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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. Final report

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& Peter R. Cobbold

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

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. Final report

Funded by StatoilHydro do Brasil and Petrobras

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1. Summary

We have undertaken a regional study of landscape development and thermo-tectonic evolution of NE Brazil, and implications for hydrocarbon prospectivity in the Camamu Basin. Our results reveal a long history of post-Devonian burial and exhumation across north-east Brazil. Uplift movements just prior to and during Early Cretaceous rifting led to further regional denudation and eventually to filling of rift basins and finally to formation of the Atlantic margin. The rifted margin was buried by around 2 to 3 km of post-rift section and then began to be exhumed in the Campanian as a result of plate-scale forces (beginning between 80 and 75 Ma). The Cretaceous cover probably extended over much of north-east Brazil where it is preserved over extensive areas at the present day. The Campanian exhumation event was followed by events in the Eocene and Miocene, beginning between 48 and 45 Ma and 18 and 15 Ma, respectively.

An end-result of these events of uplift and exhumation were two regional peneplains that characterize the present landscape, the higher and the lower surface, respectively. The plateaux in the interior highlands are characterized by the higher surface at c. 1 km above sea level. This surface was formed after the Campanian event and most likely after the Eocene event and thus formed as an Eocene–Oligocene peneplain near sea level. This surface was reburied prior to the Miocene event, in the interior by several hundred metres of continental deposits and along the Atlantic margin by more than 1 km of marine and coastal deposits. The Miocene uplift event led to the reexposure of the Palaeogene peneplain and to the formation of the lower surface by incision along rivers below the uplifted higher surface. Minor uplift in the Quaternary has caused incision below the lower surface.

The rocks of the Serra do Mar near Rio de Janeiro were also exhumed in three episodes with almost the same timing as in north-east Brazil and all closely correlated with tectonic phases of Andean orogeny. The mountain range of Serra do Mar was shaped after block faulting and uplift during and following the Miocene event.

In the onshore rift basins, low thermal gradients mean that rocks at depths of 4 km or more lie within the oil window. Hydrocarbon generation stopped at the onset of exhumation in the Campanian, but the presence of prolific source rocks have led to hydrocarbon accumulations being preserved to the present day. The absence of elevated heat flow during rifting means that hydrocarbon potential was not exhausted at an early stage in the basin history.

In the offshore Camamu Basin, rift sediments are now at maximum burial and maximum temperatures, whereas the inshore margin was exhumed during the Campanian, the Miocene and possibly the Eocene event. Major sliding in the Camamu Basin between Late Cretaceous and Eocene times due to slope instability, may have been triggered by the Campanian and Eocene uplift events that were focussed along the present coast. Weaker Eocene uplift along the south-western margin of the Camamu and of the Almada Basins may be part of the explanation of why there is less sliding there. In the deep waters, the rift sediments were heated by hydrothermal processes as a result of intrusions. Areas where source rocks have escaped the effects of these hydrothermal events would appear to provide the most attractive targets for exploration in the Camamu Basin.

2. Background

This is the final report summarizing the observations and results made through 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 project was carried out by GEUS in close cooperation with Geotrack International for StatoilHydro do Brasil Ltda and Petrobras as a multi-disciplinary research project aimed at understanding the regional burial and exhumation history of NE Brazil and the Camamu Basin. The project was initiated in January 2007 and was completed in February 2009.

Fieldwork was carried out in Brazil during four weeks in July and August 2007, in particular focussed on observations of large-scale landscapes in relation to geology and on sampling of rocks, primarily for apatite fission-track analysis (AFTA). The fieldwork was carried out in the Early Cretaceous rift systems near the Atlantic margin and on the interior highlands in the state of Bahia. Furthermore, samples for AFTA were gathered along near-vertical profiles in Serra do Mar, north-east of Rio de Janeiro, to provide a reference dataset for comparison with the results onshore and offshore Bahia. Additional samples from the Rio area were collected in connection with workshops at StatoilHydro’s office in January 2007 and June 2008. During the stay in Brazil in 2007, samples of core material were selected for AFTA from 4 offshore and 8 onshore wells. Well log data, reports etc. for 5 onshore and 14 offshore wells were also made available for the project as basis for estimating amounts of removed sections from sonic data.

Results from the project have been presented in a number of reports:

- Burial and exhumation history of North-east Brazil. Field work 2007. Japsen, P., Bonow, J.M., Cobbold, P.R. & Pedreira, A.J. 2007. GEUS Report 2007/66, 77 pp.
- Burial anomalies and magnitude of exhumation estimated from sonic data for 19 wells, onshore and offshore NE Brazil; Almada, Camamu, Recôncavo, Sanfranciscana and Tucano Basins. Japsen 2009. GEUS Report 2009/8. 129 pp.
- Geotrack Report 990 (onshore). Thermal History Reconstruction in the 1-AO-1-BA, 1-BRN-1-BA, 1-FLU-1-BA, 1-FPO-1-BA, 1-FVM-1-BA, 1-RSO-1-BA, 3-MB-3-BA and 6-MGP-34-BA wells, Tucano and Recôncavo Basins, Onshore Brazil, together with AFTA and associated thermal history interpretations in 89 outcrop samples from Bahia, NE Brazil, and 20 samples from the Serra do Mar. Green, P.F. 2009. Geotrack International, Victoria, Australia.
- Geotrack Report 1013 (offshore). Camamu Basin, offshore Brazil. Thermal history reconstruction in the 1-BAS-88-BA, 1-BAS-102-BA, 1-BAS-113-BA & 1-BAS-129-BA wells, based on AFTA and VR data. Green, P.F. 2008. Geotrack International, Victoria, Australia, 153 pp and appendices.
- Relative denudation chronology in NE Brazil based on mapping of large-scale landforms. Bonow, J.M. 2009, GEUS Report 2009/9.

Results from the project have been presented at international conferences:

- Bonow, J. M. and Japsen, P. 2008. Magnitude of tectonic uplift events along passive margins estimated from analysis of base-level governed erosion surfaces. AAPG International Meeting and Exhibition October 26-29 2008, Cape Town, South Africa, 1 p.
- Japsen, P, Bonow, J.M., Green, P.F., Chalmers, J.A. & Lidmar-Bergström, K. 2008. Cenozoic uplift around the North and South Atlantic. 33rd International Geological Congress, Oslo, August 6-14, 1 p.
- Japsen, P., Bonow, J. M., Green, P. F., Cobbold, P. R., Pedreira, A. J., Lilletveit, R., and Chiossi, D. 2008. Burial and exhumation history of NE Brazil: Preliminary results based on apatite fission-track analysis, landscape analysis and the stratigraphic record. AAPG International Meeting and Exhibition October 26-29 2008, Cape Town, South Africa, 1 p.

One paper has been submitted for possible publication:

- Bonow, J.M., Japsen, P., Green, P.F., Cobbold, P.R., Pedreira, A.J., Lilletveit, R. & Chiossi, D. Post-rift landscape development of north-east Brazil. Geological Survey of Denmark and Greenland Bulletin.

3. Regional setting

The main onshore study area is located on the Brazilian Atlantic margin, primarily in the state of Bahia but also in adjacent areas in the states of Sergipe and Alagoas (between 9°-16°S and 35°-43°W) (Fig. 3-1). Major tectonic features are the Precambrian São Francisco craton (cf. Alkim 2004) and the intracontinental Recôncavo-Tucano-Jatobá Rift that developed in Early Cretaceous times during the opening of the South Atlantic (Fig. 3-2). The offshore study area comprises the Almada and Camamu Basins that are part of the same rift system, located offshore, south-east of the Recôncavo Basin, but with the western margins of these basins exposed along the coast. Stratigraphic charts for the Almada, Camamu and Recôncavo basins are included in Appendix A (Figs A-1 to A3; Gontijo et al. 2007; Caixeta et al. 2007; Silva et al. 2007). The Serra do Mar mountains north of Rio de Janeiro were included as a reference area for the AFTA study.

3.1 Onshore study area: Eastern Bahia and adjacent areas

The coastal areas are dominated by lowland plains that have developed up to 200 km inland from the coast. Pronounced escarpments often border the lowland plains in the hinterland, and above the escarpment lay highland plains (‘planaltos’) (Figs 3-1, 4-1). The highlands and their escarpments are often referred to as 'chapadas', literally 'capped’. The highland plains are generally elevated to 1000–1400 m a.s.l., but above the plains some ridges have peaks that reach up to 2 km above sea level (a.s.l.).

According to Sabaté et al (1995), the São Francisco Craton is generally surrounded by fold belts (e.g. the Sergipana foldbelt in the north-eastern part of the study area) where tectonic activity culminated during the Brasiliano cycle (c. 900–500 Ma). The continental crust within the Craton which is the thickest in Brazil, can be subdivided into three large Precambrian stratigraphic and tectonic units: (1) a Late Proterozoic sedimentary cover related to the Brasiliano cycle, (2) a Middle Proterozoic platform cover (Chapada Diamantina) and the correlated Espinhaço fold belt (1.6–1.0 Ga), (3) an Archaean and Early Proterozoic basement (>1.6 Ga).

3.1.1 Chapada Diamantina

The plateau of Chapada Diamantina rises above the low plains c. 250 km from the Atlantic coast and has altitudes averaging around 1,000 m and peaks up to 1,700 m above sea level. The Chapada represents the divide between the São Francisco river valley to the west, and the terrain that extends eastwards towards the Atlantic coast. The central part of Chapada Diamantina comprises the Mesoproterozoic Chapada Diamantina Basin and Neoproterozoic Irecê, Ituaçu and Una-Utinga basins (Fig. 3-3). The Chapada Diamantina Basin that developed on continental crust is a quartzite-pelite-carbonate type cover sequence, represented by the Espinhaço Supergroup. Its low-grade strata are divided into the Rio dos Remedios, Paraguayu and Chapada Diamantina Groups, unconformably overlain by the Neoproterozoic Una Group according to Pedreira & Bomfim (2000).

The Rio dos Remedios Group, a few hundred meters thick, comprises acid effusive rocks and strata that are related to crustal rifting. In places, the quartzites have sedimentary structures diagnostic of eolian facies, so that the Rio dos Remedios Group may be interpreted as a product of fissural volcanism in a desert environment. Its maximum age is 1718 ± l Ma.

The Paraguayu Group comprises the Ouricuri do Ouro, Mangabeira, Ipupiara and Guine formations. The Ouricuri do Ouro Formation (about 125 m thick) comprises conglomerates and subordinated sandstones. The sandstones are epiclastic with cross bedding and a few ripple marks that indicate their subaquous deposition. The Mangabeira Formation (>2000 m thick) is fine and coarse grained feldspathic sandstones that generally are cross bedded. The great thickness of this formation and the absence of major faults associated to it, suggest slow subsidence during its deposition. The Ipupiara Formation (up to 1500 m thick) consists of sandstones and shales, with ripple marks. In most of the Chapada Diamantina, the Mangabeira Formation is overlain by the Guine Formation. The basal part is characterised by shales and siltstones with a very weathered intercalation of conglomerate, followed by interbedded sandstones and siltstones. The upper part of the formation is characterized by fluvial channels cut into rippled sandstones. The depositional environment of the Guine Formation has therefore been interpreted as deltaic.

The Chapada Diamantina Group comprises the Tombador, Caboclo and Morro do Chapéu formations. The Tombador Formation (90-400 m thick) is essentially composed by sandstones and conglomerates. The sandstones range from fine to coarse grained, are cross or horizontally bedded. The conglomerates are of two types: The first type, with rounded pebbles whose diameter is up to 5 cm, is generally associated to fluvial sands; the second type is polymictic with some metric sized boulders are interpreted as alluvial fans. The Caboclo Formation (250 m thick) begins by calcarenites followed by pelites with sandstones and carbonate lenses in its type-area. The Morro do Chapéu Formation (250 m thick) is characterized by a basal fluvial conglomerates followed by estuarine and tidal flat sandstones and shales, and deltaic sandstones (Souza Cruz et al. 2006).

The Bebedouro and Salitre formations of the Una Group lie unconformably above the Chapada Diamantina Group. The Bebedouro Formation consists of diamictites, sandstones, siltstones and shales (200–350 m thick). The Salitre Formation comprises carbonates with very subordinate terrigenuous strata (100–240 m thick).

The Brasiliano folding affected the entire Proterozoic sedimentary sequence in the Chapada Diamantina area, including the Salitre Formation.

3.1.2 The Recôncavo-Tucano-Jatobá Rift

The main rifting phase along the NE Brazilian margin occurred between 135 and 120 Ma, but the development of the Recôncavo-Tucano-Jatobá (RTJ) Rift failed following crustal separation between South America and Africa in the late Aptian (c. 120 Ma) (e.g. Milani & Davison 1988; Chang et al. 1992; Magnavita et al. 1994; Magnavita et al. 1998; Davison

1999). The rift contains Palaeozoic to Cenozoic strata and the post-Palaeozoic stratigraphy can be broken down into prerift, synrift and postrift phases (Figs 3-2, 5-3, A-1 to A-3) (e.g. Magnavita et al. 1994). The Phanerozoic sequence in the RTJ Rift and the adjacent area contains several major unconformities (Table 3-1).

The prerift sequence consists of continental sandstones and lacustrine shales of Jurassic age (Sergi and Aliança formations, respectively) which progressively thin northward from a maximum thickness of 1200 m in the south Recôncavo Basin to less than 200 m in the Jatobá Basin.

The rift phase was initiated during the Berresian to Valanginian (146–136 Ma), when the main extensional faulting occurred, and great thicknesses (locally up to 3 km) of coarse conglomerates were deposited next to major faults (Salvador Formation). In the centre of the basin a deep lake formed, which was filled by shales and turbiditic sandstones (Candeias Formation). Deltaic sandstones and shales (llhas Formation) and fluvial sandstones (São Sebastião Formation) filled in the rift. Rifting stopped during the deposition of the latter formation in Barremian to early Aptian times (c. 130–120 Ma)

The basin was blanketed by postrift fluvial and alluvial conglomerates and sandstones with occasional thin lacustrine shales of Aptian age (Marizal Formation). The Marizal Formation was deposited on an undulating eroded surface underlain by tilted synrift strata. The Marizal Formation covers most of the Tucano and Jatobá basins, but has been largely eroded from the Recôncavo Basin (Fig. 3-2). The Marizal Formation reaches a maximum thickness of approximately 400 m in the Tucano Basin. According to Magnavita et al. (1994) evidence of Albian marine incursions is preserved in the Tucano and Jatobá basins (Santana and Exu formations).

