DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/9

Relative denudation chronology in NE Brazil based on mapping of large-scale landforms

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

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Relative denudation chronology in NE Brazil based on mapping of large-scale landforms

Contribution to the project "Burial and exhumation history of NE Brazil focussing on the Camamu Basin: a multidisciplinary study based on thermal, sonic and stratigraphic data and landform analysis"

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G E U S

1. Summary

This report documents the geomorphological investigations in NE Brazil for StatoilHydro do Brazil, in the research project "Burial and exhumation history of NE Brazil focussing on the Camamu Basin: A multidisciplinary study based on thermal, sonic and stratigraphic data and landform analysis". The outcome of the entire project is reported by Japsen et al. (2009).

The aim of this report is 1) to document the landscape observations, 2) to map peneplains (denudation surfaces) of different age and 3) to make a relative chronology for the tectonic landscape development in the study area. The documentation is based on extensive field work, and observations of landforms and their relationship to the geology. The surfaces have been mapped by aid of a contour map and profiles constructed from digital elevation data (SRTM). The mapping has been complemented with information from the fieldwork and the geological maps.

The geomorphological analysis of the large-scale landforms has lead to identification of two major denudation surfaces of regional extent, the higher and the lower surface, and the coastal plain, all in stepped sequence following the valleys (Fig. 23). These surfaces all cut across rocks of different age and of different resistance. It is therefore concluded that their formation was governed by erosion relative to a general base level. The wide extent of the higher and lower surface suggests that they developed over a significant time interval with stable base-level conditions because a long time span will reduce the lithological and structural influence on the shape of these surfaces. Further any significant change of base level cannot have occurred as that would have resulted in rejuvenation of the relief.

The higher surface is well-developed across Chapada Diamantina and Planalto de Conquista. The elevation of the surface is c. 1200 m a.s.l. over Chapada Diamantina and c. 900 m a.s.l. over Planalto de Conquista, but despite that the higher surface is tilted towards the southeast they can be correlated. Therefore it is concluded that they were formed as one coherent surface. The higher surface cuts across Precambrian basement, but over wide areas Cenozoic laterites and weathered basement are preserved below the surface, thus constraining its final formation age to the Cenozoic. A winding escarpment usually separates the higher surface from the lower.

The lower surface can be identified from the coast at c. 200 m a.s.l. and it follows the major valleys up to c. 500 m a.s.l., as far as 250 km from the coast. At its upper reaches the escarpment up to the higher surface is usually pronounced. The lower surface cuts across the Aptian sedimentary sequence in the Recôncavo-Tucano Basins and Precambrian basement along the flanks. A thin cover of the Miocene-Pliocene(?) Barreiras Formation is present in areas where the lower surface is present and it is thus difficult to map the relationship between the lower surface and this cover.

The coastal plain is rather narrow, mainly defined along the major rivers. It is incised into the Barreiras Formation.

Based on the relationship between the surfaces and the geology the following relative sequence of events is suggested: The higher surface was developed during the Cenozoic and is probably Paleogene in age, based on that 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 denudational event that formed the higher surface.

The lower surface post-dates the higher surface and is suggested to be Neogene in age. The coastal plain is post-Barreiras, and this combined with the immature dissection of the landscape observed over much of the coastal zone indicates that it is a young feature.

At least some of the base level changes recorded by the denudation surfaces must be tectonic in origin, in particular the pronounced step of 500 to 700 metres between the higher and the lower surface. This step reflects the amount of uplift prior to the formation of the lower surface.

Differences in lithology and structure have influenced the development and preservation of the surfaces across the study area. Resistant rocks assist in preservation of old surfaces and halt new surfaces to develop. The rivers in areas of resistant rocks tend to form deep canyons whereas the formation of new surfaces is much faster in areas with less resistant rocks and such areas will also be the first to be rejuvenated after a base level change. Long-term denudation significantly reduces the lithological influence on the surface development.

2. Background

The aim with this report is 1) to document the landscape observations 2) to map peneplains of different age, and 3) to make a relative chronology for the tectonic landscape development in NE Brazil (Fig. 1). This report is the results of the detailed analysis based on landscape mapping (this report) and fieldwork (Japsen et al, 2007).

The geomorphological data and the interpretations presented here is part of the overall effort to integrate the results from the AFTA data for conclusions about the thermochronology history of the subsurface rocks (Apatite fission track analysis), the geological record and the large-scale landscape analysis (geomorphology) for conclusions about the relative chronology for denudational events. The purpose of this integration is to construct a regional model for the morphotectonic evolution in NE Brazil. This part will primarily deal with the geomorphology. The details of AFTA will be reported separately (Green 2008, in press). The details of the geological development as well as the integration of all data will be reported in Japsen et al. (2009).

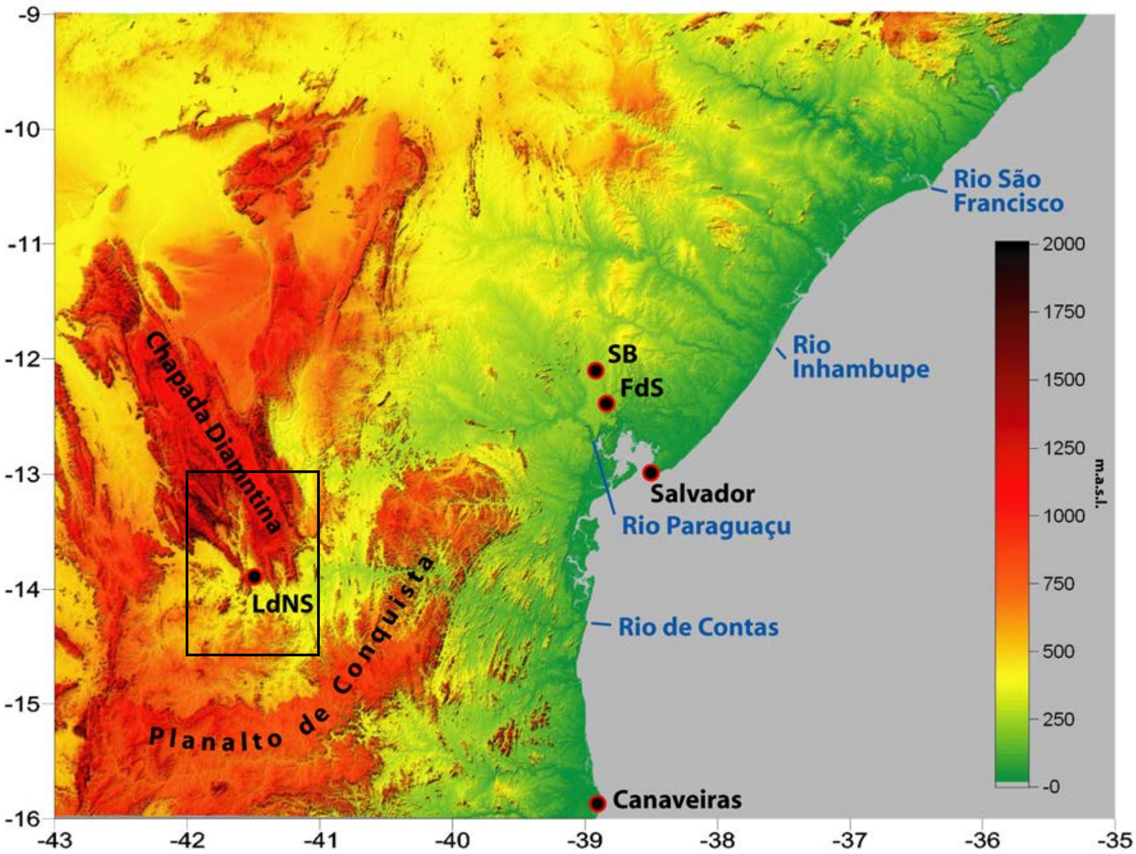


Fig. 1. The study area with place names used in this report. The black rectangle marks the location of fig 22. SB-Santa Bárbara, FdS-Feira de Santana, LdNS- Liveramento de Nossa Senhora.

2.1 Geomorphology

2.2 The approach of landscape analysis

The framework of the landscape development is based on relationships between different denudation-surfaces in stepped sequence and geology separated into basement and cover rocks (e.g. Lidmar-Bergström, 1982, 1988, 1989, 1995, 1996, Lidmar-Bergström et al., 2000, 2007; Bonow et al., 2003, 2006a, 2006b, 2007; Bonow, 2005). The denudation surfaces are thought to reflect a base-level to which it will grade. The longer time available for a surface to form, the more extensive it will be and also less controlled by different lithological conditions. Thus a surface will continue to develop, at different rate due to climatic conditions, until the base level to which it grades will change. Thus will a lowered base level (e.g. due to uplift) cause valley incision and rejuvenation of the relief, subsequently leading to the development and formation of a new. lower erosion surface. The step (escarpment or knick-point) in the landscape between the valley floor and a higher surface will thus show the amount of base level change. On the other hand will an elevated base level (e.g. due to subsidence) cause burial of the previously formed surface, thus preserving the surface and landscapes from a certain time.

