

The Atlantic margin of Brazil is characterised by elevated plateaux cut by deeply incised valleys, but this landscape has a pattern common with many other passive continental margins with elevations from 1000 to 2000 m a.s.l. or more around the world, for example in Norway, East and West Greenland and south-east Australia. Mesozoic–Cenozoic rift systems parallel to the coast are generally present offshore

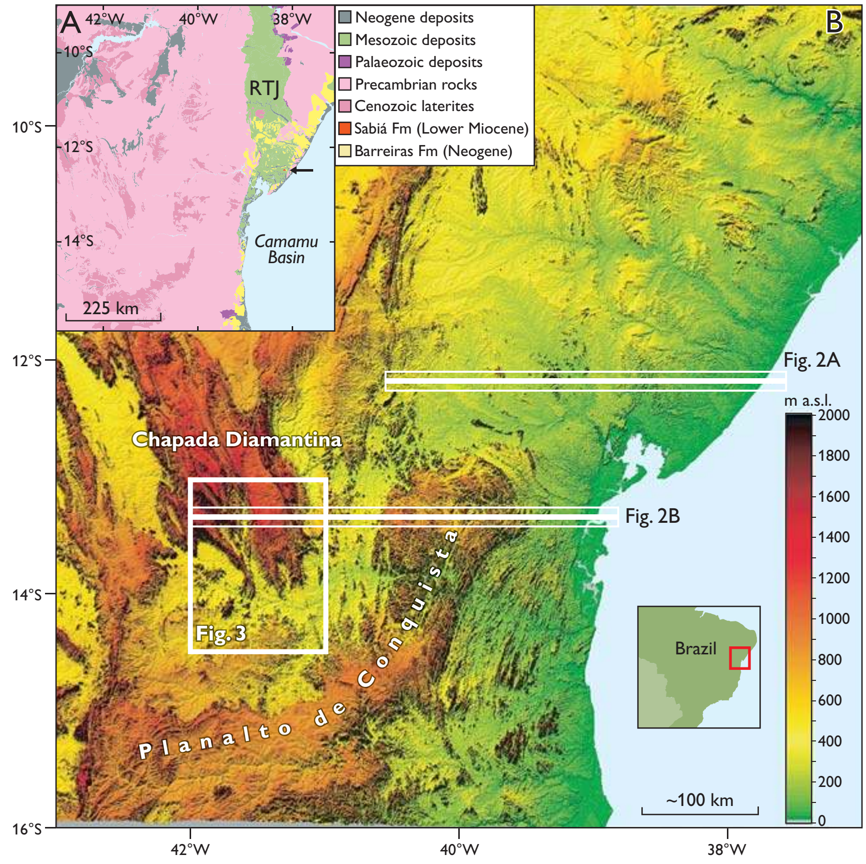

Fig. 1. **A**: Geological map of the study area (based on CPRM 2001, 2003). Precambrian basement is covered by younger sedimentary sequences, which are important age constraints for the different peneplains. **RTJ,** Recôncavo – Tucano–Jatobá Basin. The arrow points at the small Sabiá Formation outcrop. **B**: Topography of the study area. Two topographical features dominate the landscape: a lower surface, which is a plain mainly at 200–500 m a.s.l. (greenish and light yellow) and the higher surface which is a plain mainly at 900–1200 m a.s.l. (orange and reddish). Pronounced escarpments separate the two features. Elevation data source: Jarvis *et al.* (2008).

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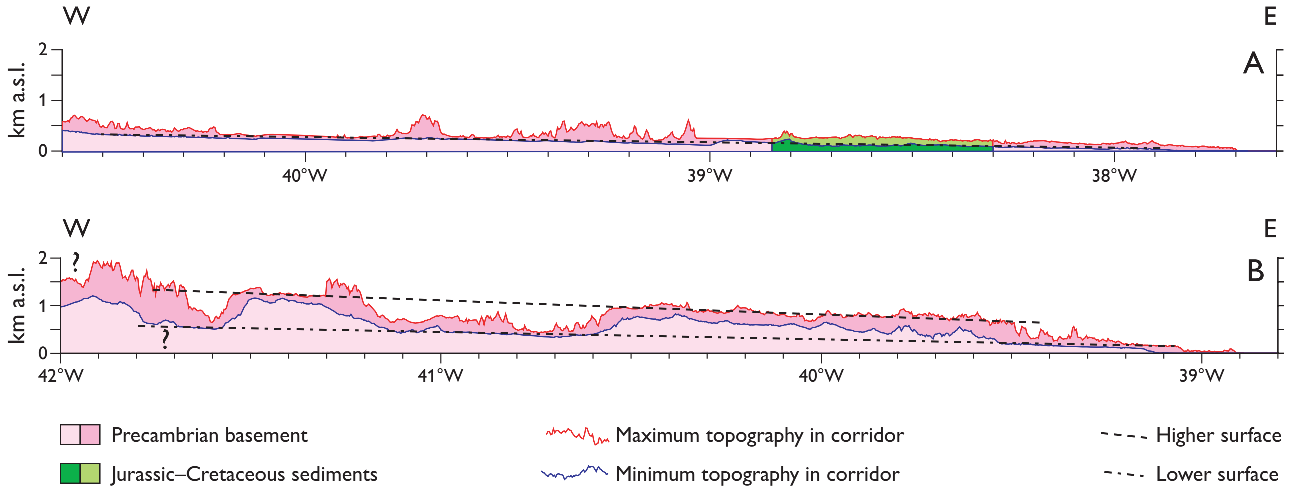