3.1.3 Mesozoic cover outside the RTJ Rift

Vast areas of Brazil are covered by Mesozoic sediment. The Phanerozoic Sanfranciscana Basin is of special interest to this study because Cretaceous sediments here crop out over more than 100,000 km2 in the western part of Bahia and further west (Fig. 3-4; Campos & Dardenne 1997a). This eastern limit of this basin reaches 80 km west of the study area. The Phanerozoic cover is composed mainly of sedimentary continental rocks and minor explosive volcanic rocks including rocks of Carboniferous to Permian, Early and Late Cretaceous as well as Quaternary age (Fig. 3-5). The Upper Cretaceous is subdivided into the Mata da Corda and the Urucuia groups. The Cenomanian to Campanian Urucuia Group is composed of sandstones interpreted as dune deposits and braided stream deposits with transport from NEE to SWW, with sources in the north-east São Francisco Craton. It is present in the entire basin. The Mata da Corda Group is primarily of Maastrichtian age and is composed by volcanic rocks and by distal epiclastic sediments. It is present in the southern sector of the basin. The Cretaceous rocks are exposed over a planar surface at an elevation of c. 1 km a.s.l. Rivers are incised into the surface that cuts across the tilted Cretaceous strata (Campos & Dardenne 1997b). No conglomerates or faults are found along the present limits of the Cretaceous deposits that consequently appear to be defined by post-depositional exhumation; i.e. during the Cenozoic. The Cretaceous sediments are overlain by the Chapadão Formation that represents the recent sandy, unconsolidated, covers of talus, residual or alluvium origin. According to Campos & Dardenne (1997b) this formation is of Quaternary origin.

Upper Cretaceous rocks also crop out on Chapada do Araripe, c. 200 km north of the study area where these strata define a plateau at an elevation of c. 1 km a.s.l. Morais Neto et al. (2006) studied AFTA data from samples in the area and found evidence for two main episodes of cooling, one in the Late Cretaceous and one after 40 Ma. The authors found that these cooling episodes were caused by regional exhumation and that the plateau surface had been more deeply buried in the past; even during the post-40 Ma episode.

3.1.4 Cenozoic cover

Palaeogene and Neogene sedimentary deposits, weathering profiles and magmatic rocks are found across all of Brazil, but these rocks are often difficult to date and/or of limited extent (Fig. 3-6), but their age and distribution are of crucial importance for understanding the burial and exhumation history over the last 65 million years.

The Lower Miocene Sabiá Formation

Thin (<20 m) lower Miocene fossiliferous marine shales have been described from at one locality in the Recôncavo Basin (Sabiá Formation) (Viana et al. 1971; Petri 1972). This outlier was found in 3 m deep trenches at an elevation of 85 m a.s.l. which thus indicates a post-depositional uplift of at least 85 m. According to Petri (1972) the sediments rest on Early Cretaceous deposits and are covered by late Cenozoic non-marine sediments (i.e. the Barreiras Group). Whereas Petri (1972) assign a Miocene age to the Sabiá Fm, Viana et al. 1971 argue that it is of Early Miocene age. Similar transgressive shales are known from northern Brazil, where the Pirabas Fm is of earliest Miocene (Aquitanian) age (Fernandes & Távora 1990). In their summary of Cenozoic geology of Brazil, Schobbenhaus & Britto-Neves (2003) write that regression culminated in the Oligocene and was followed by a pronounced transgression in the Early Miocene and that this unconformity can be traced along almost all coastal regions of Brazil. On the recently published stratigraphic chart of the Recôncavo Basin (Fig A-3), the Sabiá Fm is given a mid-Miocene age. The only reference to the age of the formation given in this publication is that of Viana et al. (1971) where the age is clearly stated as Early Miocene based on biostratigraphic evidence.

The Neogene Barreiras Group

The Barreiras Group of Miocene-Pliocene age was deposited as a fluvial sandstone cover (<100 m) along most of the Atlantic margin of Brazil (Pedreira 1971, and Bigarella 1975 as cited by Magnavita et al. 1994). The deposits even reach into the south-western part of the Tucano Basin and the basement areas south-west of the rift (CPRM 2003). The sedimentological characteristics are indicative of deposition in a braided river system related to alluvial fans under an arid to semi-arid climate (Vilas Bôas et al. 2001). The basal portion of the Barreiras Group was deposited in a proximal fluvial system whereas the upper portion was deposited in a more distal zone according to Vilas Bôas et al. (2001) who found the deposits to be indicative of steep relief resulting from tectonic action. The age of the Barreiras

Group has been a topic of debate, but Bezerra et al. (2001) argued that the top of the Barreiras Group near Natal could be taken to be Pliocene based on relative dating by palaeomagnetic and micropollen. According to Figueiredo et al. (1994) a Pliocene age of the Barreiras Group was confirmed by pollen analysis and the study of 38 species of Dicotyledoneae.

Arai (2006) argued that recent palaeontological and sedimentological studies have shown marine influence on the Barreiras Group and that its basal part dates back to the early and middle Miocene. According to Arai (2006) palynological dating and coring of the Barreiras Group with coeval lithostratigraphic units in offshore basins of the Brazilian continental margin and elsewhere in the world have permitted new interpretation in the light of sequence stratigraphic concepts. These integrated studies permitted correlation of the origin of the Barreiras Group with the Miocene global eustatic rise, which reached its maximum from the Burdigalian to the Serravalian (20-12 Ma). Deposition of the Barreiras senso lato was interrupted in the Tortonian (early late Miocene), when a global eustatic fall exposed and eroded part of the Barreiras and led to the formation of prograding wedges in the offshore portion of the continental margin basins. Renewed eustatic rise in the Pliocene (Zanclean, 5-4 Ma) initiated a second depositional phase (‘Barreiras Superior’). Erosion and reworking of the Barreiras Group during the Quaternary have contributed to the present configuration of the continental shelf. According to this interpretation of Arai (2006), the origin of the Barreiras Group is solely seen in the light of global eustacy whereas possible influence of tectonic movements is not discussed.

Guia Lima (2008) combined $^{40}Ar/^{39}Ar$ analysis of manganese oxides and (U-Th)/He of goethite grains from the Barreiras Fm in the Borborema province and found that the deposition occurred some time between 22 Ma and 17 Ma (early to mid-Miocene). These deposits would thus belong the Barreiras Inferior of Arai (2006).

Near the western margin of the Tucano Basin, the sedimentary sequences, including the Neogene Barreiras Group, appear to have been folded to form three anticlines with gentle eastern limbs and steeper western limbs (Fig. 3-7; cf. Japsen et al. 2007a). Each anticline lies between relatively straight, incised river valleys, which follow transfer faults in the rift system. The inference is that the anticlines are due to late Neogene compressional reactivation of an eastward-dipping normal fault and of the rift transfer faults.

Cenozoic sediments on plateaux north and south of the study area

In Minas Gerais (near Belo Horizonte; see Fig. 3-1), the sandy-clay sediments of the Eocene Fonseca Fm were deposited within a meandering fluvial system, but they only occur as relicts restricted to a small graben-like structure within the Precambrian basement (Sant’Anna et al. 1997). The Fonseca Fm is overlain unconformably by the undated Chapada de Canga Fm, a thick succession of continental ironstone pebble conglomerates that derives its name from the regional plateau that it forms (c. 1 km a.s.l.; up to 50 m thick according to figure 8 in Sant’Anna et al. 1997) (Fig. 3-8). Whereas the Fonseca Fm was affected by post-sedimentary brittle deformations, the Chapada de Canga Fm is cut by structures that indicate both syn- and post-sedimentary tectonics. Extensional post-sedimentary tectonics caused the downthrow of the Fonseca Fm into a small graben structure, whereas a subsequent erosional cycle removed the Fonseca Fm above the graben structure and caused general planation leading to the formation of the surface upon which the thick successions of the Chapada de Canga Formation were deposited (Sant'Anna et al. 1997). Sant'Anna et al. (1997) noted that there is no equivalent to the Fonseca Fm in the Palaeocene – Miocene geological record in the Continental Rift of South East Brazil where two units were deposited in meandering fluvial systems during calm tectonic periods, respectively in the late Oligocene and the late Miocene–Early Pliocene (e.g. Riccomini et al. 2008; see Fig. 3-6).

In Borborema, the nonfossiliferous sandstones and conglomerates of the Serra do Martins Fm (<100 m) are preserved at high elevations on the Borborema Plateau which is characterized by altitudes between 650 and 1000 m (Fig. 3-9). Morais Neto et al (2008a) presented AFTA and zircon fission-track analysis results for samples of the Serra do Martins Fm that combined with geological evidence, demonstrated that the sediment was deposited in the Palaeogene (65-25 Ma). The AFTA data also indicated that the samples reached maximum palaeotemperatures around 60°C, from which they began to cool after 30 Ma. Such palaeotemperatures correspond to heating below a sedimentary cover about 1 km thick for a palaeogeothermal gradient of 30°C/km, but Morais Neto et al. (2008a) speculated that the gradient could have been much higher (and the cover thinner) due to late Cenozoic volcanism in the area.

Cenozoic weathering profiles

Vast areas in the interior highlands of the state of Bahia are mapped as Cenozoic or Neogene laterites ("Coberturas detrito-lateríticas", CPRM 2003). These thick covers of heavily weathered basement rock (saprolites) are found on the planaltos and other elevated areas . They probably represent remnants of more extensive saprolites that have been preserved in the uplifted areas where they have not yet been removed by fluvial erosion. Direct dating of weathering phenomena in Brazil has become possible by 40Ar / 39Ar and K-Ar analysis of supergene K-Mn oxides (e.g. Vasconcelos et al. 1994). Spier et al. (2006) investigated deep weathering profiles overlying iron ore deposits in Minas Gerais, south-west of the study area (c. 44ºW, 22ºS). Laser incremental-heating 40Ar / 39Ar results for grains of manganese oxides revealed ages ranging from c. 62 to 14 Ma, where older Mn-oxides occurred near the surface, while younger Mn-oxides occurred at depth. However, many samples collected at the weathering–bedrock interface yielded ages in the 51–41 Ma range, suggesting that the weathering profiles had reached their present depth in the Palaeogene. The age versus depth distributions obtained showed that little advance of the weathering front had occurred in the lateritic profiles during the Neogene. Spier et al. (2006) found that the weathering was not controlled by the steady-state advance of weathering fronts through time, but reflected climatic and geomorphological conditions prevailing in a remote past. The geochronological results also indicated that the ancient land surfaces in the study area probably remained immune to erosion for tens of millions of years, and that the deep weathering mostly occurred in the Palaeogene during hot and wet climatic conditions. Spier et al. (2006) also noted that deep weathering profiles are a characteristic of the plateau in the area studied and thus sets it apart from the dissected landscape that surrounds the plateau: The plateau hosts much deeper weathering profiles than the surrounding landscape; local relief within the plateau is less pronounced than in the surrounding plains;

ages of weathering profiles on the plateau are much greater than ages for the surrounding plains.

Vasconcelos and Carmo (2008) found a distinct relation between Ar-Ar ages of laterites and the three main landscapes in Minas Gerais and other areas in Brazil. Ar-Ar ages were 70–30 Ma for the upper surface (South American), 15–6 Ma for the intermediate surface (Velhas) and less than 4 Ma for lower surface (Paraguaçu). Furthermore, the authors highlight the importance of major gaps in the record that they interpret as periods of 'erosion-prone conditions': prior to 70 Ma and between 30 and 15 Ma.

Guia Lima (2008) found similar results in her study of weathering chronology in the eastern part of the Borborema province north of study area. The weathering profiles on the highlands that cap the "Borborema Surface" are deep (up to 100 m) and can be considered as typical lateritic profiles. In the lowlands, the weathering profiles are shallow and poorly developed (2-5 m deep) whereas the profiles along the coastal area are moderately developed (up to 25 m deep) and are characterized by thick saprolites and mottle zones. Guia Lima (2008) found that the sedimentary mesas on the Borborema Plateau are characterized by ancient, thick and complex lateritic profiles. Furthermore, Guia Lima (2008) highlighted the marked gap in the estimated weathering ages between a narrow Palaeogene peak around 30 Ma and a broad range of ages younger than 15 Ma. Younger (<5 Ma), narrow and incipient weathering profiles were found in the dissected areas between the mesas, and Guia Lima thus suggested that scarp retreat may explain the regional landscape evolution.

Diatomite

Finally, there are several occurrences of fresh-water diatomite deposits in the highlands of e.g. Chapada Diamantina and Planalto da Conquista, and apparently none in the lowlands. These deposits are exploited in numerous small-scale mines, but the literature on this subject is very sparse.

3.1 Offshore study area: Camamu-Almada Basin

The Camamu-Almada Basin lies mainly offshore and to the SE of the Recôncavo Basin (Figs 3-2, 3-10). Numerous wells have penetrated the sedimentary cover on the shelf (Gonçalves 2002; Gonçalves et al. 2000; Mohriak 2003; Menezes and da Silva 2008). However, the deeper offshore was less well known until recently. No deep reflectors could be tied with any certainty to the Moho. This situation has changed radically, with the advent of 3D seismic surveys and associated gravity data (Cobbold et al. 2008a, 2008b).

3.1.1 Relief on the sea bottom

The continental margin of the Camamu-Almada Basin is only about 40 km wide and this is unusual. The water depth reaches 3500 m. The slope of the sea bottom is therefore nearly 10% on average and reaches 20° near the shelf break. Such a slope is potentially unstable, if there are underlying surfaces of easy slip. According to data from 3D seismic surveys, the relief is regular on the whole. Regularly spaced canyons incise the continental slope. However, there is a prominent salient in the north.

3.1.2 Basin fill

Our knowledge of the Camamu-Almada Basin comes mainly from about 20 wells on the shelf, and 3 deepwater wells (cf. stratigraphic charts in Appendix; Caixeta et al. 2007, Gontijo et al. 2007). The fill is up to 7 km thick, but there are patches of missing section under deep water (Fig. 3-11). Well 1-BAS-129 goes no deeper than the Aptian. Unconformable upon Precambrian basement are Jurassic sandstones of regional extent. Neocomian strata, up to 3 km thick, accumulated in a continental rift. Shale in the lower part is equivalent to the main source rock of the neighbouring Recôncavo Basin. Aptian strata are also continental, but consist mainly of coarse clastic sediment and evaporite. Late Cretaceous strata are thin or absent and the Tertiary succession is only about 1 km thick, above a prominent middle Eocene unconformity.

3.1.3 Deep structure

The new 3D seismic survey shows some continuity of stratigraphic markers around Well 1-BAS-129. The Aptian sequence of continental clastic sediment is about 1 km thick. Above it are structures, which appear to be compressional (folds and reverse faults). A prominent unconformity, which appears to be Middle Eocene, truncates these structures.

Regional 2D seismic sections provide better views of most structures. They are thin-skinned, extensional near the edge of the continental platform, and compressional toward the toe of slope. The structures have detached on Aptian evaporite, and at the base of Neocomian shale. The structural patterns are characteristic of gravitational sliding. The largest slide is about 5 km thick, and occupies the entire continental slope, for about 100 km along strike. It has a strong degree of mirror symmetry about a vertical plane perpendicular to the margin. The main phase of sliding occurred sometime between the late Aptian and the middle Eocene. Sliding continued in the Neogene, albeit at a slower rate, and active sliding today is responsible for characteristic scars on the sea floor.