2.3 The study area

Geomorphological studies regarding general landscape development are few in Brazil, and no detailed investigation has been made of the landscapes in study area. Generally the Brazilian landscapes have been looked upon as a result of regional uplift at the time of break-up of the Gondwana (e.g. Zonneveld, 1993; Ab'Sáber 2000 and references therein), ephasising the pre-Cenozoic development, a conclusion also derived from landscape studies in central Argentina (Demoulin et al. 2005). Recent geomorphological studies of northern Brazil have suggested a generally continuous rise of the landmass since rifting (Peulvast and Claudino Sales 2004, Peulvast et al. 2008). However, Valadão (1998) regarded the stepped landscapes in NE Brazil to reflect mainly a Cenozoic development. Based on river patterns and sedimentary record in the scale of South America, Potter (1997) regarded the continent to mainly have been stable since break up.

The most complete geomorphological analysis so far of NE Brazil has been made by Lester King (King 1956, 1967). His work has had a significant impact of the geomorphological thinking in more recent geomorphological literature, but also on literature describing different aspects of tectonics and stratigraphy often relate to his different erosion surfaces. Therefore will his surface mapping and thoughts briefly be reviewed in this report. King's mapping was mainly field based (e.g. King 1967 p 233), and occasionally based on less accurate topographical maps. Today mapping of denudation surfaces (i.e. peneplains) can be made based on high resolution digital elevation models. A new method of such systematic surface mapping has therefore been possible to develop (e.g. Lidmar-Bergström 1988; Bonow et al., 2006 and references therein, see section above). This method of mapping has been applied in this study and is described in the method chapter below.

In NE Brazil, including the present study area, King identified four different denudation surfaces that he interpreted to represent cyclic, low-relief base-level governed erosional surfaces (Fig. 2). King regarded the highest surface to be the oldest and that the youngest surfaces subsequently formed after break-up of the Gondwana supercontinent in the Cretaceous. King called the surface formed a *pediplain* and the formation process for *pediplanation,* in which the surface formed from the valleys by widening by parallel scarp retreat (King 1953). King's terminology shall be seen in the light of his desire to differentiate his landscape model from the one by Davis (1899), "The geographical cycle" which described the landscapes to develop by slope decline, thus not resulting in stepped surfaces. The end result of the denudation cycle, Davis (1899) named the *peneplain*, which is indistinguishable in appearance from the *pediplain*.

In NE Brazil King (1967) interpreted that the two oldest surfaces (and highest) were Mesozoic in age and he named them *Gondwana* and *post-Gondwana*. The Gondwana surface was thought as a pre-break-up surface that had developed across both present South America and Africa. In Brazil, Gondwana and post-Gondwana surfaces are only well preserved in the highest areas in the interior. According to King (1967), only small areas exist of these surfaces in the study area, specifically in Chapada Diamantina and in the north respectively south part of Planalto de Conquista. More frequent, according to King (1967), is the early Cenozoic *Sul-Americana* surface, that is well preserved and dominating in the highlands of Chapada Diamantina, and with remnants on the Planalto de Conquista. Its age is determined as it is regarded to cut across silicreted sands of presumed early Cenozoic age, in locations west of the São Francisco river, thus far west of the study area. The erosional cycle *Velhas* is not present in the Chapada Diamantina, but exists on the flanks of the Planalto de Conquista. The Velhas is regarded to have been formed during the late Cenozoic and is characterised by a smooth surface occasionally with inselbergs. King (1956, 1967) assign the main part of the study area to belong to the youngest cycle, the *Paraguaçu*, which he mapped also into the coastal area and he thought that this cycle was due to recent tilting along the present coast line.

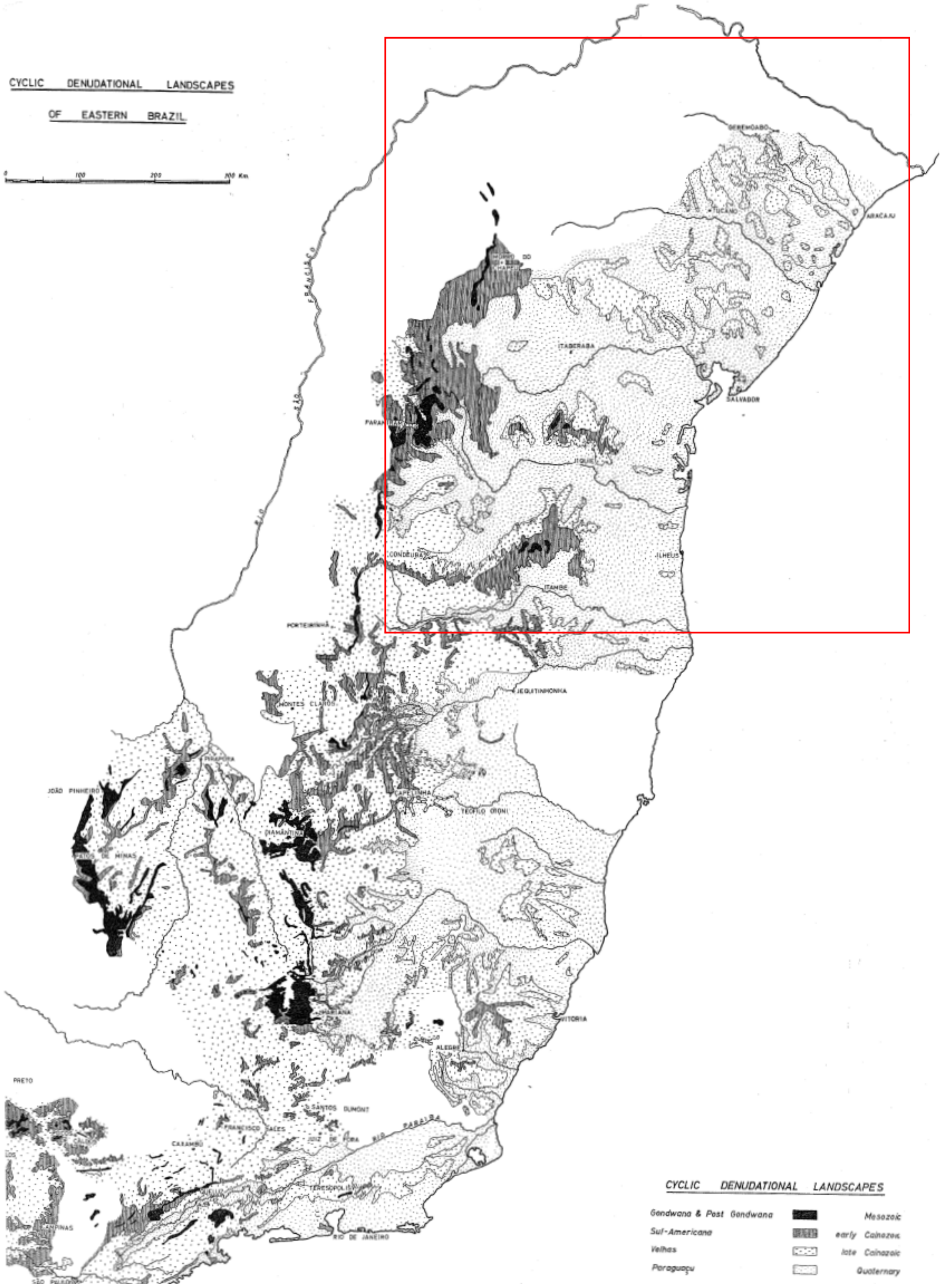


Fig. 2. Lester King's map of “cyclic denudational landscapes” in NE Brazil (Fig. 121 in King 1967, here slightly cropped). The red box marks the study area in this report.

3. Method of landscape analysis

The large-scale landforms were analysed in two steps: 1) Mapping of different erosion surface, and 2) Comparing the mapped surfaces with the geology. The Shuttle Radar Topography Mission (SRTM) was used as the basic elevation data set. The spacing between data points is approximately 90 m (Jarvis et al., 2008). The information about the general geology was extracted from the geology map of Brazil (CPRM, 2001) and the details from the geology map of Bahia (Dalton de Souza et al. 2003). This resulted in an erosion surface map.