Fig. 2. Two profiles to illustrate the surface mapping. The dotted lines show the interpreted peneplains. The surfaces cut across both the basement, consisting of rocks that have different resistance to erosion, as well as the sedimentary sequence of the RTJ Basin. This shows that the peneplains are erosional features. See Fig. 1B for profile location and corridor width.

with a transition from continental to oceanic crust farther offshore. Several aspects related to elevated, passive continental margins are controversial: the origin of the plateaux, the timing of their uplift to their present elevation and their relation to the adjacent rift systems (Japsen *et al.* 2009). For example, Gallagher *et al* . (1994) found that the almost 3 km high mountain chain Serra do Mar, near Rio de Janeiro, is the remnant of a rift shoulder from the Early Cretaceous break-up in the South Atlantic, whereas Cobbold *et al.* (2001) argued that these mountains were formed during Neogene block-fault tilting.

King (1967) mapped stepped surfaces (i.e. erosion surfaces at distinct levels in the landscape) through the elevated terrains along many passive continental margins, e.g. in eastern Australia, southern Africa and north-east Brazil. King used remnants of sedimentary rocks to constrain the ages of these surfaces and concluded that the main surfaces were formed during the Cenozoic, and consequently that the margins had been uplifted in that same time interval. Furthermore, King found that the highest peaks in the interior of the continents represented remnants of a pre-break-up topography. Subsequent geomorphological research into the development of the passive margins of southern Africa and eastern Australia has, however, regarded the elevated terrains along these passive margins as mainly reflecting preserved rift-shoulders (e.g. Ollier 1985), a model that is commonly used as input to thermochronological studies (e.g. Gallagher *et al.* 1994).

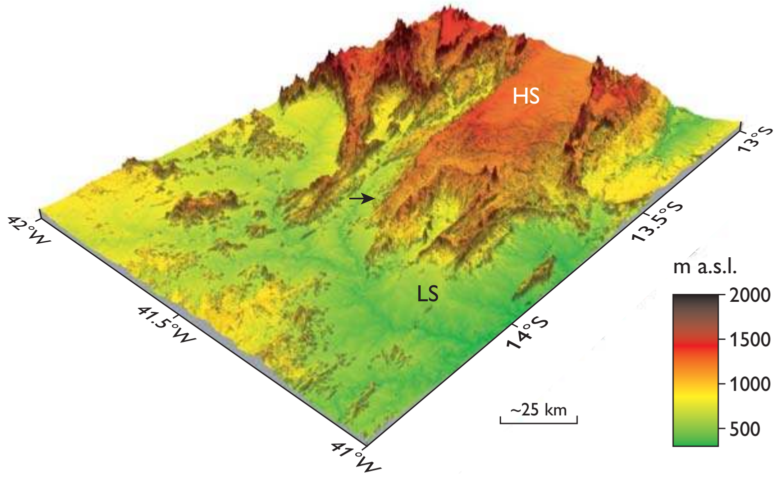
The burial and exhumation history of the study area is currently investigated by combining the cooling history from apatite fission-track analysis from both outcrop and borehole samples with the denudation history from landform analysis and the stratigraphic record. Based on field work carried out during four weeks in July and August 2007, we here report results focused on the rift systems near the Atlantic margin and on the interior highlands in north-east Brazil.