Under deep water, the new 3D seismic data allow one to distinguish reasonably well between oceanic crust and continental (or transitional) crust. It is also possible to infer the position of the ocean-continent boundary (OCB) from gravity data and from best fits of the conjugate margins. The 3D seismic data reveal a strong reflector at depth, which could be the Moho. In places this reflector rises to a depth of only 6 seconds TWT. There is a very marked positive free-air gravity anomaly. Everywhere throughout the seismic volume, even though the deep reflector is not a cylindrical surface, it appears to be in phase with marked undulations in the gravity field. On this basis alone, the reflector appears to be the Moho. Unfortunately, it is not visible on most 2D seismic profiles. However, it shows up well on a composite depth-converted 2D-3D line. Recent gravity modelling of this line has confirmed that the deep reflector could well be the Moho. If so, it rises to as little as 12 km below sea level, 10 km beneath the sea bottom, and perhaps 2 km beneath the base of the Aptian sequence. Moreover, this Moho uplift appears to be associated with at least one large normal fault, and the crust immediately to the east of it appears to be of oceanic or proto-oceanic character.

3.1.4 Shallow structures from 2D seismic sections

As mentioned previously, 2D seismic sections, being longer, provide better views of thin-skinned structures than do the 3D seismic data. The 2D coverage is quite dense, especially on the continental shelf. The structural style changes progressively, from north to south, in part because the thickness of Aptian salt increases, and in part because the intensity of sliding decreases.

In general, a sharp hinge line marks the edge of the continental platform (Fig. 3-12). This hinge line has a series of straight segments, which are fault-controlled. Where visible, the main faults have reverse components of slip, although the occasional flower structure is a strong indication of strike-slip.

At the foot of the scarp, the slope of the sea bottom increases to 20° or more. This area has abundant evidence for recent and older slope instability, in the form of slumps, mass gravity flows, and landslides. Underlying strata of Tertiary, Cretaceous and Jurassic ages have been tilted, so that in places they are almost parallel to the sea bottom. The inference is that much of the tilting is recent.

On some seismic lines, typical hummocky topography indicates oceanic basement. Underlying oblique reflectors are seaward dipping near the surface. Deeper oblique reflectors may be the old walls of magma chambers. A strong horizontal reflection at about 6.5 seconds TWT may mark the base of oceanic crust. According to magnetic anomalies and models of sea-floor spreading, this oceanic crust is Albian. Strong reflections within overlying sedimentary strata may mark sills, dykes, lavas, or tuffs.

Landward of recognizable oceanic crust, Aptian salt (halite or anhydrite) is relatively common in the south, where it forms large rollers and domes. In the north, the salt forms occasional domes, but otherwise it is very thin. The best evidence for salt is a strong detachment. The seaward edge of the salt is probably close to the boundary between continental and oceanic crust. Across the hinge line and adjacent steep segment, the Aptian salt rises abruptly by several km. As the salt probably formed in shallow water and at a single base level, its offset is evidence for post-Aptian tectonics at the hinge line.

3.1.5 Submarine slides

The main structures on the margin are due to slope instability. Large slides have formed by detachment at several levels (Cobbold et al. 2008a, 2008b). The resulting structures are so intense that they tend to mask underlying rift faults. In general, slides are bigger in the north of the basin, than they are in the south.

Regionally, there are two major detachments (Fig. 3-12). The upper one is in Aptian salt, whereas the lower one is at the base of Neocomian shale. The slides have mostly formed under the steepest slopes. Listric normal faults mark the trailing edges of the slides, near the hinge line, whereas folds and thrusts mark their leading edges, near the continent-ocean boundary. Folds are common above thick salt, whereas imbricate toe thrusts are common in areas of thin salt or no salt. These areas of local thickening have been subject to later erosion and slope instability.

The main area of sliding near Salvador straddles the entire continental margin. The lower detachment, at the base of Neocomian shale, reaches a depth of about 12 km. The slide is about 60 km wide and its sides are strike-slip zones. This slide has strong mirror symmetry about a vertical plane striking NW-SE. The symmetry is common to folds, faults, and also the shape of the sea bottom.

Significant relief at the sea bottom indicates that the giant slide is active today. On a map of the sea bottom over the entire Camamu-Almada Basin, there is a significant perturbation in the area of the giant Salvador slide. Large scars and canyons, bounded by normal faults, mark the trailing edge and upper sides of the slide, whereas an area of relatively high sea bottom marks the leading edge and the lower sides of the slide. The pattern of relief is typical of a landslide.

A strong erosional unconformity is prominent in the north of the Camamu-Almada Basin, less so in the south. In the north, the unconformity truncates all structures above the Aptian detachment and some of those below it. Thus most of the sliding in this area occurred in the late Cretaceous. In three deep-water wells (1-BAS-102, 1-BAS-126, and 1-BAS-129), folded and thrust-repeated strata are of all ages from Neocomian to Albian. In 1-BAS-126, the first flat-lying strata above the unconformity are Campanian; in 1-BAS-102, they are probably of the same age (by correlation with 1-BAS-83); and in 1-BAS-129, they are probably Eocene. In all three wells, the Cenomanian-Turonian highstand is not recorded. Possibly the unconformity in the north is due to rapid erosion of topographic irregularities that appeared during one or more events of sliding. Even so, the relief of the unconformity surface is pronounced in places, especially over the area of toe thrusts, where there is a steep scarp. Thus erosion did not flatten all the relief that resulted from sliding.

In contrast, in the south, sliding has occurred on Aptian salt, from the Albian until the present day, resulting in growth faults and growth folds. There is less evidence there for a major regional unconformity.

3.1.6 Early Mesozoic rifting

Over much of the area, Jurassic sandstones of the Sergi Formation appear to be continuous. In some places, they are offset across relatively minor faults. However, at other locations, faults have offsets of 1000 m or more. Several of these larger offsets line up on a map in a NNE-SSW direction. Careful picking of seismic horizons may reveal other series of offsets, indicating significant rift faults.

On the shelf above the main slide, the Jurassic sandstones appear to be thicker than on the adjacent slope. Locally, the sequence appears to thicken eastward, as if in a half-graben. On this basis, rifting may have started in the Jurassic, and not in the early Cretaceous.

In the Recôncavo Basin, Jurassic strata are offset across steep faults at many localities (Magnavita et al., 2005). Seismic evidence for growth faulting is less abundant. However, growth faults are visible in roadside outcrops (Magnavita et al., 2005, their figure 18). Thus the prevailing idea that the Jurassic sequence is only “pre-rift” may be an oversimplification. In general, in the Recôncavo Basin, Jurassic strata thicken westward, whereas Neocomian strata thicken eastward (Magnavita et al., 2005). This difference implies a change or interruption in the process of rifting between the Jurassic and the Cretaceous.

3.1.7 Compressional reactivation of the margin

There are several lines of evidence for compressional reactivation of the margin since the Aptian (Cobbold et al., 2008a, 2008b).

1) Reverse faults are visible near the shelf edge. In most examples, the reverse fault that marks the shelf break dips landward. In some instances, a conjugate reverse fault has formed to landward of the shelf break and the two faults converge downward, forming a positive flower structure, which is a typical product of transpression.
2) At the shelf edge, the Aptian salt has been offset by several km.
3) Thicker Jurassic sequences on the shelf are today in a higher position than thinner sequences on the slope. The most likely explanation is that Jurassic normal faults dip landward and have been reactivated in compression, inverting the basins.
4) On the shelf, values of vitrinite reflectance in well cores are abnormally high. The current depth to early maturity (vitrinite reflectance of 0.6 %) is about 1500 m on the shelf, instead of a more typical 3000 m. The reflectance increases with depth at a rate that is diagnostic of a normal geothermal gradient.
5) Also in the neighbouring onshore Recôncavo Basin, vitrinite values from wells are abnormally high (Daniel et al., 1989; Magnavita et al., 1994). The current depth to early maturity of Neocomian strata is as little as 0.8 km on the edges of the basin. The inference is that the basin edges have been exhumed by more than 1800 m. Some of this exhumation occurred in the Aptian, because there is a strong erosional unconformity of that age. Albian marine limestones now crop out at an altitude of over 600 m in parts of the basin and have therefore been uplifted.
6) The large slide in the northern Camamu Basin formed between Late Cretaceous and mid Eocene times. It presumably resulted from tilting of the margin.
7) By extrapolation from neighbouring outcrops, the underlying crystalline basement of Precambrian age contains SE-verging thrust faults. These are good candidates for reactivation, first as normal faults in the early Mesozoic, and then as reverse faults in the Late Cretaceous and Tertiary.

3.1.8 Conclusions for the Camamu Basin

1) In the Camamu Basin, the continental shelf is very steep. The sea bottom goes from about 100 m to 1500 m, over a distance of about 10 km, at a gradient of about 15%.
2) Marking the sharp shelf edge is a steep fault zone, like a flower structure (Cobbold et al., 2008a, 2008b). This appears to have a reverse component. Reverse motion on the fault zone would account for the inversion of Jurassic rift basins, which are visible on some seismic lines.
3) Large slides have developed on the margin since the Aptian. They appear to have formed by slip on two main detachment surfaces, an upper one in or near an Aptian evaporite sequence, and a lower one at the base of Neocomian shale. The slides are as much as 4 km thick. Within them the bedding has tilted by as much as 30°. In the upper parts of the slides, listric normal faults are diagnostic of horizontal extension, whereas in the lower parts, folds and thrusts indicate shortening. All these structures are truncated by widespread erosion surfaces. Stratigraphic data from Well 1-BAS-129 indicate that the erosion may have occurred as late as the middle Eocene. The reason for sliding would appear to be slope instability.
4) On the shelf, vitrinite data from wells show that there has been as much as 1500 m of exhumation, following uplift.

3.2 Onshore reference area: Serra do Mar

3.2.1 Landscape

In general, highlands predominate in SE Brazil (Figs. 3-13–3-15). Two large areas of land are over 1000 m: the Ponta Grossa arch, to the W of Curitiba, and an area to the E of Poços de Caldas. These areas appear to be offset right-laterally across a line of valleys, which runs approximately ENE, from Curitiba, through São Paulo, Taubaté, Volta Redonda and Além-Paraiba, to Campos.

East of São Paulo and Poços de Caldas, there are three main mountain ranges.

1) The Serra da Mantiqueira provides the main drainage divide between the Paraná basin and the bay of Santos. It reaches 2787 m at Agulhas Negras, the highest peak in SE Brazil. The range is strongly asymmetric: the scarp faces SSE at a gradient of about 20%, whereas the dip slope has an average gradient of about 1% and is remarkably planar. The juvenile landscape is characteristic of recent block faulting, after peneplanation (Almeida 1976; Karner & Driscoll 1999; Cobbold et al. 2001; Riccomini et al. 2004; Zalán and Oliveira 2005; Romer 2008). The peneplains are of regional extent and seem to be Cretaceous (Japi Surface) or Eocene on geological evidence (King 1956; Almeida 1976; Almeida & Carneiro 1998; Riccomini et al. 2004). Correlation between regionally extensive surfaces and minor occurrences of geological deposits can, however, be difficult, especially if the deposits are in down-faulted positions.

2) The Serra do Mar (coastal range) rims the bay of Santos, from Florianópolis in the SW to Rio de Janeiro in the NE. Between the cities of Santos and Rio de Janeiro, the range is continuous, asymmetric and culminates at nearly 2000 m. The main scarp, facing the sea, rises to about 1000 m, over a distance of 5 km, at an average gradient of about 20%. In detail, however, the scarp is heavily incised. Erosional remnants of late Precambrian granites (such as the famous Sugar Loaf at Rio de Janeiro) form characteristic inselbergs.
3) The Serra dos Órgãos lies immediately to the N and NE of Rio de Janeiro and peaks at more than 2200 m. Its southern edge, a straight scarp, rims the Bay of Guanabara.

The drainage pattern in SE Brazil indicates recent uplift of the Serra do Mar (King 1956; Bacoccoli & Aranha 1984; Karner & Driscoll 1999; Cobbold et al. 2001). The main rivers are the Paraíba do Sul and the Tietê. The Paraíba do Sul is about 600 km long, yet never far from the sea. Its source is on the Serra do Mar, south of Taubaté. First, the river flows westward. Near São Paulo, it turns through 180° and flows eastward, in a flat valley (about 600 m high), between the Serra da Mantiqueira and Serra do Mar. At Volta Redonda, the river bends sharply to the SE and drops into a deeper valley (at an altitude of about 300 m). Although the headwaters of this deeper valley are within 10 km of the sea near Ilha Grande, the Paraiba do Sul flows ENE, along a deep and almost straight gorge, as far as the Campos area, where it forms a delta. Such an unusual course is evidence for river capture.

The River Tietê also rises in the Serra do Mar, within about 10 km of the sea. Nevertheless, it flows WNW, through São Paulo, enters the Paraná Basin, and empties into the river Paraná. From there, the waters flow about 1200 km southward, before empting into the Atlantic Ocean near Buenos Aires.

3.2.2 Geological structure

At outcrop, the mountains of SE Brazil consist mostly of crystalline basement (Almeida 1967; Almeida et al. 1981; Asmus & Baisch 1983; Almeida & Carneiro 1998). Archaean rocks of high metamorphic grade (including granulite) form cratons (Figs. 3-16 and 3-17). In the North is the São Francisco Craton, whereas in the South was the Congo Craton, before opening of the Atlantic. During the Brasiliano (Pan-African) orogeny (750-480 Ma), the two cratons welded, forming the Ribeira Belt (Almeida 1967; Hasui et al. 1975; Campanha 1981; Almeida & Hasui 1984; Machado et al. 1996; Unrug 1996). This belt has the form of a doubly vergent flower structure at crustal scale (Machado and Endo 1993; Campos Neto & Figueiredo 1995; Machado et al. 1996). In the middle are steep right-lateral shear zones, including the Além-Paraíba shear zone (Almeida et al. 1975; Campanha 1981; Campos Neto & Figueiredo 1995). Towards their ends, the shear zones curve sigmoidally into more N-S trends, becoming thrust zones (DNPM 1981; Schobbenhaus et al. 1981; Campanha 1981; Campos Neto & Figueiredo 1995). Thus the Ribeira Belt results from right-lateral transpression in the late Precambrian (Trouw et al. 2000). The present landscape seems to have many features that are due to reactivation of basement structures.

3.2.3 Parana Basin

To the SW, the Ribeira Belt disappears (Figs. 3-17 and 3-18) beneath flat-lying Palaeozoic and Mesozoic strata of the Parana Basin (Schobbenhaus et al. 1981; Zalán et al. 1990a, 1990b, 1990c). Its infill consists mainly of Palaeozoic shallow-marine siliciclastic sequences. Overlying them are Triassic to early Jurassic continental deposits, late Jurassic to Early Cretaceous continental flood basalts of the Paraná Large Igneous Province (Rocha Campos et al. 1988; Misuzaki et al. 1992; Renne et al. 1992; Stewart et al. 1996), Late Cretaceous continental sandstone (Bauru Group), and sparse Tertiary deposits. The Bauru Group is of Coniacian to Maastrichtian age (Fernandes et al. 2007). About 250 m of clastic sediment accumulated in a continental basin, to the west of an eroding Serra do Mar.