3.1 Method of surface mapping

The SRTM was used as the basic elevation data set and was used to construct a contour map with 100 m contours (Fig. 3) using Surfer Software (Golden Software 2002). The DEM was also used to extract topographical profiles in north to south and west to east respectively, spaced at every 0.1 degrees (Fig. 4). Centred along the topographical profile a 0.2 degree wide corridor was extracted and analysed for maximum and minimum height values. The resulting three profiles (i.e. topographical, maximum and minimum) were plotted together in a single profile (Fig. 5). The profiles were made with a length-scale equal to the constructed contour map, so that they easily can be compared, but the vertical scale was exaggerated five times, so that break-of-slope becomes easier to identify. In areas where the topographical line and the maximum line coincide, it shows where the altitude level is for the surface, which can be mapped on the contour map.

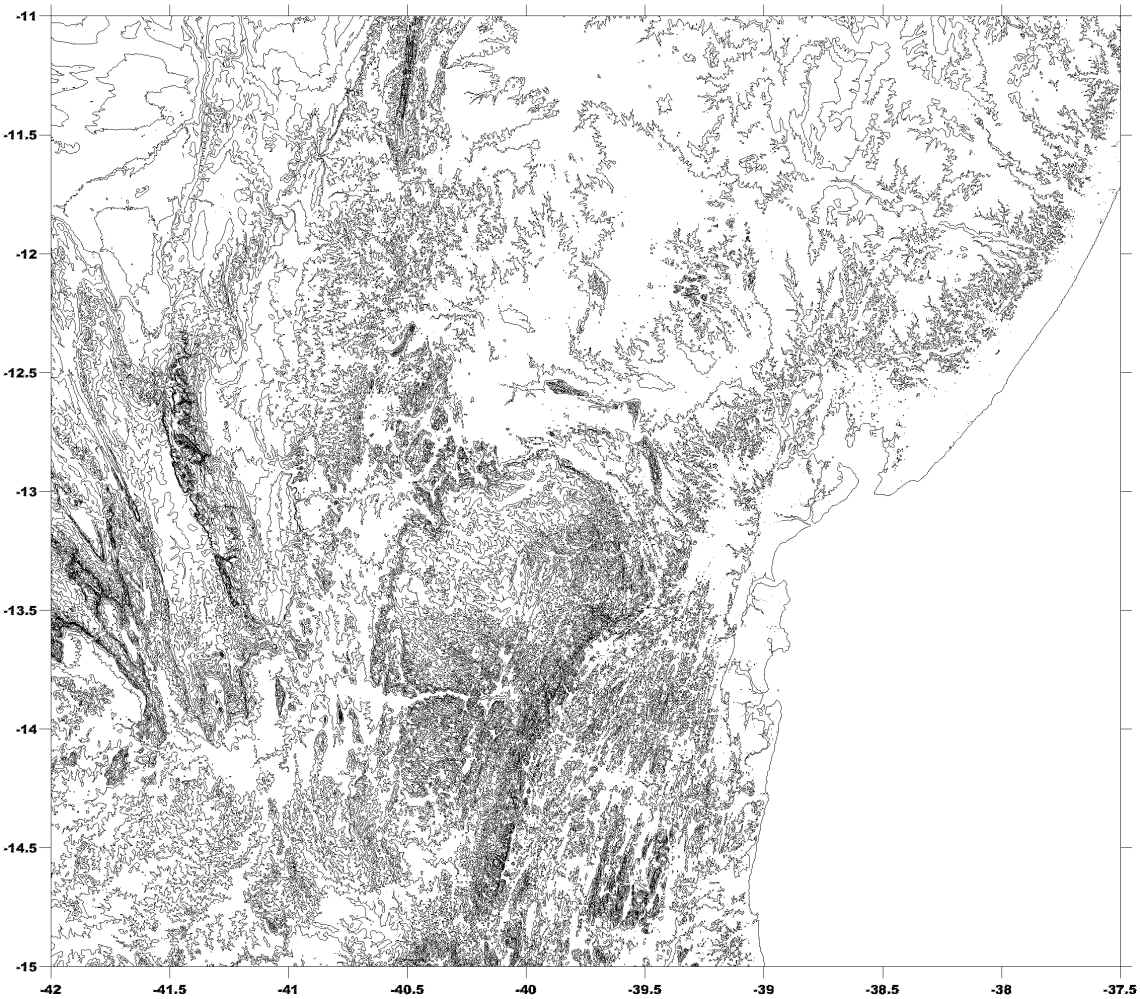


Fig. 3. The contour map with 100 m contours used as the base for the surface mapping. The map was constructed from elevation data obtained by the SRTM- mission (Jarvis et al., 2008).

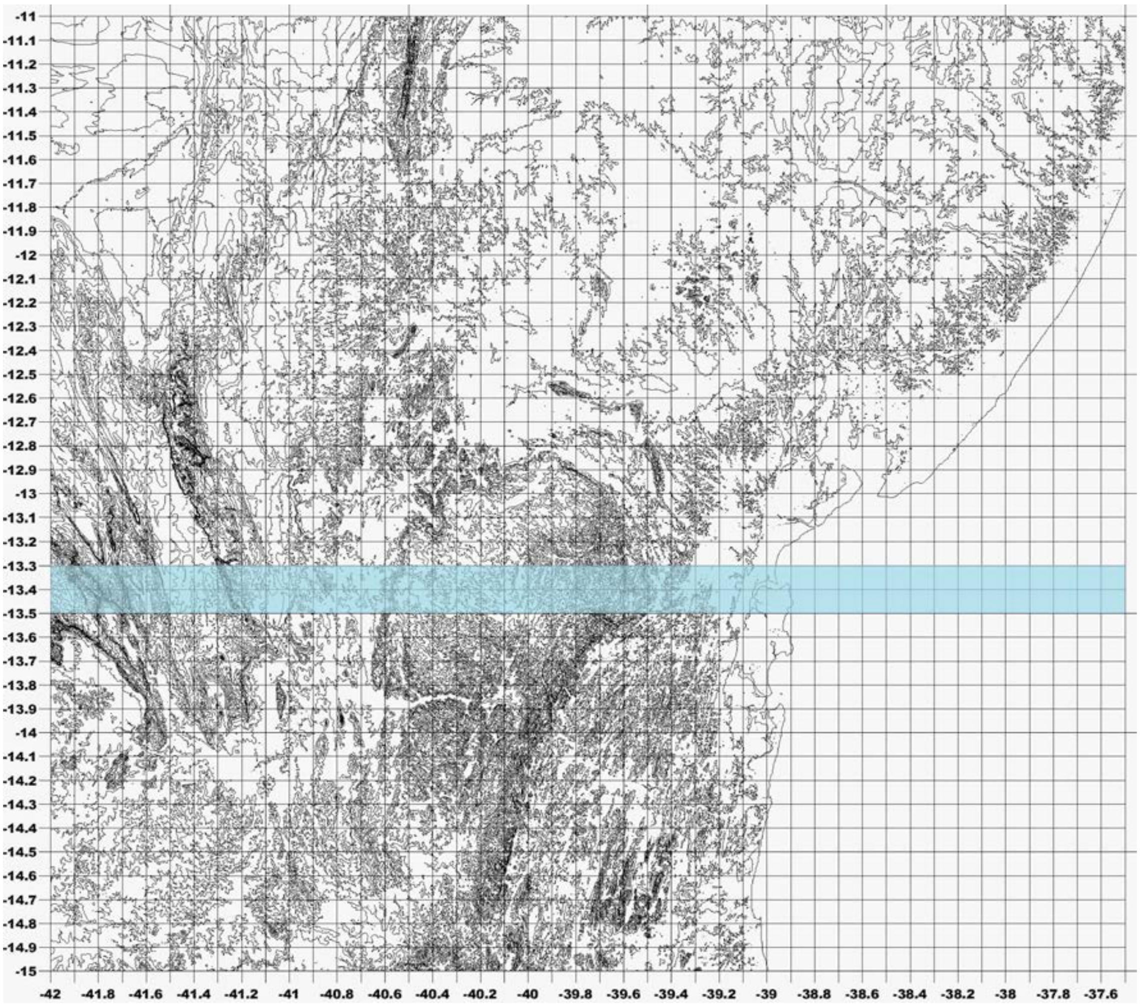


Fig. 4. The map shows an example for one of all the 80 constructed profiles (West-East and North- South) used to identify different peneplains. The blue area mark the corridor for the maximum and minimum values plotted together with the profile along latitude -13.4. The systematic construction of overlapping corridors allow inclined surfaces to be mapped on the contour map.