Large-scale landforms

A geomorphological analysis based on the method described by Bonow *et al.* (2006) has led to the identification of two major erosion surfaces (peneplains) of low, relative relief and of regional extent within the study area: a lower surface extending from near-coast areas and far into the interior (up to 500 m a.s.l., greenish colours in Fig. 1B) and a higher surface that includes the plateaux ('planaltos') of Chapada Diamantina (*c.* 1200 m a.s.l., reddish colours in Fig. 1B) and Planalto de Conquista (Fig. 1B; *c.* 900 m a.s.l.). Both surfaces cut across rocks of different ages and resistances and must therefore be erosional features (Fig. 2). These observations show that the surfaces were originally formed by denudation to a near-horizontal plain because even slightly tilted surfaces will be incised by fluvial valleys and the relief rejuvenated, until a new and younger peneplain is formed. The location of these surfaces near the present coast indicates that sea level was the most likely baselevel to which the surfaces graded. After uplift of what is now the higher surface, the lower surface was developed by incision along the main rivers in the area (Figs 1, 3, 4).

The higher surface can be correlated from Chapada Diamantina to Planalto de Conquista at a slightly lower elevation (Fig. 2). It is characterised by an undulating plain with shallow and wide valleys, and it is preserved on high ground with resistant rocks. The higher surface must have developed across a larger area than that presently preserved, as the lower surface has developed at the expense of it. Escarpments often

Fig. 3. Digital terrain model with a higher surface (**HS**) and a lower surface (**LS**) that are separated by escarpments in the Chapada Diamantina area. The higher surface forms a coherent plateau at 1200–1400 m a.s.l. (reddish) with only minor valley incisions. This plateau is presently being dissected by rivers along the escarpment, eroding down to the lower surface, here at 500–400 m a.s.l. (greenish). Escarpments are also found above the higher surface, maybe representing steps towards older surfaces at higher elevations. The arrow indicates the location and direction of the photograph in Fig 4. Elevation data source: Jarvis *et al.* (2008).



separate the lower surface from the higher surface (Figs 3, 4). In detail, these escarpments usually coincide with bedrock boundaries, thus reflecting bedrock resistance. The valley patterns and the incision of rivers in the Recôncavo and Tucano basins also show that the lower surface is rapidly being dissected by incising rivers, due to a change in baselevel after formation of the lower surface.

Geological constraints

The lower surface cuts across post-rift strata within the rift and Precambrian basement outside the rift (Figs 1, 2). The formation of the surface thus post-dates the Aptian Marizal Formation (e.g. Magnavita *et al.* 1994). The age of the surface may, however, be further constrained by an outlier of the early Miocene, marine Sabiá Formation within the Recôncavo Basin (Fig. 1A) where this sedimentary unit has been found in deep trenches (Viana *et al.* 1971). This outlier testifies to a marine transgression that occurred before the formation of the lower surface because the outlier is truncated by that surface, and thus the lower surface is younger than early Miocene.

The areas where the higher surface is defined are characterised by laterites (deep weathering profiles) of Cenozoic age (Fig. 1; CPRM 2001, 2003). Both the higher surface and the laterites are currently being destroyed by erosion along the escarpments that outline the plateaux. Consequently, the laterites must have formed at the end of the erosional process that shaped the higher surface. Based on the age of the laterites we can deduce that the higher surface formed during the Cenozoic.

This time interval can be further narrowed if we take into account that the younger, lower surface was formed subsequent to the deposition of the Sabiá Formation. The age of the higher surface may thus tentatively be estimated to be Palaeogene, which implies that the landscape at that time was a peneplain close to sea level. This suggestion is in agreement with observations from similar plateaux north and south of the study area where the plateau surfaces were exposed during the Palaeogene according to stratigraphic data (Sant'Anna *et al.* 1997; Morais Neto *et al.* in press) and geochronological constraints on deep weathering (Spier *et al.* 2006; Lima 2008). Alternatively, both the higher and the lower surface in the study area may have formed during the Neogene, which also agrees with the Cenozoic age of the laterites. Geomorphological analysis alone cannot definitely conclude which alternative is correct, but we prefer the first alternative because it is consistent with independent constraints from outside the study area.

Fig. 4. The lower surface with the escarpment and the higher surface in the background. See Fig. 3 for location.

Conclusions

The landscape in the study area is dominated by two main peneplains, a higher surface and a lower surface that were both formed as low-relief erosion surfaces. The higher surface developed during the Cenozoic, probably during the Palaeogene as other similar plateaux in Brazil. The lower surface formed during the Neogene after the deposition of the Sabiá Formation and an uplift event that raised the higher surface to its present elevation around 1000 m a.s.l.