3.2.4 Continental margin

The Atlantic margin of Brazil formed in Jurassic to Early Cretaceous time, as part of the East Brazil Rift System (Campos et al. 1974; Figueiredo 1985; Chang et al. 1992; Cainelli & Mohriak 1999; Meisling et al. 2001). Rifting eventually led to opening of the Atlantic in the Albian, after formation of a wide salt basin in the Aptian.

In the offshore Santos and Campos basins, the sedimentary infill is mainly of marine origin and spans the Early Cretaceous to Recent. In the central Santos Basin (Figs. 3-19 and 3-20), the total sediment package is as thick as 12 km (Macedo 1989). At its base are the Parana basalts, showing that post-Neocomian vertical displacement across the margin is as much as 13 km, over a distance of 150 km. Some of this displacement accumulated during rifting. However, there is no stratigraphic record of it onland. Instead, the marine sequences are truncated by erosion at a hinge line, which bounds the continental platform (Williams and Hubbard 1984; Gamboa et al. 2008). Much of this truncation is clearly of post-rift origin. Indeed, there is stratigraphic and structural evidence offshore for at least three phases of post-rift reactivation, of Late Cretaceous, Eocene, and Miocene ages (Cobbold et al. 2001; Fetter 2008).

A noticeable feature of the Santos Basin is its very thick accumulation of prograding clastic shallow-marine sediment of Late Cretaceous and Palaeogene age, beneath a much thinner cover of Neogene sediment. In contrast, the Campos Basin has little Cretaceous and Palaeogene sediment, but a thick cover of prograding Neogene sediment. A simple explanation for this contrast is uplift and exhumation of the adjacent mountains in several phases and their effects on sediment routing. Whereas the Late Cretaceous and Eocene phases provided abundant sediment to the Santos Basin (Fig. 3-13), the Neogene phase uplifted the Serra do Mar, shutting off sediment supply to the Santos Basin and routing it instead to the Campos Basin, further North (Baccocoli & Aranha 1984; Cobbold et al. 2001).

3.2.5 Neocomian igneous intrusions

Dykes that are synchronous with Early Cretaceous rifting and the Paraná-Etendeka flood basalts are known from two main areas. Along the coast, between Santos and Rio de Janeiro, a major dike swarm is parallel to the SW-NE-trending main extensional faults of the rift phase. Its age is between 133 Ma and 129 Ma by ^{40}Ar-^{39}Ar methods (Turner et al. 1994). Another major dyke swarm in the Ponta Grossa area is also broadly contemporaneous with the flood basalts (Turner et al. 1994; Renne et al. 1996), but it trends NW-SE, almost at right angles to the extensional faults (Figure 3-18). The origin of this dyke swarm is controversial. The angular relationships are reminiscent of a classic triple junction, in which the Ponta Grossa dyke swarm would be the aborted arm. However, the dikes are not oriented radially above an inferred plume (Peate 1997). Perhaps the Ponta Grossa dyke swarm, like the Salado and Colorado basins in Argentina, resulted from NE-SW extension, during counterclockwise rotation of southern South America, relative to northern South America (Leyden 1976; Chang et al. 1992). Alternatively, perhaps the dyke swarm is parallel to a major continental strike-slip zone (Nürnberg and Müller 1991), or a Neocomian transfer zone. Also in the Ponta Grossa area are several intrusions of alkaline igneous rocks (Amaral et al. 1967), which are broadly contemporaneous with the Paraná flood basalts (Amaral et al. 1967) and have been attributed to the Walvis hotspot (White & McKenzie 1989; Peate 1997). Two belts of intrusions, one immediately to the SW of São Paulo and the other around Curitiba, strike WNW-ESE, parallel to the transfer faults (Amaral et al. 1967; Herz 1977; Cobbold et al. 2001).

3.2.6 Post-rift intrusive rocks

Alkaline intrusions of Late Cretaceous to Palaeogene age are relatively common in SE Brazil (Fig. 3-17), where they tend to form alignments (Amaral et al. 1967; Almeida 1986; Woolley 1987; Gibson et al. 1995; Thompson et al. 1998). The main belt of at least 22 intrusions trends ESE, from Poços de Caldas to Cabo Frio. Compositionally, the rocks are syenites, nepheline syenites and phonolites, with occasional carbonatites. They are therefore similar to the alkaline intrusions of Neocomian age, which were emplaced coevally with rifting. Geochemically, this Late Cretaceous to Palaeogene magmatism is indistinguishable from ocean-island basaltic magmatism (Thompson et al. 1998). The intrusion at Poços de Caldas is the widest (35 km) and one of the oldest (75-85 Ma). From there, the ages decrease systematically, to 54 Ma at Cabo Frio (Thompson et al. 1998). To a first approximation, the sizes of the intrusions also decrease eastwards. Three explanations have been found for this belt: (1) it is the onland extension of an oceanic fracture zone (Marsh 1973); (2) it is a hotspot track (Herz 1977); (3) it was displaced southwards from the track of the Trindade hotspot, by a deflection at the base of the lithosphere (Thompson et al. 1998). The explanation of Thompson et al. (1998) seems plausible. Additionally, however, because the igneous intrusions lie along the main transfer zones between the Campos and Santos basins, Cobbold et al. (2001) have suggested that they were emplaced at dilational jogs, during episodic reactivation of the transfer zones.

Another belt of alkaline intrusions of Late Cretaceous age lies along the northeastern edge of the Paraná Basin. This belt is about 100 km wide, 600 km long and trends NW-SE (Herz 1977; Woolley 1987; Thompson et al. 1998). The northwestern end of the belt coincides with the calculated position of the Trindade hotspot at 85 Ma, when it probably first impacted the continental lithosphere (Gibson et al. 1995). The southeastern end of the belt is displaced southwards from the calculated hotspot track.

Other alkaline intrusions of Late Cretaceous and Tertiary ages, notably the set around São Sebastião, appear to have been emplaced within magmatic belts, that were active during Neocomian rifting. Again, the belts appear to coincide with transfer zones.

3.2.7 Onshore Tertiary basins

Particular to SE Brazil is a string of small basins (Fig. 3-18), which lie within 50 km of the coast and contain Tertiary sediments of continental origin (Almeida 1976; Melo et al. 1985). These basins are of great significance for interpreting the Tertiary history of the margin, because they contain syn-sedimentary faults (Cobbold et al. 2001; Riccomini et al. 2004). Three of the basins (Taubaté, Resende and Volta Redonda) line the valley of the river Paraíba do Sul; two others (São José de Itaboraí and Barra de São João) occur along the main rift transfer zones, between Rio de Janeiro and Cabo Frio.

The Taubaté Basin

The Taubaté Basin separates the Serra da Mantiqueira from the Serra do Mar and is the largest basin onshore. Its subsurface structure is known from seismic profiles (Marques 1990) and from magnetotelluric, gravity and geothermal surveys (Padilha et al. 1991). The sedimentary infill reaches a thickness of 850 m. Fluvial and alluvial sediment of Miocene age (Pindamonhangaba or Caçapava Fm) overlies lacustrine mudstones (Tremembé Fm). The mudstones are organic-rich and have yielded fossil vertebrates (Kellner & Campos 1999). They have been dated as Oligocene (Lima et al. 1985). Beneath them are alluvial sediment (Resende Fm) and interbedded ankaramitic lava flows of Eocene age (Riccomini et al. 2004). In detail, the Taubaté Basin consists of a series of sub-basins, between transfer zones (Marques 1990). Sub-basins are typically asymmetric and they are bounded by master-faults, mainly of extensional type. However, the master faults are steep to vertical, more in the style of pull-apart basins. The master faults trend ENE. They are associated with growth strata, including stratigraphic wedges and the occasional rollover, showing that sedimentation was synkinematic. Master faults tend to alternate in vergence, from one sub-basin to another. On seismic profiles, erosional truncations of the Taubaté Group are visible at the ground surface. Some faults and folds offset the entire sedimentary sequence, indicating post-Oligocene activity. At one locality, Marques (1990) identified a reverse fault, trending N-S. More generally, within the Taubaté Basin, he identified numerous flower structures, some positive and some negative. At several localities in the Taubaté Basin, faults offset the current stone line, indicating Quaternary activity (Riccomini & Assumpção 1999). Fault-slip data appear to indicate two phases: one of E-W extension, responsible for normal faults and some strike-slip faults; another, of E-W shortening, responsible for strike-slip and reverse faults (Riccomini et al. 1989). At one roadcut in the Taubaté Basin, listric extensional growth faults of Oligocene age have reactivated as reverse faults, trending NNE (Cobbold et al. 2001). Striations have northerly pitches of 10° to 40°, indicating components of right-lateral slip and a Neogene tectonic context of transpression, where the principal horizontal compression was oriented approximately NE (Cobbold et al. 2001; Riccomini et al. 2004).

The Resende and Volta Redonda basins

The Resende and Volta Redonda basins lie along a major transfer zone. In the Volta Redonda Basin, flows of ankaramitic basalt (rich in olivine and augite) are of Eocene age (Riccomini et al. 1983).

São José de The Itaboraí Basin

In the small São José de Itaboraí Basin, near Rio de Janeiro, ankaramitic lavas are also of Eocene age (Riccomini & Rodrigues Francisco 1992). Fossil Palaeocene vertebrates are common in fresh-water limestones (Kellner & Campos 1999). Flat-lying travertines fill a small half-graben (Sant'Anna et al. 2004). The master fault (São José fault) dips steeply to the NNW and carries striations with normal and right-lateral components (Cobbold et al. 2001). Variations in stratigraphic thickness against the master fault provide evidence for synkinematic sedimentation. Minor faults in the limestones are post-depositional and carry excellent striations, in the form of imbricate calcite fibres. Strike-slip components predominate and dip-slip components are either normal or reverse. The principal direction of shortening is horizontal and ENE; that of stretching, horizontal and NNW. Thus the tectonic context was one of strike-slip.

The Barra de São João Basin

The Barra de São João Basin, near Cabo Frio, lies mostly on the shallow continental shelf, but it has an onshore extension (Mohriak & Barros 1990; Mohriak et al. 1995, fig. 3-15). Offshore, seismic profiling has revealed a sedimentary infill, up to 800 m thick. Two sequences are separated by a regional unconformity. The upper sequence is flat-lying and crops out onshore as red sands of the Barreiras Formation (Neogene?). The lower sequence is tilted against extensional master faults that strike ENE. By correlation with the nearest well on the platform, this lower sequence is probably Eocene in age. One of the master faults, the Pai Vitório fault, crops out onland (Heilbron et al. 2000). Flat-lying sands of the Barreiras Formation are in the footwall and brecciated Precambrian orthogneisses are in the hanging wall. The fault zone dips steeply northwards and the cataclasites contain sigmoidal cleavage traces, which indicate a right-lateral component of motion.

On a regional scale, the various Tertiary basins appear to be separated by major transfer zones (Cobbold et al. 2001). This is especially clear at the northeastern end of the Taubaté Basin. The available data point to two phases of Tertiary tectonics: a Palaeogene phase of transtensional deformation, which produced the basins; and a Neogene phase of transpressional deformation, which partly inverted them (Cobbold et al. 2001; Riccomini et al. 2004).

3.2.8 Thickness of crust and lithosphere

The high altitudes of SE Brazil appear to be compensated isostatically at the Moho. Such a pattern contrasts with traditional models of a rifted margin. Offshore, according to refraction seismic experiments (Leyden 1976; Leyden et al. 1971) and deep seismic reflection profiles (Mohriak & Dewey 1987), the crust varies in thickness under the Santos and Campos basins, from 30 km near the coast, to as little as 10 km next to oceanic crust. This variation appears to be primarily a consequence of early Mesozoic rifting (Chang et al. 1992). Onshore, crustal thicknesses have been measured at two sites, by refraction seismic experiments. One site, in the São Francisco craton, yielded a depth of 42 km (Giese & Schütte 1975); the other, in the Serra do Mar near Ubatuba, yielded 36.2 ± 2.6 km (Bassini 1986). Other estimates of Moho depth, by receiver function analysis (Assumpção et al. 1997), range from 38-43 km under the Serra do Mar, to 42-47 km under the Paraná Basin. Elsewhere, gravity measurements provide estimates of crustal thickness (Sá et al. 1993; Ussami et al. 1993). In the highlands of SE Brazil, there is no large free-air anomaly, but there is a large negative Bouguer anomaly (- 80 milligal). As elsewhere in Brazil, there is a reasonable inverse correlation between Bouguer anomalies and topography. If compensation is at the Moho, isostatic anomalies for SE Brazil are small and positive, and the predicted Moho depth is 37.5 to 40 km (Ussami et al. 1993). This prediction correlates well with the other independent estimates. Thus, onland, the crust would appear to be thicker than normal, and decidedly thicker than for most rifted margins.

For South America, Mantovani et al. (1999) measured tidal gravity anomalies and used them to estimate an effective elastic thickness for the lithosphere. According to their calculations, the effective elastic thickness is relatively small in SE Brazil (60 - 64 km), whereas it is greater (up to 100 km) under adjacent Archaean cratons.

3.2.9 Onshore geological evidence for post-rift exhumation

In the centre of the Paraná Basin, Late Cretaceous eolian sands (Bauru Formation) and Tertiary fluvial sediments accumulated above the Neocomian basalts, while the southeastern edge of the basin underwent uplift, tilting and erosion. On geological maps, the Palaeozoic sedimentary strata and Cretaceous basalts form nearly parallel bands (Fig. 3-18). Their isopachs, as reconstructed from subsurface data, are truncated (Macedo 1989; Zalán et al. 1990a, 1990b, 1991; Milani et al. 1990; Milani 1992). Some of the exhumation occurred before eruption of the basalts, which overstep Palaeozoic sediments onto Precambrian basement (Fig. 3-19); but much of it occurred later, as witnessed by eroded basalt outliers, perched on the mountains. Near Rio de Janeiro, there is a large dike swarm, but no flood basalts are visible, probably because of erosion (Peate 1997). Similarly, none of the alkaline igneous intrusions of Palaeogene age seem to connect upwards with lava flows, and this is good evidence for several km of Neogene exhumation. In Guanabara Bay, phonolitic hyaloclastic breccias have accumulated on peneplaned basement amongst Palaeogene strata and have been dated at 65.65 ± 0.05 Ma by $^{40}Ar/^{39}Ar$, indicating that the Japi Surface is Cretaceous in that area (Ferrari et al. 2001; Riccomini et al. 2004).