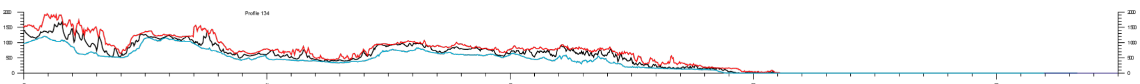


Fig 5. Example of a profile used for the analysis of surfaces. The red and blue line in the profile is the maximum respectively minimum values for the blue corridor in the figure above. The black line is the topographical line along the -13.4 latitude. The coincidence between the red and black line illustrates where the surface level can be seen in the contour map. Based on the contour map, surface levels were plotted onto the profiles and the profiles was used to extend the surface mapping from well preserved areas to less preserved areas.

From the contour map several areas with extensive coherent levels could be identified, e.g. Chapada Diamantina, Planalto de Conquista and the areas west of the Recôncavo-Tucano-Jatobo basin. As a consequence these areas could be used as a first starting point in order to begin the surface mapping. The identification of surfaces was made by combining coherent areas on the contour map in combination with cross interpretation of these areas in different single profiles (topographical, maximum, minimum). In this way different surfaces can be followed from profile to profile, showing surface outliers, steps between different surfaces, offsets within a surface and the tilt of each surface or tectonic block. Rapid change of inclination in the contours was used to determine the extent for mapping of each surface. Thus, this kind of mapping allows the identification of both sub-horizontal and inclined surfaces (Lidmar-Bergström 1988, 1996; Bonow et al. 2006). I must be emphasised that it is very important to use the combination of profiles and contour map, and trying to interpret surfaces along single profile lines can never give any confidence in landscape levels and identification of tectonic blocks, a method unfortunately common among many authors. Thus, the profiles shown in this report are only illustrations to the mapping. To further support the identification of surfaces ordinary topographical maps were consulted. The lithological influence on the surfaces was checked against geological maps. By doing this it is possible to distinguish between flat areas due to resistant rocks and surfaces formed by denudation by fluvial systems (cf Japsen et al in press). Field work, including documentation of landforms, in the study area took place in 2007 (Japsen et al. 2007).

4. Geomorphological results

This section presents a topographical overview of the study area, an overview description and illustration of the different surfaces, and some more detailed maps and photographs.

4.1 Topographical overview

Three areas with different characteristics were identified (Fig. 6): 1) A coastal plain, developed as incised valleys up to 200 m a.sl. (Figs 7, 8, 9), A low inland plain, developed along the major valleys up to 500 m a.s.l and 250 km from the present coastline (Figs 10, 11, 12, 13, 14, 15, 16, 17, 18) and 3) A highland plain in the interior above 1000 m a.s.l. (Figs 19, 20, 21).

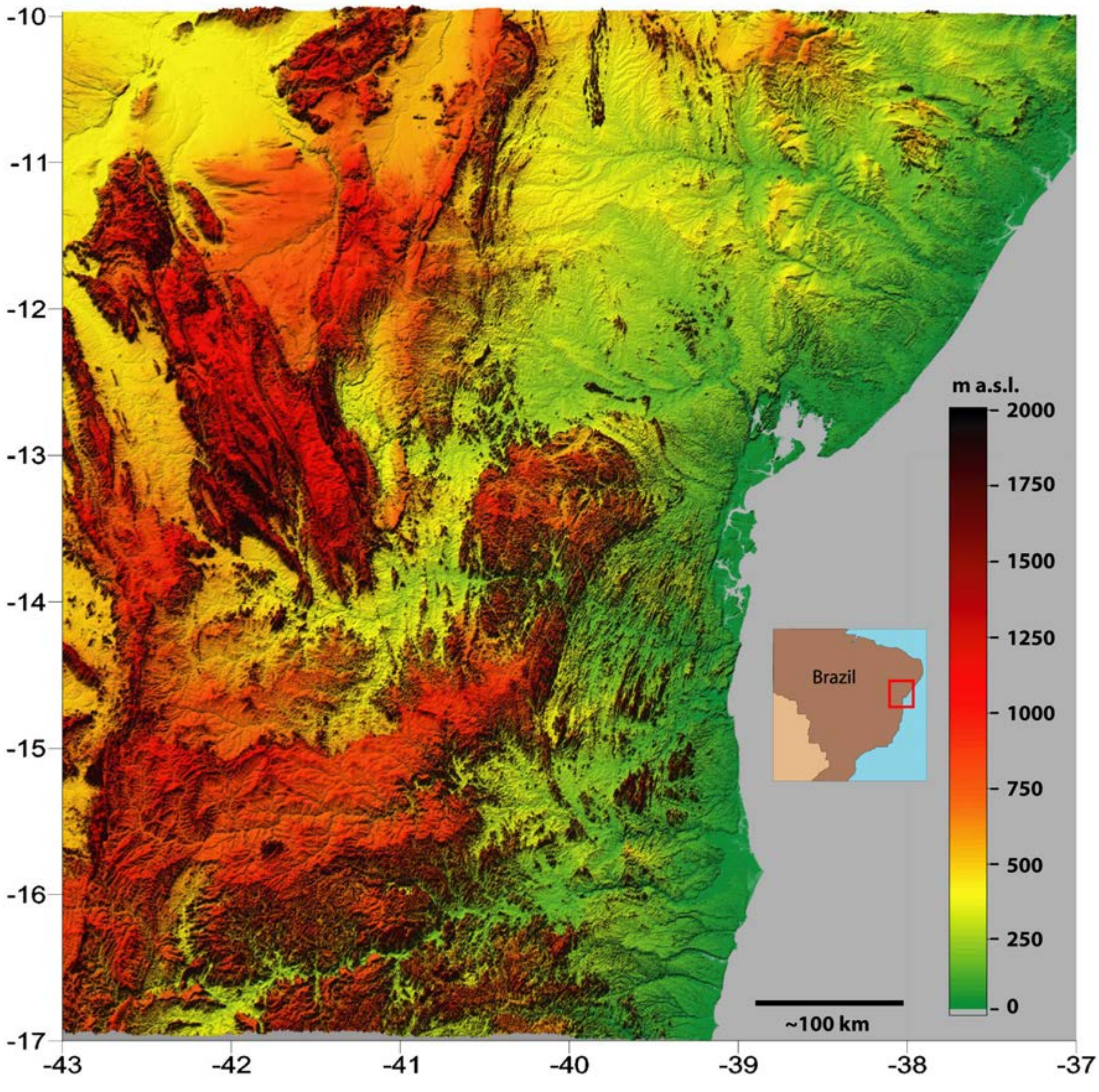


Fig. 6. The topography of the study area. The high areas of Chapada Diamantina and Planalto de Conquista are dominant in the central and western part, while lowland plains dominate in the eastern and coastal areas. Many of the details in topography are structurally controlled. See fig 1 for place names.

The coastal areas are generally characterised by a narrow low-land plain, gently sloping inland towards the west (Fig. 6). The coastal plain is cut into the Miocene-Pliocene(?) Barreiras Formation. The incision has also occurred along valleys that usually are rather narrow and the surface thus of limited wideness, but for Rio Imhambupe and Rio Paraguaçu (Fig. 1), where the backward erosion is extensive along the rivers and here the surface is also of some wideness. In this area the incision is far beyond the Barreiras Formation and have cut into either the Tucano Basin (Rio Imhambupe) or into the basement areas (Rio Paraguaçu) (Figs 1, 6).

Fig. 7. At Canaveiras, the present coastal areas are low-lying and very flat. Occasionally there is a small escarpment (c 30 m high) within the coastal plain, showing the most recent development of denudation. This scarp is probably erosional. Photo location: S 15' 33''; W 39' 00'', see also Fig.1.

Fig. 8. The well preserved and wide coastal plain at Canaveiras, cut across the Barreiras. The summits of the inselbergs in the background are at about 500 m a.s.l. Photograph towards the west. Photo location: S 15' 30''; W 39' 12''.

Fig. 9. This incised valley is thought to represent the latest incision in the study area, thus belonging to the coastal plain. The landscape is of valley in valley type and the top of the valley shoulders here are gently sloping and eventually merges with the lower surface at higher elevation. Photograph from southern Sergipe. Photo location: S 10' 50''; W 37' 34''.

At about 200 m a.s.l., the coastal plain is replaced by a less tilted plain (Figs 10, 11) extending up to about 500 m a.s.l. and the valleys in the plain are shallow and wide (Fig. 12). This lower inland plain is of widest extent in the northern part of the study area. It has developed to a distance of more than 200 km from the coast, but occurs also to less extent along the larger rivers in the southern part as well as far into the interior (Fig 6). It is generally slightly tilted towards the sea in the east. This plain is of low relative relief, often less than a few tenth of metres, but occasionally mountain complexes (Fig. 14) or isolated inselbergs, consisting of resistant bedrock (often granitic intrusions) (Fig. 15), rises considerably above the plain. This is especially prominent in the northern part of the study area. Commonly, at the upper reaches of the plain, there is a more or less well developed escarpment (Figs 16, 17, 18).