The uplift resulted in rejuvenation of the relief and subsequent formation of the lower surface. Progressive backward erosion along the main rivers has resulted in escarpments that separate the two surfaces. The escarpments are pronounced at geological boundaries with large differences of erosional resistance. Even the lower surface is presently under destruction due to minor subsequent uplift. In summary, we find that the passive margin topography in the study area was shaped many millions of years after the Early Cretaceous break-up of the South Atlantic. The conclusion that the landscape is mainly Cenozoic is thus in agreement with that of, e.g. King (1967). A better understanding of the timing of uplift events will be achieved from apatite fission-track data as well as the amount of exhumation involved in the formation of the erosion surfaces.

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References

Bonow, J.M., Lidmar-Bergström, K. & Japsen, P. 2006: Palaeosurfaces in central West Greenland as reference for identification of tectonic movements and estimation of erosion. Global and Planetary Change **50**, 161–183.

Bonow, J.M., Japsen, P., Green, P.F., Wilson, R.W., Chalmers, J.A., Klint, K.E.S., van Gool, J.A.M., Lidmar-Bergström, K. & Pedersen, A.K. 2007: A multi-disciplinary study of Phanerozoic landscape development in West Greenland. Geological Survey of Denmark and Greenland Bulletin **13**, 33–36.

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

Cobbold, P.R., Marais-Gilchrist, G., Chiossi, D., Fonseca Chaves, F., Gomes de Souza, F. & Lilletveit, R. 2008: Large submarine slides on a steep and narrow continental margin (Camamu Basin, NE Brazil). American Association of Petroleum Geologists Annual Convention, San Antonio, Texas, 20–23 April, 1 p.

CPRM-Geological Survey of Brazil 2001: Geological map of Brazil, 1:5 000 000 (CD-ROM).

CPRM-Geological Survey of Brazil 2003: Geologia e Recursos Minerais do estado da Bahia 1:1 000 000 (CD-ROM).

Davison, I. 1999: Tectonics and hydrocarbon distribution along the Brazilian South Atlantic margin. Geological Society, London, Special Publications **153,** 133–151.

Gallagher, K., Hawkesworth, C.J. & Mantovani, M.S.M. 1994: The denudation history of the onshore continental margin of SE Brazil inferred from apatite fission track data. Journal of Geophysical Research **99**, 18117–18145.

Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A. & Lidmar-Bergström, K. 2006. Elevated, passive continental margins: long-term highs or Neogene uplifts? New evidence from West Greenland. Earth and Planetary Science Letters **248**, 315–324.

Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A., & Lidmar-Bergström, K. 2009: Formation, uplift and dissection of planation surfaces at passive continental margins. Earth Surface Processes and Landforms **34,** 683–699.

Jarvis, A., Reuter, H. I., Nelson, A. & Guevara, E. 2008: Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT). Available from http://srtm.csi.cgiar.org.

King, L.C. 1967: The morphology of the Earth, 2nd edition, 699 pp. Edinburgh: Oliver and Boyd.

Lima, M. da Guia 2008: A história do intemperismo na província Borborema oriental, Nordeste do Brasil: Implicações paleoclimáticas e tectônicas, 251 pp. Unpublished Ph.D. thesis, Universidade Federal do Rio Grande do Norte, Brazil.

Magnavita, L.P., Davison, I. & Kusznir, N.J. 1994: Rifting, erosion, and uplift history of the Recôncavo-Tucano-Jatobá Rift, northeast Brazil. Tectonics **13**, 367–388.

Morais Neto, J.M., Green, P.F., Karner, G.D. & Alkmim, F.F. in press: Age of the Serra do Martins Formation, Borborema Plateau, northeastern Brazil: constraints from apatite and zircon fission track analysis. Boletim de Geociências da Petrobras **16**.

Ollier, C.D. 1985: Morphotectonics of passive continental margins: introduction. Zeitschrift für Geomorphologie N.F., Suppl. **54**, 1–9.

Sant'Anna, L.G., Schorscher, H.D. & Riccomini, C. 1997: Cenozoic tectonics of the Fonseca Basin region, eastern Quadrilátero Ferrífero, MG, Brazil. Journal of South American Earth Sciences **10**, 275–284.

Spier, C.A., Vasconcelos, P.M. & Oliviera, S.M.B. 2006: ^{40}Ar/^{39}Ar geochronological constraints on the evolution of lateritic iron deposits in the Quadrilátero Ferrífero, Minas Gerais, Brazil. Chemical Geology **234**, 79–104.

Viana, C.F., Gama Junior, E., Simões, I.A., Moura, J.A., Fonseca, J.R. & Alves, R.J. 1971: Revisão estratigráfica da bacia Recôncavo/Tucano. Boletim Técnico da Petrobras **14**, 157–192.

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