3.2.10 Other onshore evidence for exhumation

Several researchers have attempted to constrain the timing of cooling and exhumation in SE Brazil by apatite fission track (AFT) dating (Hawkesworth et al. 1992; Gallagher et al. 1994, 1995; Brown et al. 1999; Oliveira et al. 2000; Tello Saenz et al. 2003, 2005; Hackspacher et al. 2004; Ribeiro et al. 2005).

Gallagher et al. (1994) studied apatites in (1) Early Cretaceous basalts, (2) Palaeozoic sediments from the Paraná Basin and (3) Precambrian basement gneisses.

1) For basalts perched at high altitudes, fission tracks are long, indicating rapid cooling. The AFT central ages (weighted means of the logarithmic distributions of single-grain ages) are close to 130 Ma (Early Cretaceous) and indistinguishable from those obtained by $^{39}Ar/^{40}Ar$ methods (Hawkesworth et al. 1992). They are therefore considered to be formation ages.
2) For undisturbed Palaeozoic sediments from the Paraná Basin, AFT ages range from 119 Ma to 157 Ma. These relatively young ages indicate that the sediments were hotter in the past, due to burial, but then cooled during Mesozoic and Cenozoic exhumation. For sediments baked by Cretaceous volcanism, ages are nearer 130 Ma.
3) For Precambrian gneisses, ages vary from 330 Ma to 50 Ma, depending on sample location. Near the Poços de Caldas igneous intrusion, AFT ages of 80 Ma to 81 Ma coincide with those obtained by other methods on the igneous rocks themselves.

Elsewhere in the Precambrian gneisses, the variation in AFT ages must reflect the regional thermal history. To interpret the ages requires a thermal model. One of the simplest is where cooling results from progressive uplift and denudation, so that samples rise vertically through steady isotherms. The last samples to rise are the last to cool and therefore yield the youngest AFT ages. Such a model predicts an increase in age with altitude (an uplift profile). In SE Brazil, AFT central ages from basement gneisses tend to increase with altitude, but there is no simple uplift profile. Indeed, for altitudes above 800 m, there is considerable scatter. Much less scatter is visible on a plot of age versus distance from the coast. The plot may therefore be a tilting profile. The steepest slope (indicating the quickest cooling) is for ages between 100 Ma and 200 Ma (Jurassic to Early Cretaceous), when rifting was active.
To better examine the regional distribution of AFT central ages, Cobbold et al. (2001) plotted them on a map. The central ages are in 3 groups, Pre-Rift (older than 200 Ma), Rift (200 to 100 Ma) and Post-Rift (100 to 50 Ma). The groups form domains, roughly parallel to the coast. Pre-Rift ages (Domain A) occur in the Archaean to Proterozoic highlands, NE of Poços de Caldas. The dip slope of the Serra da Mantiqueira and the Proterozoic rocks at the tip of the Ponta Grossa arch, NW of Curitiba, have yielded Rift ages (Domain B). The Serra do Mar has yielded Post-Rift ages (Domain C). On the coastal plain at the foot of the Serra do Mar, a few central ages are Palaeogene. The boundary between Rift and Post-Rift domains is the River Paraíba do Sul, amongst Tertiary faults and basins. Thus the various fault blocks appear to have differing patterns of central ages (Oliveira et al. 2000; Ribeiro et al. 2005).

The current elevations of the fault blocks (1000 m or more for the Serra do Mar 2000 m or more for the Serra da Mantiqueira) may reflect more recent uplift, which has led to no exhumation, or for which exhumation is undetectable by AFT dating.

3.2.11 Earthquakes and current stress

SE Brazil is a seismically active region and is currently deforming under a state of horizontal compressive stress. Such a tectonic context contrasts with the traditional view, in which the Atlantic margin of Brazil is a passive margin.

The World Stress Map (Zoback 1992; Heidbach et al. 2008) includes data for South America, especially breakout data from boreholes in sedimentary basins (Lima et al. 1997) and new earthquake data from the continental margin (Assumpção 1992, 1998).
According to the earthquake catalogues, deep seismicity concentrates at the active Andean margin of South America. However, low-magnitude crustal events are widespread over cratonic areas, especially the highlands between the Central Andes and eastern Brazil. The largest number of events is in SE Brazil. According to focal mechanisms and borehole breakouts, the greatest principal stress is compressive, horizontal, and strikes about E-W (Assumpção 1998; Riccomini & Assumpção 1999). Onshore, strike-slip faulting is dominant and thrust faulting is subsidiary. Offshore, thrust faulting is dominant ((Lima & Beneduzi 1998).

3.2.12 Conclusions

The data that are available so far for SE Brazil are consistent with the idea that the margin has been through several phases of reactivation, since the end of rifting in the Aptian. Cobbold et al. (2001) argued for three phases, in the Late Cretaceous, Eocene, and Neogene. Zalan and Oliveira (2005) argued for Neogene reactivation. However, there is no consensus as to the style or mechanism of reactivation.

Zalan and Oliveira (2005) upheld a model of mainly extensional reactivation, involving thick-skinned gravitational collapse of the margin. However, according to fault-slip data, reactivation seems to have occurred mainly in strike-slip mode, under the action of horizontal compression (Riccomini et al. 1989, 2004; Cobbold et al. 2001). The structures that have rejuvenated would appear to be mainly Precambrian shear zones and thrusts of the Ribeira Belt. Cobbold et al. (1996, 2007) correlated three phases of reactivation in SE Brazil with well-known phases of Andean orogenesis (Peruvian, Incaic and Quechua). This points to plate-wide horizontal stress as an important factor in the exhumation of the Atlantic margin. The underlying idea is very simple. A current or recent stress field, if strong enough and suitable oriented, is likely to reactivate those structures which formed under a similar stress field in the past. That would explain why the mountains of SE Brazil are in the same position and have the same shape as the late Precambrian orogen.

Table 3-1. *Major unconformities and main sedimentary sequences in the Phanerozoic sequence in the RTJ Rift and adjacent areas. Primarily based on Magnavita et al. (1994), Caixeta et al. (1994) and updated according to the geological map of Bahia (CPRM 2003). Geological ages from Gradstein et al. (2004) (Fig. 5-3). From Japsen et al. 2007a.*

Deposits of Quaternary age (2–0 Ma).

Late Neogene unconformity; hiatus possibly around 2 Ma (Plio-Pleistocene).

Deposits of possibly Pliocene age (5–2 Ma) (Figueiredo et al. 1994); Barreiras Group.

Early Neogene unconformity; hiatus possibly 15 to 5 Ma (mid to late Miocene).

Deposits of early Miocene age (c. 23–16; possibly Aquitanian to Burdigalian); Sabiá Fm.

Late Mesozoic to mid-Cenozoic unconformity; hiatus c. 100 to 25 Ma (Late Cretaceous to Oligocene).

Deposits of late Aptian age and Albian age (115–100 Ma); Marizal Fm, Santana and Exu Fms (Tucano, Jatobá).

Aptian (break-up) unconformity; hiatus c. 125 to 115 Ma (mid-Aptian).

Deposits of Tithonian to earliest Aptian age (151–125 Ma); Brotas, Santo Amaro, Ilhas and Massacará Groups.

Early Mesozoic unconformity; hiatus c. 250 to 150 Ma (Triassic to Middle Jurassic).

Deposits of Permian age (299–251 Ma); Santa Brigida Fm (Tucano Norte, Jatobá), Aracaré Fm (Sergipe-Alagoas), Afligidos Fm (Recôncavo, Tucano Sul).

Late Palaeozoic unconformity; hiatus c. 360 to 300 Ma (Carboniferous).

Deposits of Silurian (444–416 Ma) and Devonian (416–359 Ma) age; Taracatu Fm of the Jatobá Group and Curituba Fm, respectively.

Early Palaeozoic unconformity; hiatus c. 540–440 Ma (Cambrian to Ordovician).

Precambrian basement of Neoproterozoic age (1000–542 Ma).

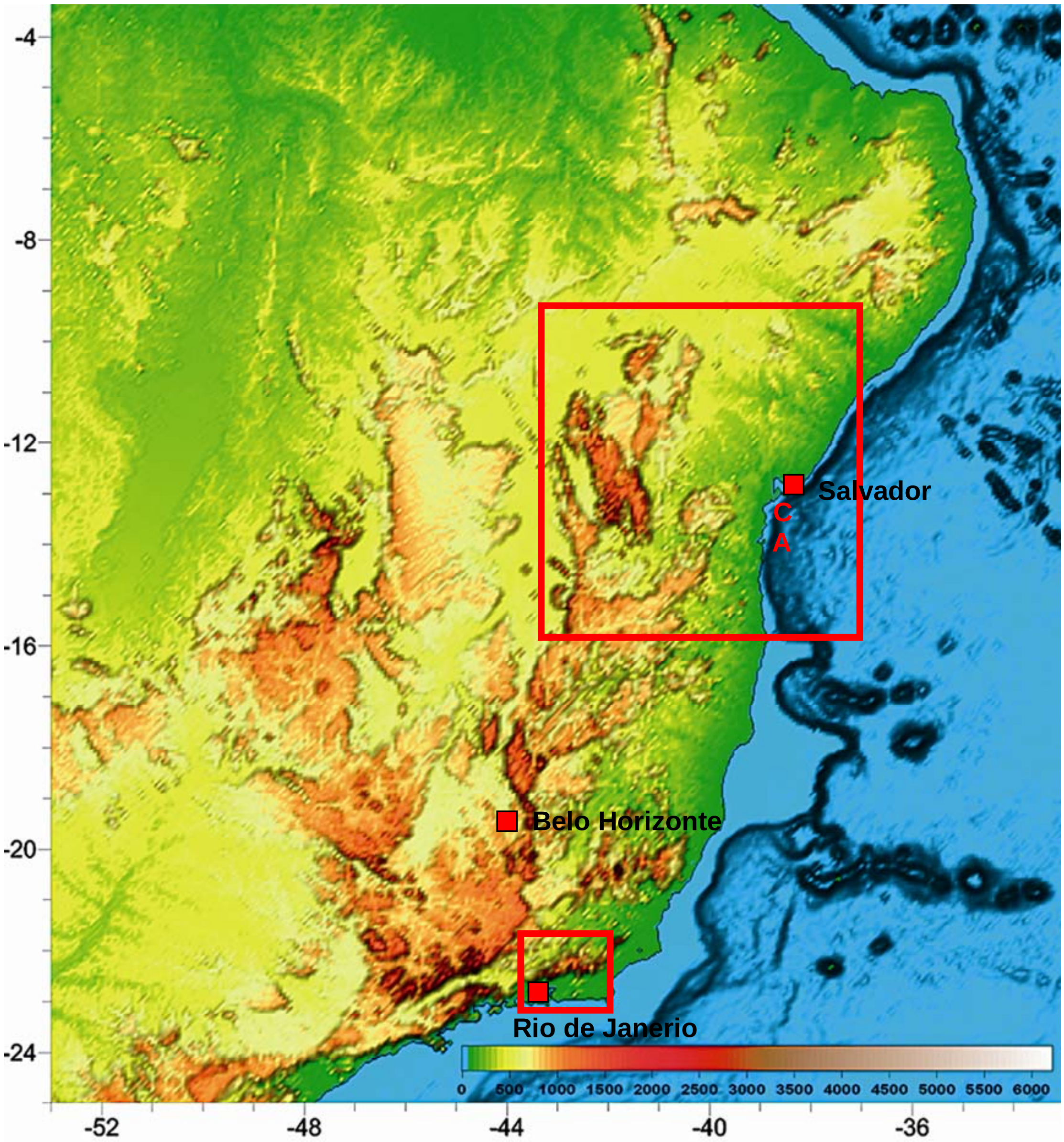


Figure 3-1. *Topographic map of eastern Brazil with indication of the offshore Almada and Camamu Basins (A and C), the onshore study area focussed around eastern Bahia and the onshore reference area in Serra do Mar, north-east of Rio de Janeiro.*

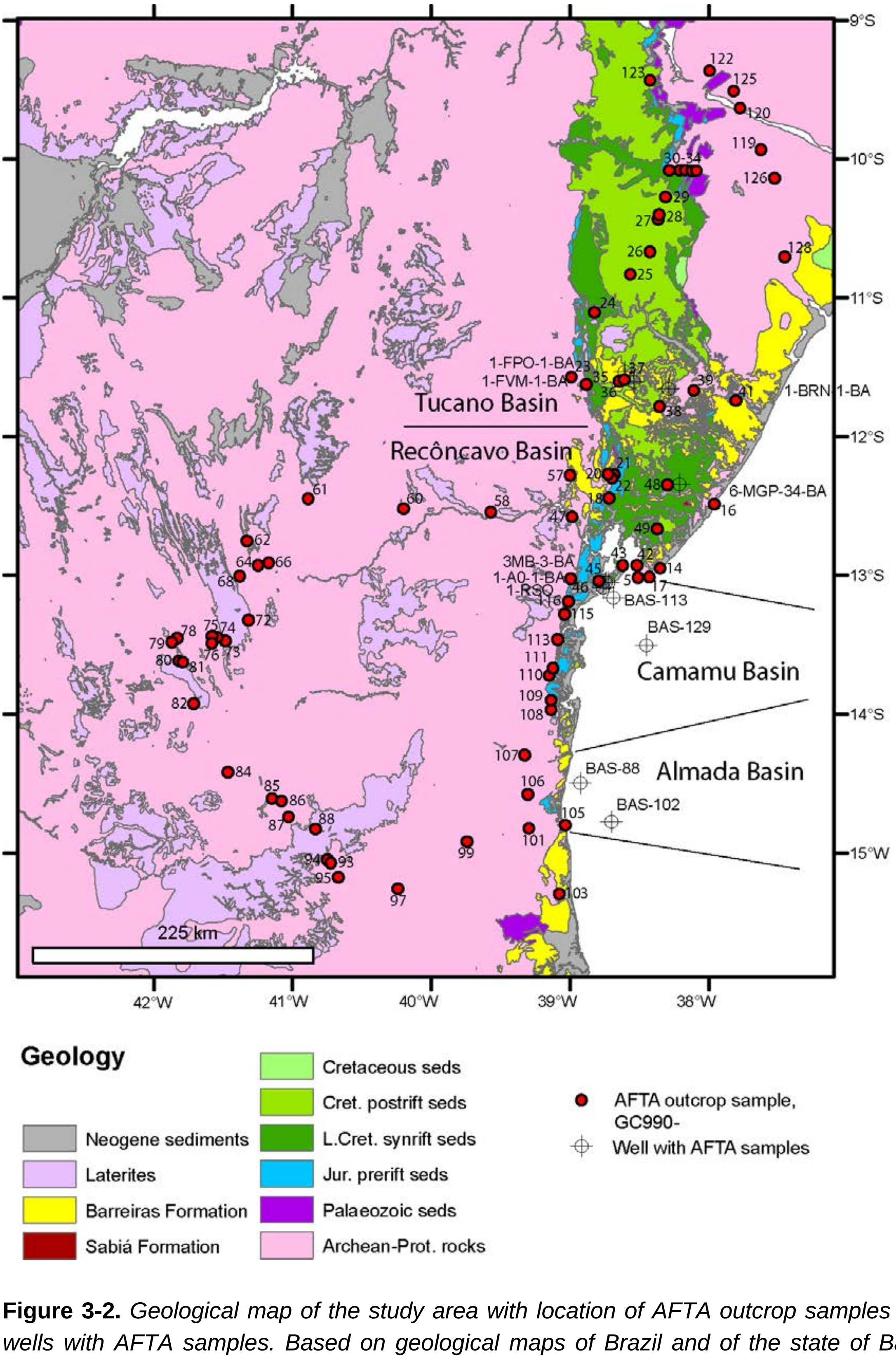


Figure 3-2. *Geological map of the study area with location of AFTA outcrop samples and wells with AFTA samples. Based on geological maps of Brazil and of the state of Bahia (CPRM 2001, 2003).*