Fig. 10. The low-relief inland plain, here cut across basement rocks in northwest Sergipe. The horizon is only broken by some low inselbergs. Photograph towards northwest Photo location: S 09' 53''; W 37' 38''.

Fig. 11. The low-relief plain west of Feira de Santana, here at c 200 m a.s.l.. Photograph towards the north. Photo location: *c.* S 12' 20''; W 39' 00''.

Fig. 12. The low-relief plain has wide and shallow valleys. Photograph towards the west c. 100 km west of Feira de Santana. Photo location: S 12' 29''; W 39' 50''.

Fig. 13. Small ridges of resistant rocks rise slightly above the low-relief plain. Photo location: S 12' 32''; W 39' 34''.

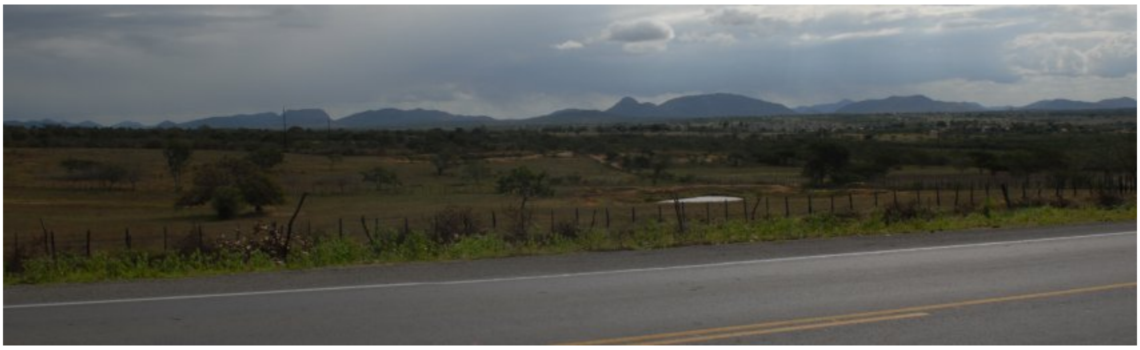


Fig. 14. A hill complex of crystalline rock at the western side of the Tucano Basin. In the foreground is the Jurassic sequence, but the border to the basement is far east of the complex, thus not seen in the topography. Photograph towards northwest, 5 km south of Santa Bárbara. Photo location: S 11' 58''; W 38' 58''.

Fig. 15. Inselberg on the low relief plain 125 km west of Feira de Santana. The plain is here at c. 250 m a.s.l.. Inselbergs are sometimes regarded as the last remnant of an older landscape, but here the summit is well below the higher surface in the landscape. Photo location: S 12' 31''; W 40' 03''.

Fig. 16. The low plain, here at c 350 m a.s.l. is limited by a sharp break-of-slope at its uppermost part. The summits of the escarpment are at c. 1300 m a.s.l. (dotted line). Photo location: S 12' 38''; W 41' 10''.

Fig. 17. The low plain in the westernmost part of the study area, here at c. 500 m a.s.l. is clearly bordered by escarpments. The escarpment to the left is part of Chapada Diamantina and in the centre-left is part of the Planalto de Conquista. Photograph towards the south-east just outside Liveramento de Nossa Senhora (c.f. Fig 22). Photo location: S 13' 40''; W 41' 50''.

Fig. 18. Detail of the contact between the escarpment and the low plain. The bottom of the valley is at c 500 m .a.s.l. and the summit of the escarpment is at c. 1100 m a.s.l.. Photograph towards the west outside Liveramento de Nossa Senhora (c.f. Fig. 22). Photo location: S 13' 37''; W 41' 48''.

Above the escarpment another plain of low relief has been identified at between c 900-1200 m a.s.l., dominating the landscape in the western and central part of the study area (Fig. 6). The lower altitude occurs in Planalto de Conquista area, while the higher altitudes are common in Chapada Diamantina area (Figs 19, 20, 21, 22). Both these areas have wide and shallow valleys incised in the surfaces, but usually the surface is more dissected than the lower surface. In the Chapada Diamantina area there is some higher relief, up to slightly above 2000 m a.s.l., represented by rather narrow ridges of resistant rocks. Thus relatively flat areas of large areal extent occur both in high and in low positions of the landscape, and it seemed possible to map their extent in more detail.

Fig. 19. The high plain in Chapada Diamantina is limited in the east by a resistant bedrock ridge. The plain reaches out of sight to the north and is here at about 1200 m a.s.l. (c.f. Fig. 22). Photo location: S 13' 28''; W 41 28''.

Fig. 20. In the west and in the east the plain is bordered by ridges of resistant rocks, rising a few hundred metres above the plain. Note the shallow valley slightly incised into the plain (red arrow). (c.f. Fig. 22). Photo location: S 13' 28''; W 41' 28''.

Fig. 21. The high plain on the Planalto de Conquista plateau is at c. 900 m a.s.l, and the inselbergs in the background rises to slightly above 1000 m a.s.l.. Photo location: S 14' 49'; W 40' 50'.

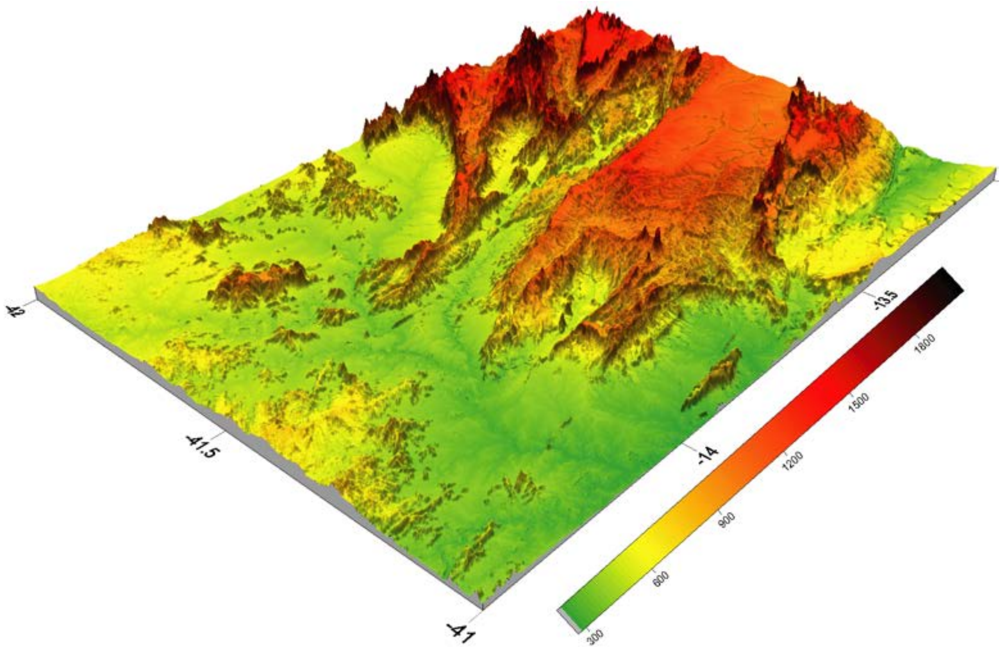


Fig. 22. 3D model of Chapada Diamantina. The higher surface is between 1200-1300 m a.s.l. and it is incised by shallow valleys. The escarpment to the lower surface is pronounced and around 700 m high. Location in Fig. 1.

4.2 The denudation surfaces

Based on the method described above, two major and regionally developed surfaces were identified and mapped; here labelled the higher surface (HS) and the lower surface (LS). Both these surfaces cut across different types of bedrock. Therefore they are interpreted as denudation surfaces controlled by a general base level (Fig. 23). A younger denudation generation (or surface), here labelled the coastal plain, has also been identified. It is developed as a rather narrow incised valley below the lower surface, and it is almost only along the river Rio São Francisco, that it has developed as a surface beyond the immediate river valley. The relief above the higher surface is highly irregular and it has not been possible to identify any coherent surface here.