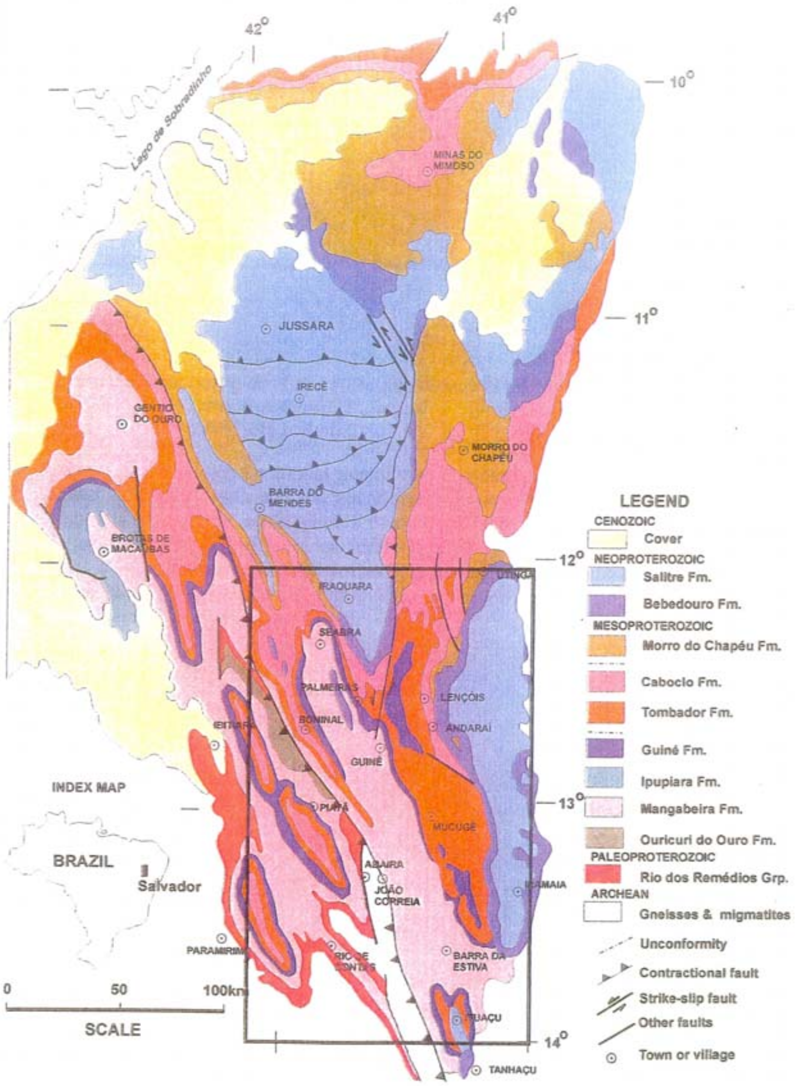


Figure 3-3. *Geological map of Chapada Diamantina. The rectangle corresponds roughly to the topographic 3D model shown in Figure 4- 7. From Pedreira & Bomfim (2000).*

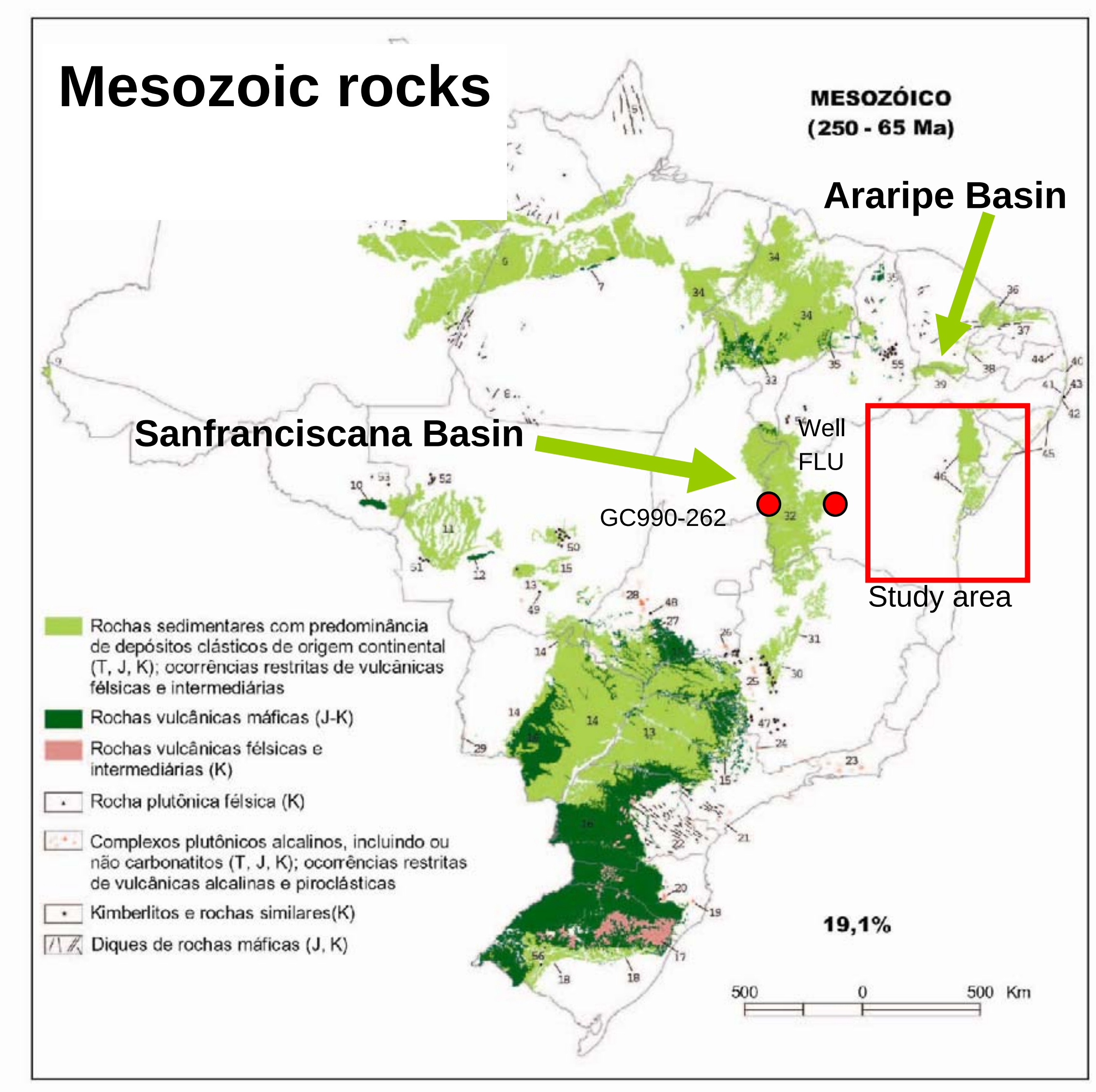


Figure 3-4. *Extent of Mesozoic sediments and volcanic rocks in Brazil with indication of the Sanfranciscana and Araripe Basins (green arrows), Location of well FLU-1 and AFTA sample GC990-262. Adapted from Schobbenhaus & Brito Neves (2003) where full legend is indicated.*

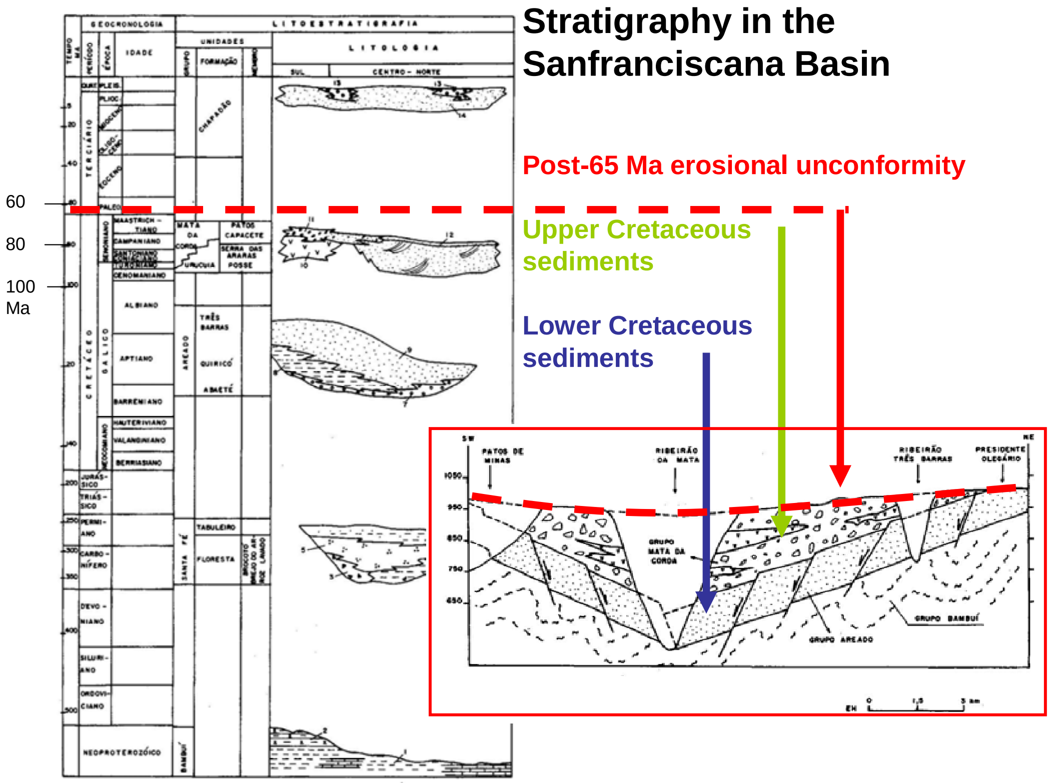


Figure 3-5. *Stratigraphy in the Sanfranciscana Basin and a profile illustrating the truncation of Cretaceous strata below a regional low-relief surface at an elevation of c. 1 km. The surface must have formed by erosion during the Cenozoic. Rivers are incised into the surface that cuts across the tilted Cretaceous strata (Campos & Dardenne 1997a, b)*

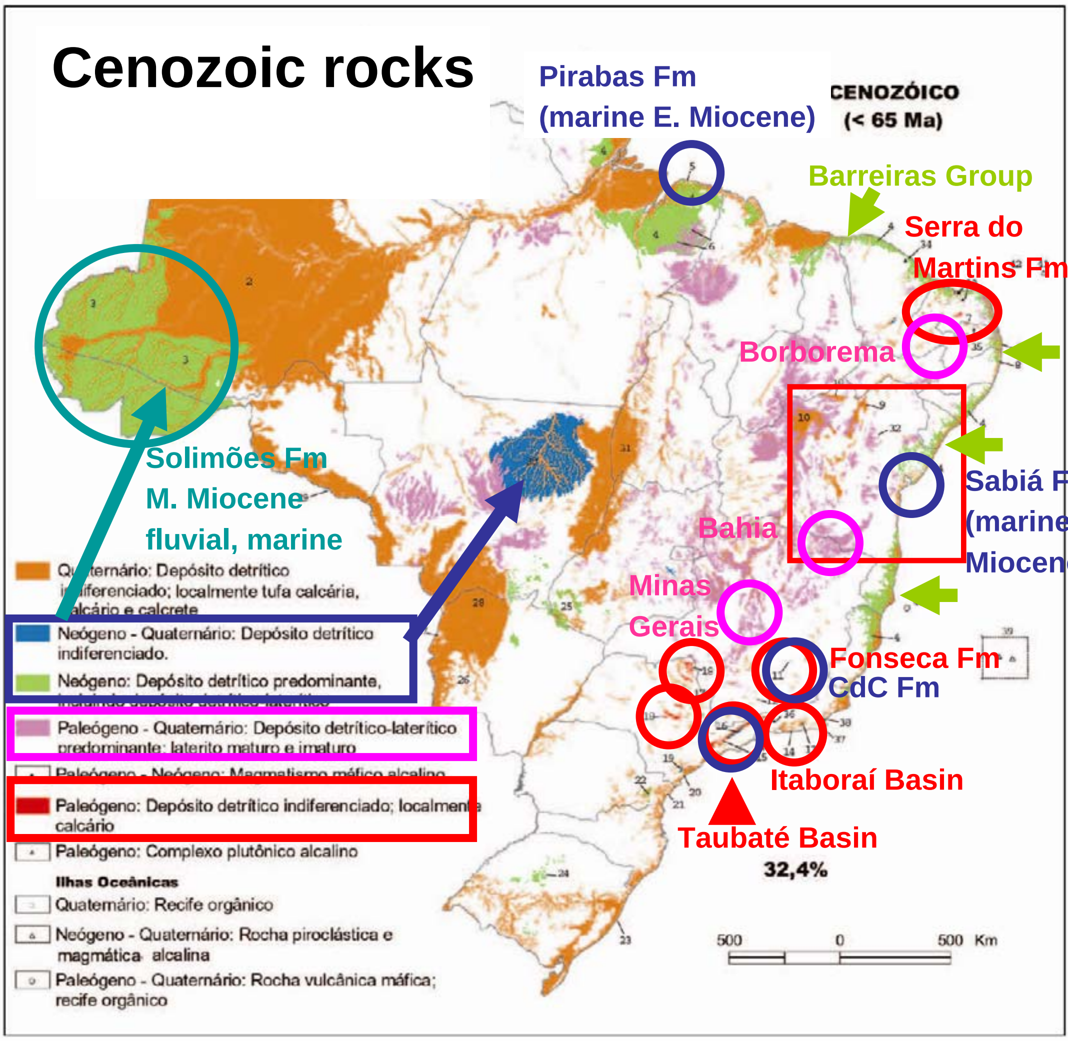


Figure 3-6. *Extent of Cenozoic sediments and volcanic rocks in Brazil with indication of the following deposits: Palaeogene Serra do Martins Fm (Morais Neto et al. 2008a); Palaeocene–Miocene deposits of the Continental Rift of Southeastern Brazil, including the Itaboraí and Taubaté Basins (Riccomini et al. 2008; Sant'Anna et al. 2004); Eocene Fonseca and the late Cenozoic Chapada de Canga (CdC) Fms (Sant'Anna et al. 1997); Lower Miocene Pirabas Fm (Fernandes & Távora 1990); Lower Miocene Sabiá Fm (Viana et al. 1971); Middle Miocene Solimões Fm (Hoorn 1996); the Neogene Barreiras Group (Vilas Bôas et al. 2001). Also indicated are some areas with weathering profiles / laterites in plateau areas: Bahia (Cenozoic; CPRM 2003); Borborema (Palaeogene; Guia Lima 2008); Minas Gerais (Palaeogene; Spier et al. 2006). Adapted from Schobbenhaus & Brito Neves (2003) where full legend is indicated.*

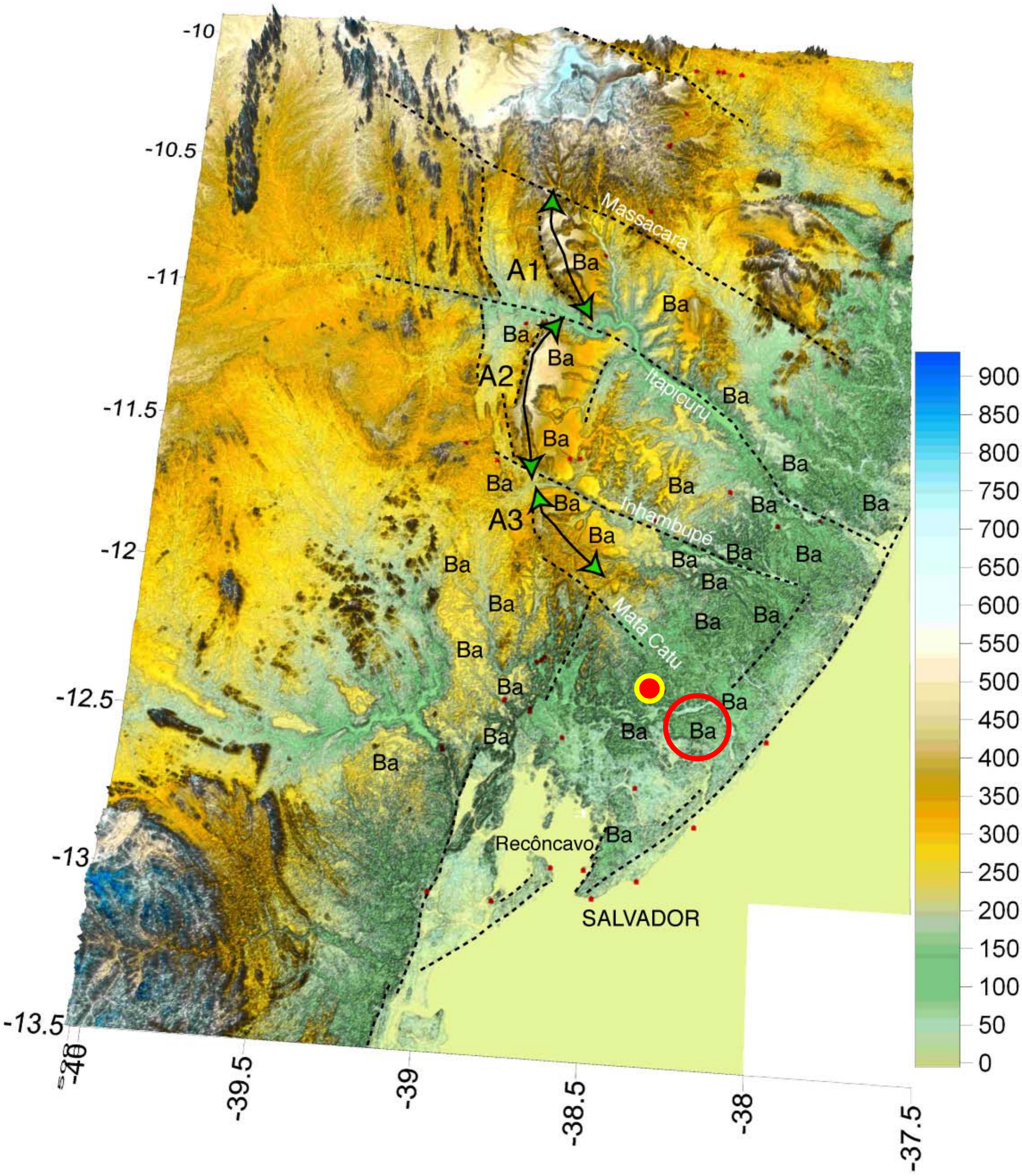


Figure 3-7. *Areas of outcropping Barreiras Fm (Ba), superimposed on a DTM of the Tucano and Recôncavo basins. Areas indicated by 'Ba' based on the geological map of Bahia (CPRM 2003), GoogleEarth images and the DTM. Dotted lines indicate traces of inferred faults (partly after Figueiredo et al. 1994), which may have been active today or in the Neogene. Full black traces, ending with green arrows, indicate doubly plunging anticlinal hinges (A1, A2 and A3). Small river valleys have incised the gently dipping eastern limbs of these folds. One valley has breached the hinge of a fold (the Biritinga Monocline, A2). Red dots: sample locations; big red dot: location of well MGP-34; red ellipse: outline of the area where the Lower Miocene Sabiá Fm is located within the Recôncavo Basin. See also the geological map in Fig. 3-2.*

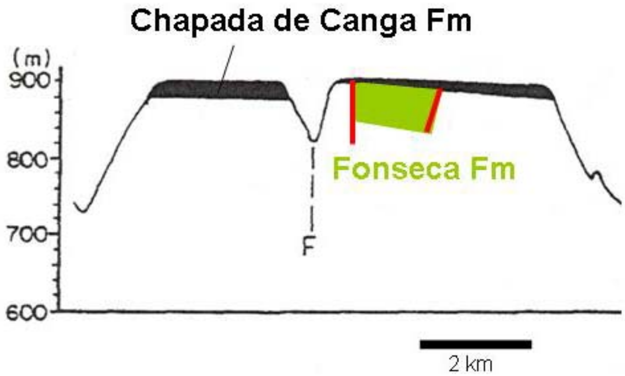


Figure 3-8. *Sketch of the relation between the Eocene Fonseca Fm and the overlying Chapada de Canga Fm that defines the plateaux in this part of Minas Gerais. Modified after Sant'Anna et al. (1997).*

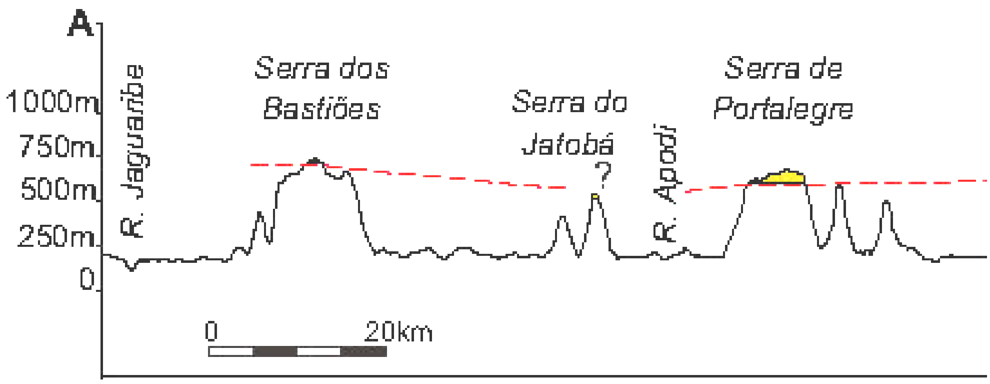


Figure 3-9. *Profile of along plateau remnants (mesas) capped by the Palaeogene Serra do Martins Fm (yellow). Dashed red line indicates interpreted level of the South American or Borborema Surface. Part of east-west profile at 6°S and 38°W modified from Morais Neto (2008a).*

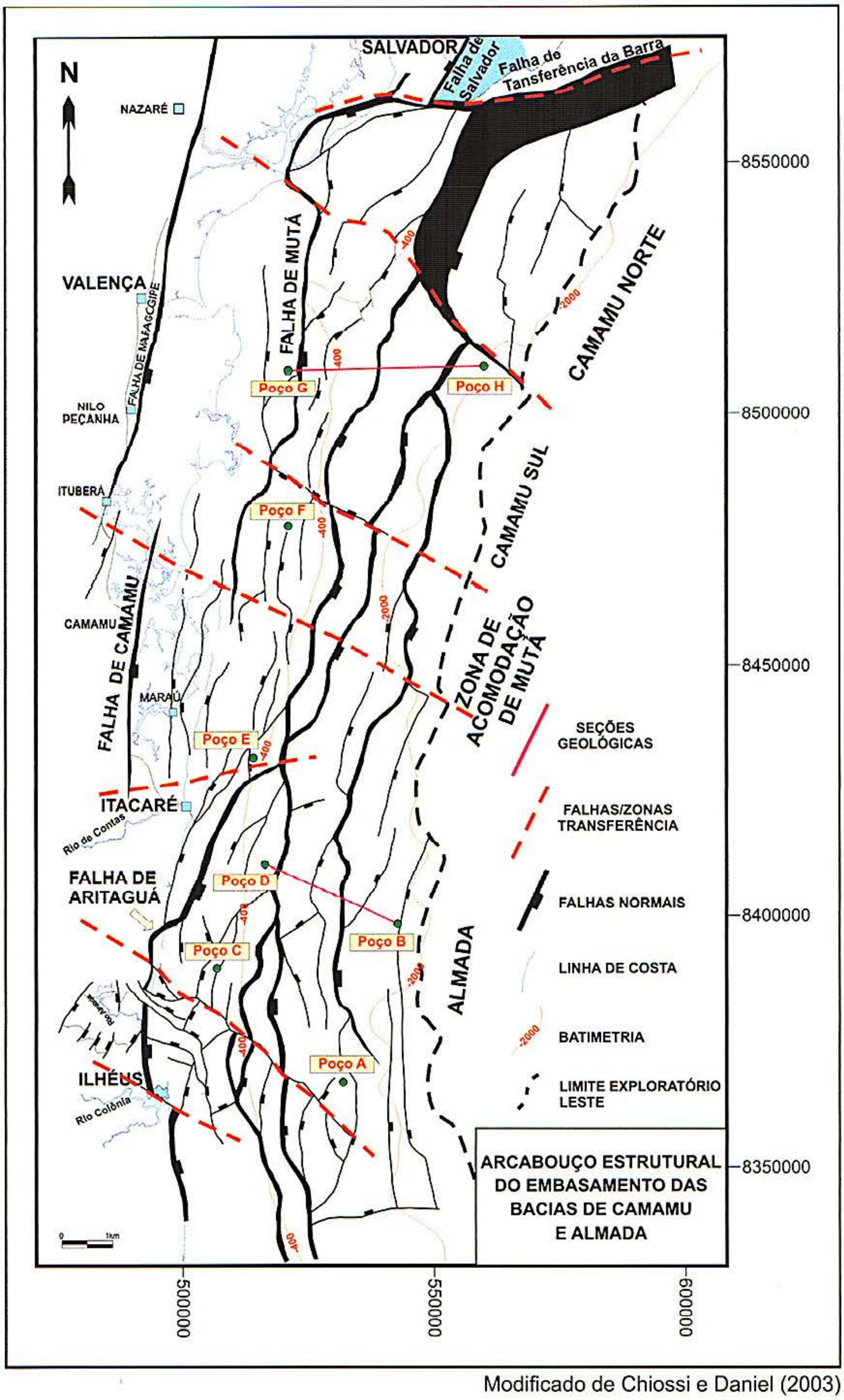


Figure 3-10. *Structural basement map of the Almada and Camamu Basins with indication of rift faults, according to interpretation of Menezes and da Silva, 2008. Location of the profiles between wells BAS-128 and -129 (poços G and H) and BAS-118 and -126 (poços D and B). Falha: fault.*

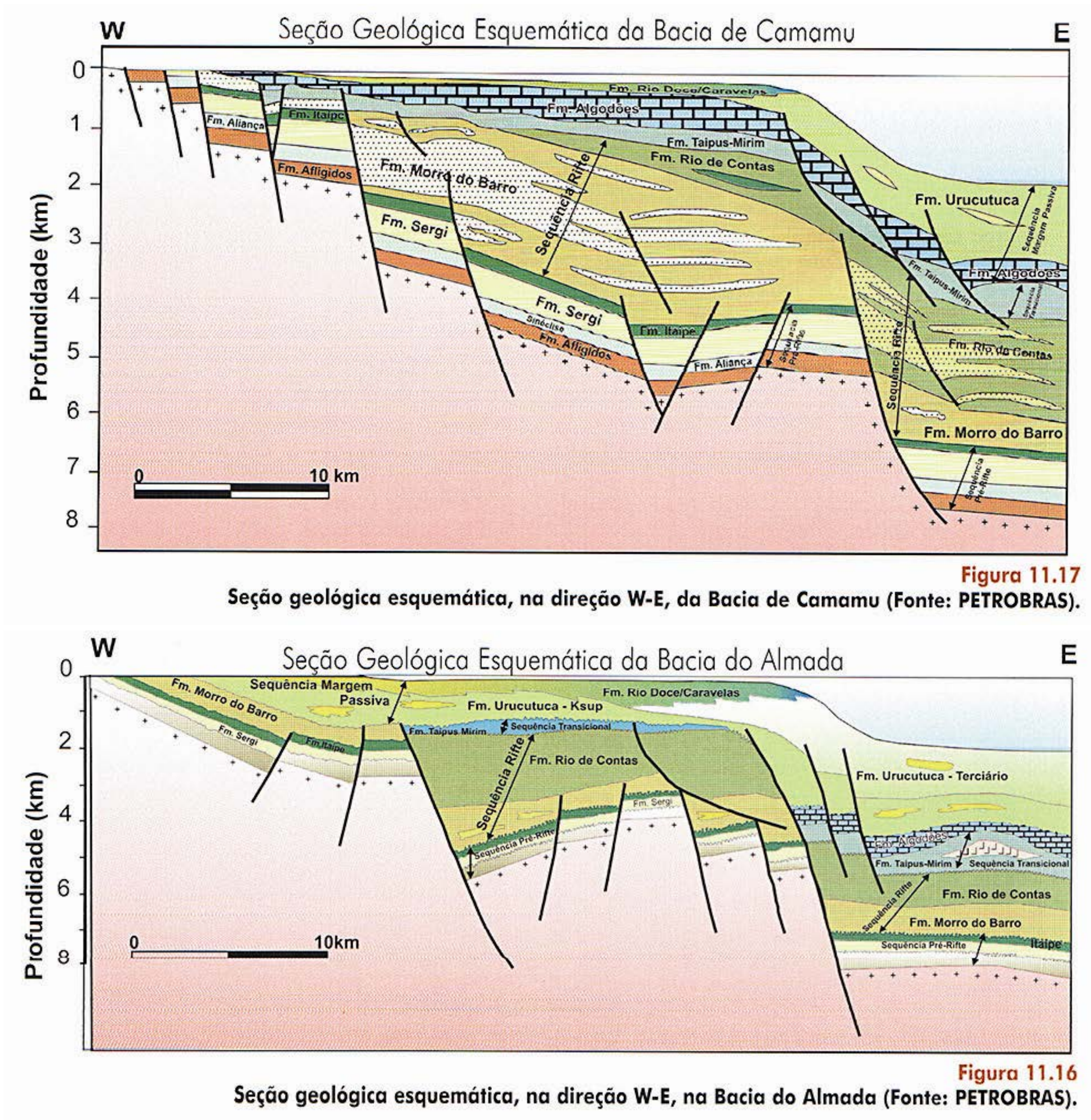


Figure 3-11. *Geological cross sections across the Camamu (upper) and Almada (lower) Basins. Note the pronounced unconformity above the mid-Cretaceous Taipus Mirim and Algodões Fms in both basins. A passive margin sequence (e.g. Palaeogene sediments as in well BAS-77; Fig. 5-9) is preserved near the coast in the Almada basin in contrast to the Camamu Basin. From Menezes et al. 2008.*