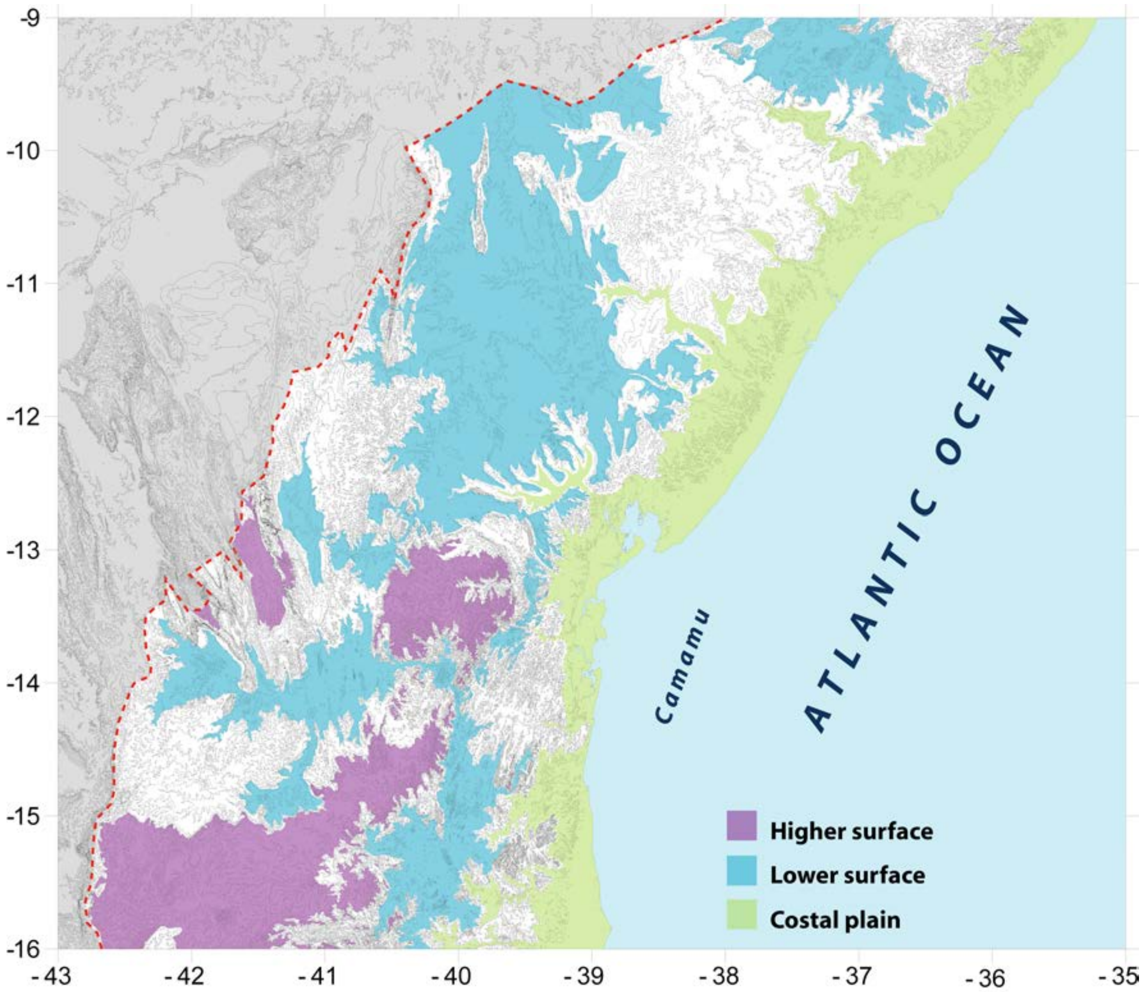


Fig. 23. The three denudation surfaces in the study area all cut across bedrock of different age and resistance. The white in the map are areas with slopes or areas that not have any identifiable coherent surfaces (e.g. ridges). The map is limited by the present coast and the water divide (red line).

4.2.1 The higher surface

The higher surface is a regional surface, and it is preserved in the southern and central part of the study area, i.e. Planalto de Conquista and Chapada Diamantina (Fig. 23). Mainly it is coherent with very few break-of-slopes within the surface, that could indicate offsets of the surface after its formation. The area, on which the surface exists, is thus regarded to be on a coherent tectonic block that has been internally stable since the formation of the higher surface. The mapping on the contours and correlation through the profiles (Figs 3 ,4) shows that the surface is tilted towards the south-east. The surface is at the highest elevation in Chapada Diamantina area, between c. 1300-1100 m.a.s.l., and at lower elevations in the Planalto de Conquista area, around 900 m a.s.l.(Figs. 19, 20, 21, 22)

4.2.2 The lower surface

The lower surface is also a regional surface, but it is more widespread than the higher surface (Fig. 23). It is developed along the major rivers in the area, i.e. Rio São Francisco, Rio Paraguaçu and Rio de Contas. It is especially well developed in the central part of the study area, north of Planalto de Conquista along the Rio Paraguaçu. Here it forms a coherent area covering more than 45.000 km^2. The lower surface is clearly a denudation surface as it cuts across rocks of different age and resistance. The mapping shows that the surface is tilted towards the coast, thus at highest elevation in the west. It can be followed from about 500 m a.s.l. at its upper reaches and down to about 200 m a.s.l where the lower surface is cut off by the more steeply tilted coastal plain. However the lower surface exact relationship to the Barreiras Fomration is unclear, whether it cuts off or if the Barrieras Formation is on top of the lower surface. At the lower surface’s upper reaches the transition to the higher surface is often sharp, characterised by a winding escarpment (Figs 16, 18, 22).

4.2.3 The coastal plain

The coastal plain is tilted and can be followed from the present coast up to about 200 m a.s.l. (Fig. 23). The incision dissects the lower surface and the Barreiras at the coast. But how wide the plain has grown varies considerably across the study area. The surface is especially wide along the rivers Rio São Francisco and Rio Paraguaçu . At c 150 m a.s.l. the surface associated with the Rio Paraguaçu is wide, but narrows noticeably, and here the river forms a canyon before it enters the sea. Thus it is possible that the river here is antecedent. (Figs 7, 8, 9).

4.2.4 Illustrations of the surface mapping

Four profiles have been selected to illustrate the mapping (Figs 23, 24, 25, 26). In the profiles the location for the higher and lower surface has been indicated, and these lines for the surface line are based on the mapping made on the contour map (Fig. 23).

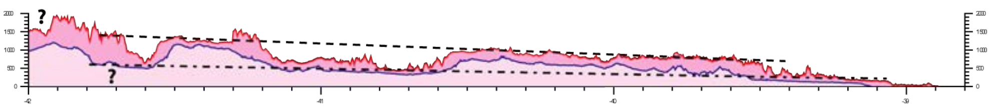


Fig. 24. West-east profile along -13.4 degrees.

Fig. 24 is drawn to illustrate how the landscape appears in a profile where the higher surface is well preserved. In the west, lies Chapada Diamantina where the surface is at c 1200 m a.s.l., and in the east the surface cross Planalto de Conquista, at c 900 m a.s.l., before it ends at the coast. The correlation in the western areas is not clear, but maybe the surfaces also exist on the west side of the present water divide. The mapping shows that the surface is clearly tilted generally towards the southeast, which appears as an east tilting in the profile. The surface is preserved in areas with metamorphic rocks that are resistant to weathering. No clear breaks can be seen in the profile line that could indicate movements on individual tectonic blocks. The lower surface can clearly be seen in the east along the coast. Some inselbergs rises from the surface that almost can be correlated with the level for the higher surface. In the central part of the profile the lower surface forms a bottom level along the incised river Rio de Contas that cuts across the high area south of this profile (c.f. Figs 6, 23).

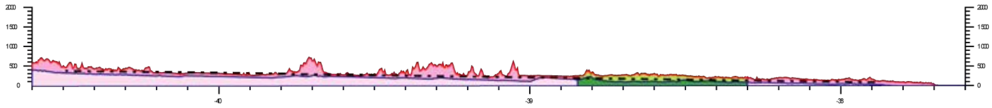


Fig. 25. West-east profile along -11.3 degrees. Note that no change of inclination occurs despite the crossing of the Tucano Basin.

Fig. 25 shows the situation in the northern part of the study area where the lower surface is well developed, but also where the higher surface (if it ever existed here) has been totally obliterated. In the west the profile starts east of the northern part of Chapada Diamantina. The lower surface is here at its uppermost reaches at c 500 m a.s.l. and the interpretation is that it is slightly tilted towards the east. In the eastern parts the lower surface cut across the Recôncavo-Tucano-Jatobo Basin, but the difference in geology cannot clearly be seen in the regional pattern. In the central part resistant rocks form hill complexes and inselbergs, however the cross correlation with other profiles from the mapping indicates that the summits do not reach the level for the higher surface (cf. Fig. 26).

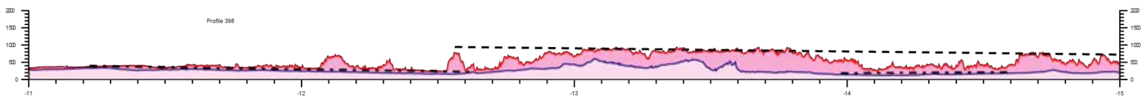


Fig. 26. North-south profile along -39.8 degrees.

Fig 26 is a north-south profile relatively close to the sea. It crosses the easternmost part of Planalto de Conquista, where the higher surface is well preserved. The line for the higher surface shows the slight tilt of the surface towards the southeast. To the north the surface seems to have been eroded and cannot be seen in the landscape. The summits of the inselbergs in the northern part do not correspond to a projected surface level, thus suggesting that it has been significantly eroded. The lower surface is well represented in the profile. In the southern part the line represents a valley network of incised valleys, in a landscape otherwise dominated by ridges (c.f. Fig.6). Although not clear at all in the profile, but in the surface map (Fig. 23) the lower surface has a very different appearance in the landscape in the northern part. Here the lower surface is well developed and wide with only shallow valleys, but for some inselbergs and mountain complexes. The lower surface here is tilted towards the Rio Paraguaçu, situated immediately north of the highland area.

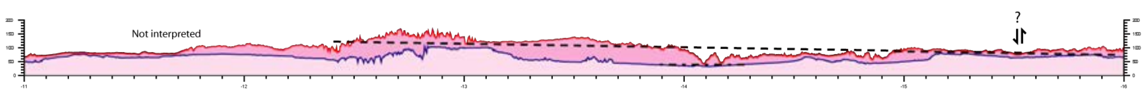


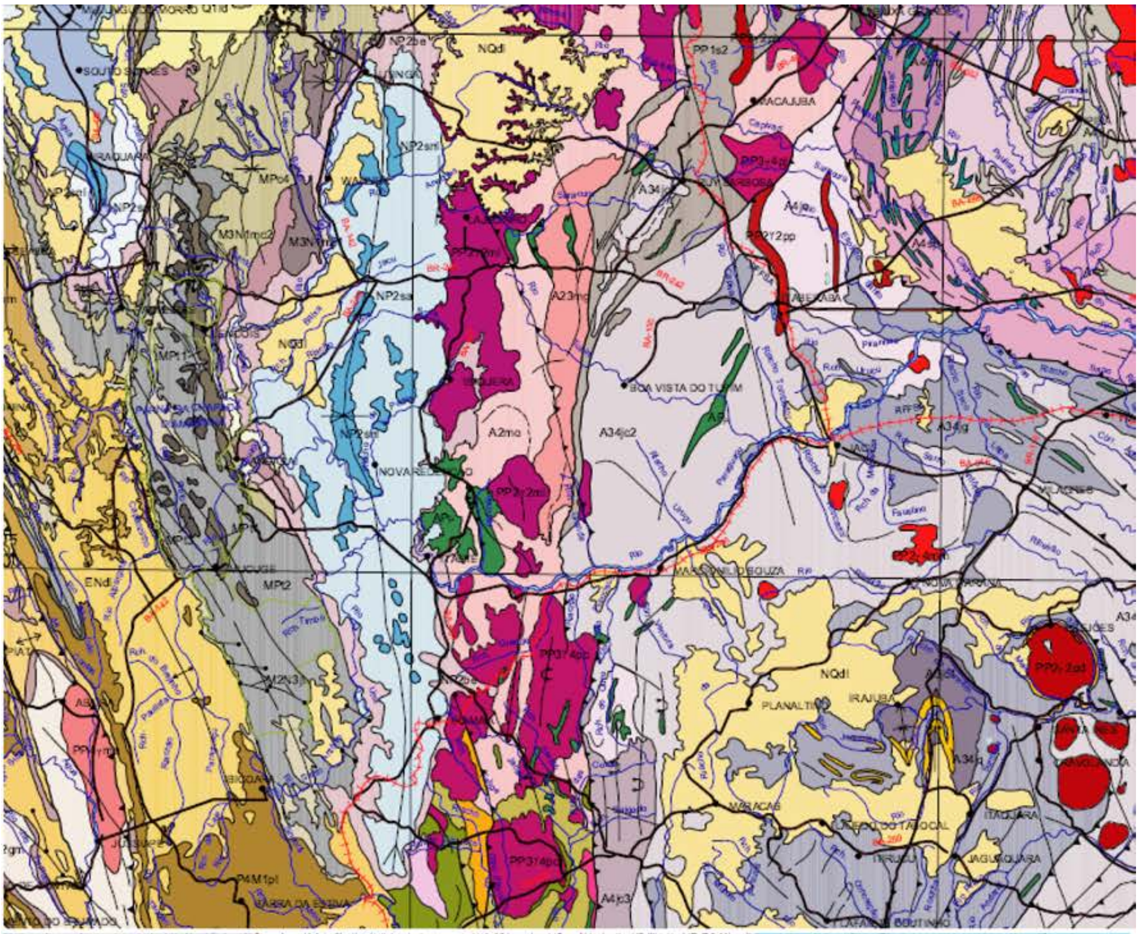
Fig. 27. North-south profile along -41.5 degrees.

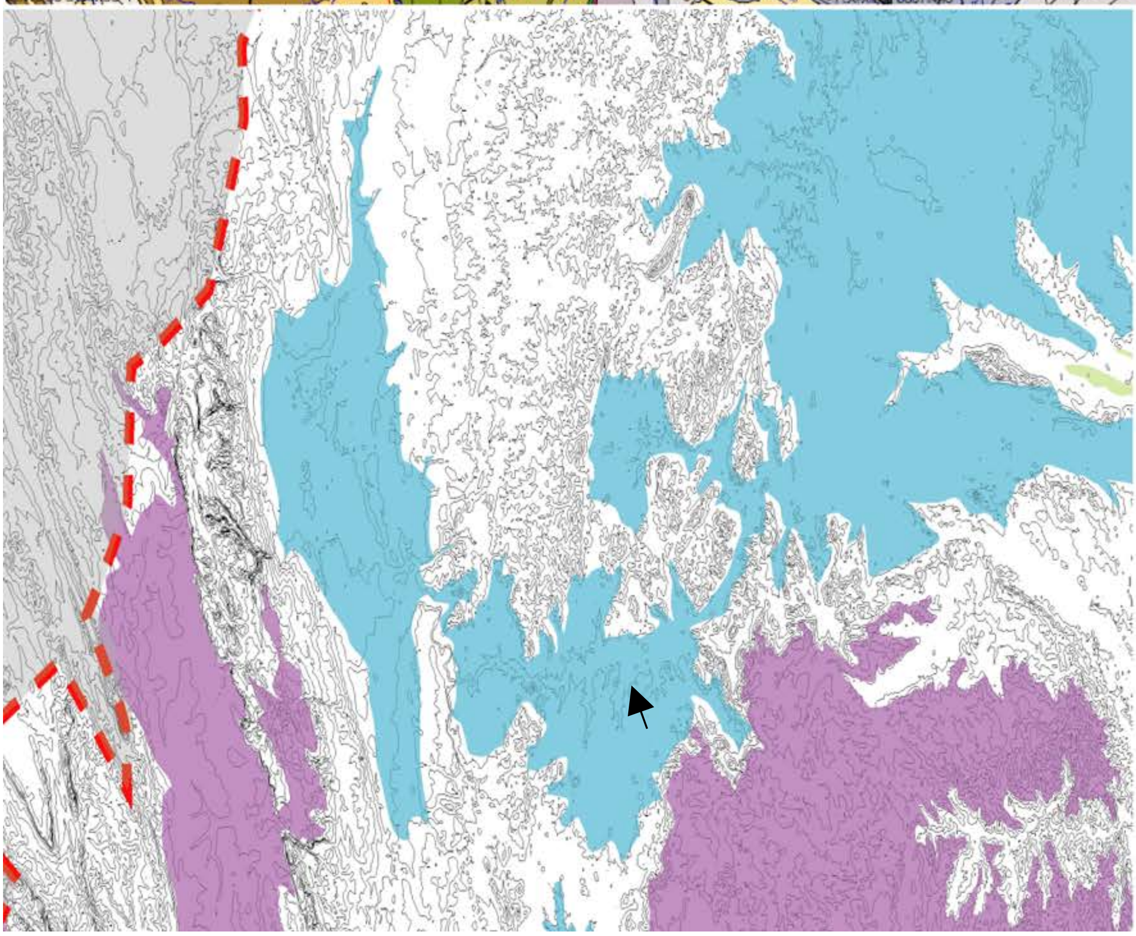
Fig. 27 is selected to illustrate the correlation of surface level between Chapada Diamantina (in the centre) and Planalto de Conquista in the south in the westernmost part of the study area, and also to show the appearance of the lower surface at its uppermost reaches. Above the upper surface level some narrow ridges which clearly stand above the higher surface. The correlation from Chapada Diamantina to the eastern areas shows that the surface might be offset in the eastern part. This is marked in Fig 27 and coincide with a rather large valley in west-east direction (cf. Fig. 6). If true this offset is small, around 100 m, and must have occurred post surface formation. The lower surface is typically concave with a low-point in the valley centre as can be seen in the blue bottom line. The valleys have dissected the higher surface, and the sharp break-of-slope in the maximum line shows the position of escarpments, that separates the lower surface from the higher.

4.3 The surfaces in relationship to geology

The landscape analysis has resulted in a geomorphological map of different surfaces (Fig. 23). This map has been analysed in relationship to the basement geology and to the sedimentary sequences within the study area, in order to distinguish between flat areas due to resistant rocks and surfaces formed by denudation by fluvial systems. The result of this analysis is imbedded in the surface map (Fig. 23). To demonstrate how the geology influences on the development and preservation of surface, an example will be shown here from Chapada Diamantina and the area east of it (Fig. 28). The area is typical for the study area, with north-south trending ridges (folds), containing rocks of different age and resistance.

The lower surface (blue in Fig. 28) is at its uppermost reaches, and the latest development is clearly connected to the geology. The Rio Paraguaçu has cut across an area with granitic and gneissic rocks (e.g. PP2myml, A2mo) and into an area with limestone and calcite (NP2sa and NP2snl, bluish in geology map). While the surface is of limited extent in the granitic/gneissic areas the surface has widen considerable in the limestone area. Thus the conclusion is that the erosion has been much faster in the latter area, and the local lithology have enhanced the development of the lower surface. But at the same time will a surface formed across resistant rocks last much longer than if it is formed across easily eroded rocks. Therefore this is the most likely case in areas with quartzitethat is the case in both Chapada Diamantina and Planalto de Conquista. However the geology will only temporary halt the denudation and eventually only minor, low, ridges of the more resistant strata will be left in the landscape (c.f. Figs 13, 14). The final result after long time of denudation will be a rather flat landscape also in areas with very different geology (see Fig. 25 as an example).


NQdl
NP2sa
A2mo
A34jc2
BOA VISTA DO TUPIM
A23mo
MPt2
ENdl
P4M1pl
BARRA DA ESTIVA
PLANALTINO
IRAJUBA
ITAQUARA
JAGUAQUARA
PACAJUBA
A4jc3



Previous page: Fig. 28. A selection of the Bahia geology map (Dalton de Souza et al. 2003) and from the surface map (Fig. 23.), covering the same area. To the left is Chapada Diamantina and to the right Planato de Conquista. The bedrock is all basement. Lower map: Blue-lower surface, Pink-higher surface. Contours 100 m, the black arrow points at the 300 m contour line. Red-water divide.

5. Geomorphological implications and discussion

The surface mapping in the area (Fig. 23) shows that two major surfaces (peneplains), can be followed along the major valleys as an inclined plain, and the mapping further shows that the surfaces cut across rocks of different age and resistance (Fig. 28). These conditions leave no other options than that the surfaces must have been governed by a general base level. The condition that the surfaces are regional shows that they must have been formed at a time with tectonically stable conditions. The denudation of resistant rocks to form a surface also suggests a long time for the development of surfaces. Therefore, the regional, low-relief surfaces in the study area are witnesses of two different periods when the landscapes were at low elevation and close to the general base level. Thus a relative denudation chronology can be constructed, however that history may not include all the burial and exhumation events that may have occurred in the landscape, but likewise is significant and detectable by other methods (e.g. AFTA, Green 2008, in press).

The higher surface is only preserved in areas with resistant rocks, but it seems highly likely that it originally was completed across a much wider area, indicated by remnants in the east (e.g. inselbergs) that once may have reached the level for the higher surface. The higher surface may also have been present in the west, but in that case it has been deeply cut by the headwaters of the São Francisco river. A candidate for the preserved surface in the west could thus be the Cretaceous rocks in the São Francisco Basin, presently under destruction in its eastern part by the São Francisco river.

The relief above the higher surface may or may not be part of an older surface. If ever existed, it has been significantly eroded. Any attempt to constrain that surface, e.g. as an envelope surface has limited value in landscape analysis.

The lower surface was developed at the expanse of the upper surface due to base-level change. The backward erosion has resulted in winding escarpments, and the winding is especially pronounced in areas with large differences in bedrock resistance. As the amount of base level change, estimated from the valley floor of the lower surface to the elevation of the higher surface, is about 700 m, the change must have had a tectonic component. The lower surface is represented in the whole study area and it is occasionally wide also far away from the present base level. In the eastern part of the study area the lithology play an insignificant role for the surface appearance, while in the west it has mainly developed in areas with less resistant rocks (c.f. 28).

King's geomorphological map (Fig. 2) (King 1967) is in overview analogous to the new map presented here, but for the details, especially the borders for the different surfaces. King identified a high area, which he divided into two surfaces (named Sul-Americana and Velhas) and a low-land plain, (Paraguaçu), in which the former two surfaces are almost analogous to the higher surface and the latter to the lower surface of this study. A difference is that King does not acknowledge a coastal plain cutting off the lower surface, which has implications for the event chronology and timing for surface development in the area (see further discussion in Japsen et al. 2009).

5.1 Surface chronology and timing of events

This latest base-level change has resulted in incision of rivers along the coast and in the the Recôncavo and the Tucano Basin, dissecting Barreiras and Marizal Formations. The apparent rapid dissection of the lower surface here suggests that this is due to relatively recent base level change and must post-date the Barreiras. The age constraints on the Barreiras group are rather broad, between Miocene-Pliocene(?) (Arai and Shimabukuro, 2003). Anyhow the rapid incision together with the preservation of the easily eroded sediments, still forming coherent patches of a once larger surface, indicates that this latest event most probably is young. Such surface would have been rapidly dissected, unless covered or situated in a low position close to the base level.

The lower surface cut across both basement and the rift section. Therefore must the surface post-date the Aptian Marizal formation. However from the geomorphological mapping it is not totally clear whether the lower surface cuts across the Barreiras or if the Barreiras is deposited on the lower surface. The relationship is not clear because the intersection angle is to low to provide a definitive answer. This leaves two possibilities: If the Barreiras are deposited onto the lower surface, the basement beneath the Barreiras is an exhumed surface, with the consequence that another erosional event is required. If so that event is pre-Barreiras, but post higher surface. If the lower surface cuts the Barreiras and basement, the lower surface must be post Barreiras. If however the Barreiras can be of two different ages as suggested by Arai and Shimabukuro (2003), this relationship might be different in other parts of the study area.

The higher surface is primarily found in areas with Proterozoic rocks, thus badly constraining its formation age. However the surface is corresponding to large areas covered with Cenozoic laterites, thus this shows that the higher surface formed in post-Cretaceous times. Further, because some extensive time is needed to form the lower surface after completion of the higher surface, it seems likely that the higher surface formed during the Paleogene, while the lower surface formed mainly in the Neogene and the coastal plain from the Late Pleistocene to present. The landscape as seen today is thus reflecting tectonics and base-level changes in the Cenozoic.

6. Conclusions

The geomorphological analysis of the large scale landscapes at the passive Atlantic margin of NE Brazil shows two major denudation surfaces formed along the major rivers, the higher and the lower surface, and a minor surface in the present coastal areas, the coastal plain (Fig. 23). The higher surface is situated at 1200 to 900 m a.s.l in Chapada Diamantina and Planalto de Conquista. The higher surface is cut across Precambrian basement, and occasionally covered by Cenozoic laterites. The higher surface must therefore be Cenozoic and most likely Paleogene in age, thus formed long after the rift-flank uplift. The lower surface cuts across basement and the rift sequence in the Recôncavo-Tucano Basin and must therefore be post-Aptian in age. The lower surface is extensive and has developed by eroding the higher surface, and this condition suggests that the surface is probably Neogene in age. The coastal plain cut into the Barreiras Formation, constraining its age to post-Miocene, but the rapid development of incision suggest that this reflects a much more recent base-level change.

The height difference of c 500-700 metres between the higher and the lower surface suggests that the base level change must have had a tectonic component.

Resistant rocks facilitate preservation of old surfaces while less resistant rocks facilitate the formation of new surfaces. However long-term denudation decreases the lithological influence significantly of surface the appearance.

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