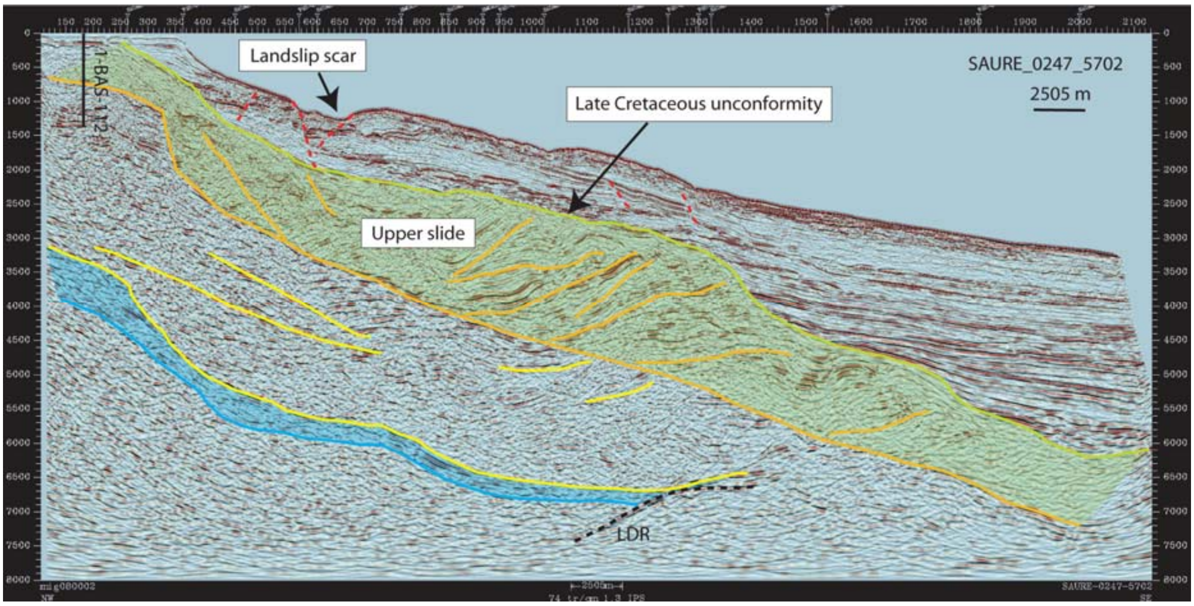


Figure 3-12. *Regional (2D) seismic line, running NW-SE, through Well 1-BAS-112 on the shelf and anticlinal structure close to Well 1-BAS-129 (after Cobbold et al., 2008). Notice (1) Jurassic sandstone of Sergi Formation (blue infill), (2) lower detachment at base Cretaceous and associated faults (yellow lines), (3) upper detachment in Aptian salt and associated faults (orange lines), (4) Late Cretaceous to middle Eocene unconformity (green line), (5) upper slide (green overlay), (6) recent extensional faults (dashed red lines), (7) active landslip scar, and (8) landward-dipping reflector (LDR), which may be the Moho.*

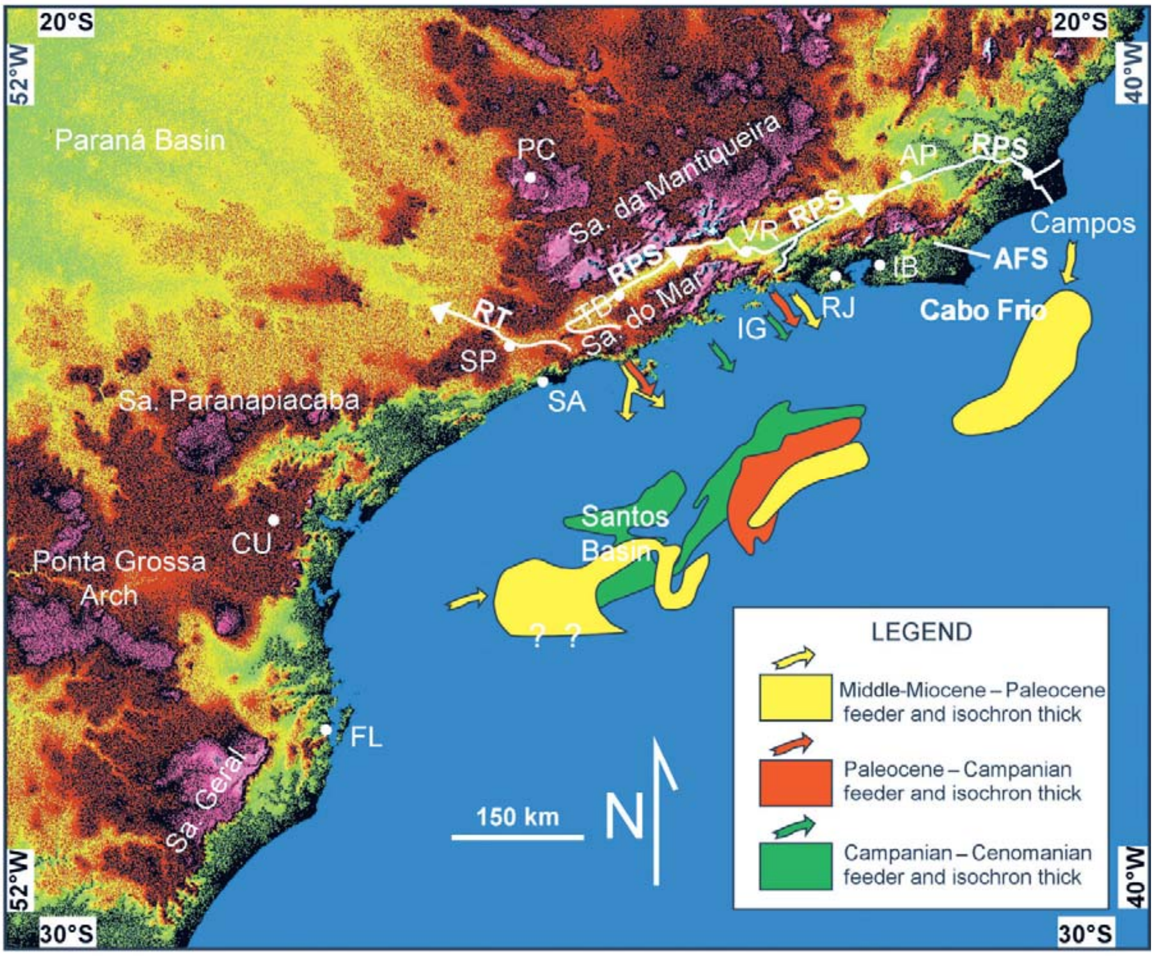


Figure 3-13. *Digital topographic map of onland SE Brazil and sediment patterns of offshore Santos Basin (after Cobbold et al. 2001). Topographic data are from USGS files. Relief has been accentuated by artificial illumination from NW. Highlands over 1000 m (browns) are dominant to W of Curitiba and to E of Poços de Caldas. At 2787 m (whites), highest peak is in Serra da Mantiqueira, near Volta Redonda. Courses of two major rivers (Paraíba do Sul (RPS) in the east and Tietê (RT) in the west) are highlighted (white lines). Note active fault scarp of Serra dos Orgãos (AFS). Onshore localities are (from SW to NE): Florianópolis (FL), Curitiba (CU), São Paulo (SP), Santos (SA), Poços de Caldas (PC), Taubaté (TB), Ilha Grande (IG), Volta Redonda (VR), Rio de Janeiro (RJ), Itaboraí (IB), Além- Paraíba (AP).*

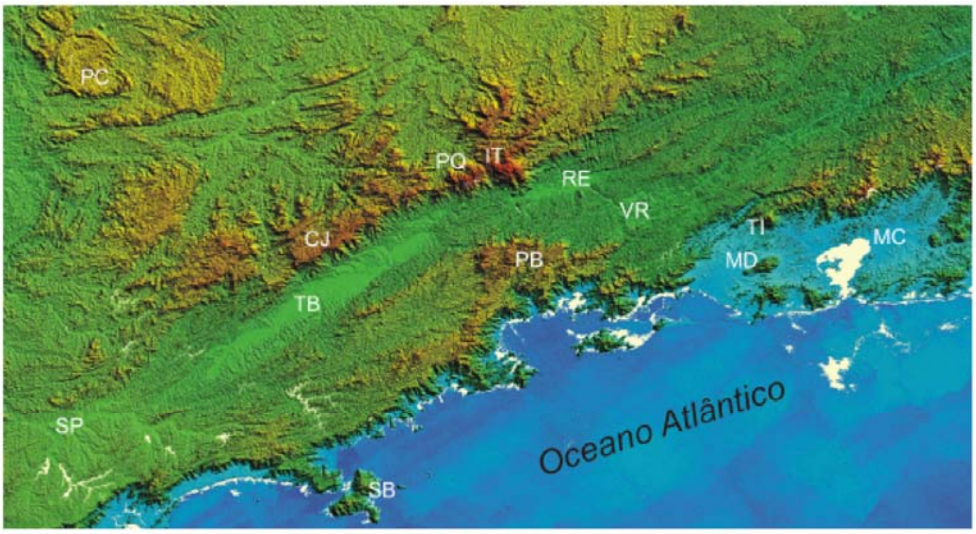


Fig. 2 - Principais feições geomorfológicas do RCSB, entre as bacias de São Paulo e Macacu. No modelo de elevação do terreno destacam-se as bacias sedimentares de São Paulo (SP), Taubaté (TB), Resende (RE), Volta Redonda (VR) e Macacu (MC), os planaltos da Bocaina (PB), na Serra do Mar, e de Campos do Jordão (CJ), na Serra da Mantiqueira, além dos maciços alcalinos de Poços de Caldas (PC), Passa Quatro (PQ), Itatiaia (IT), São Sebastião (SB), Tinguá (TI) e Mendanha (MD), dentre outros. Notar a marcante estruturação do embasamento, segundo a direção geral ENE a NE, com zonas de cisalhamento proterozóicas reativadas no Mesozóico e Cenozóico. Fonte: Shuttle Radar Topography Mission (SRTM), United States Geological Survey (USGS), 2002.

- The main geomorphological features of the CRSB between the São Paulo and Macacu basins. Features highlighted in the digital elevation model: São Paulo (SP), Taubaté (TB), Resende (RE), Volta Redonda (VR) and Macacu (MC) sedimentary basins; the Bocaina Plateau (PB), in the Serra do Mar, and the Campos do Jordão Plateau (CJ), in the Serra da Mantiqueira; and the Poços de Caldas (PC), Passa Quatro (PQ), Itatiaia (IT), São Sebastião (SB), Tinguá (TI) and Mendanha (MD) alkaline massifs. Note the striking ENE to NE Proterozoic structures of the basement, reactivated in the Mesozoic and Cenozoic. Source: Shuttle Radar Topography Mission (SRTM), United States Geological Survey (USGS), 2002

Figure 3-14. *Topographic image of area between São Paulo and Rio de Janeiro (after Riccomini et al. 2004). Detailed caption is beneath figure.*

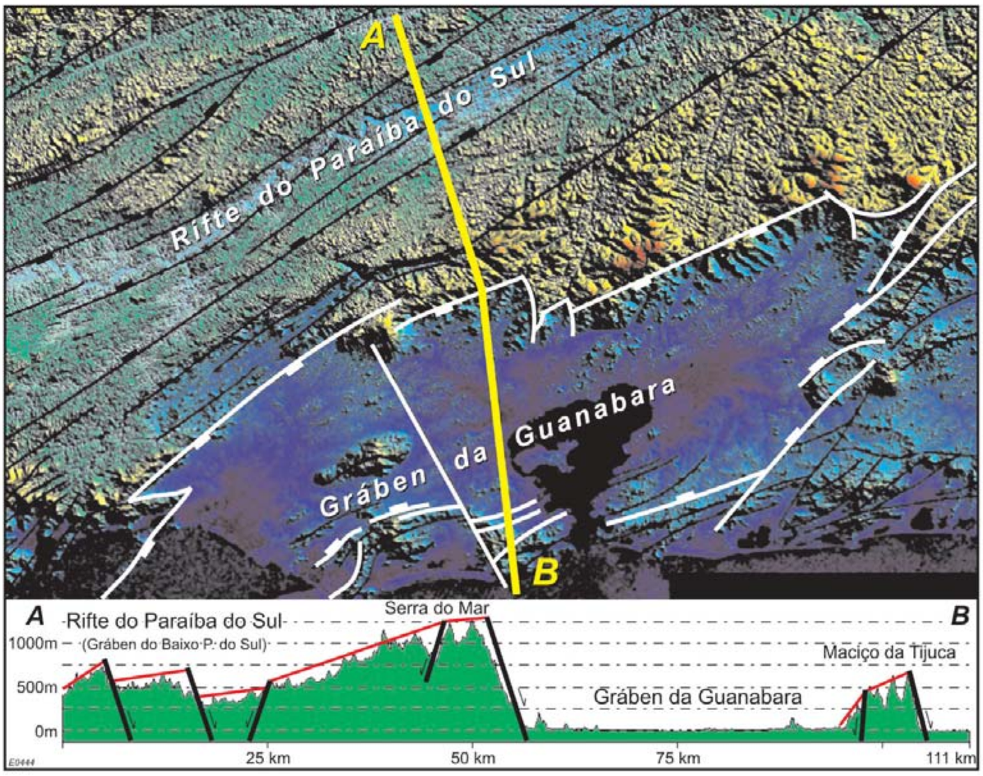


Figure 3-15. *Topographic image of Guanabara Basin (after Zalán & Oliveira 2005).*

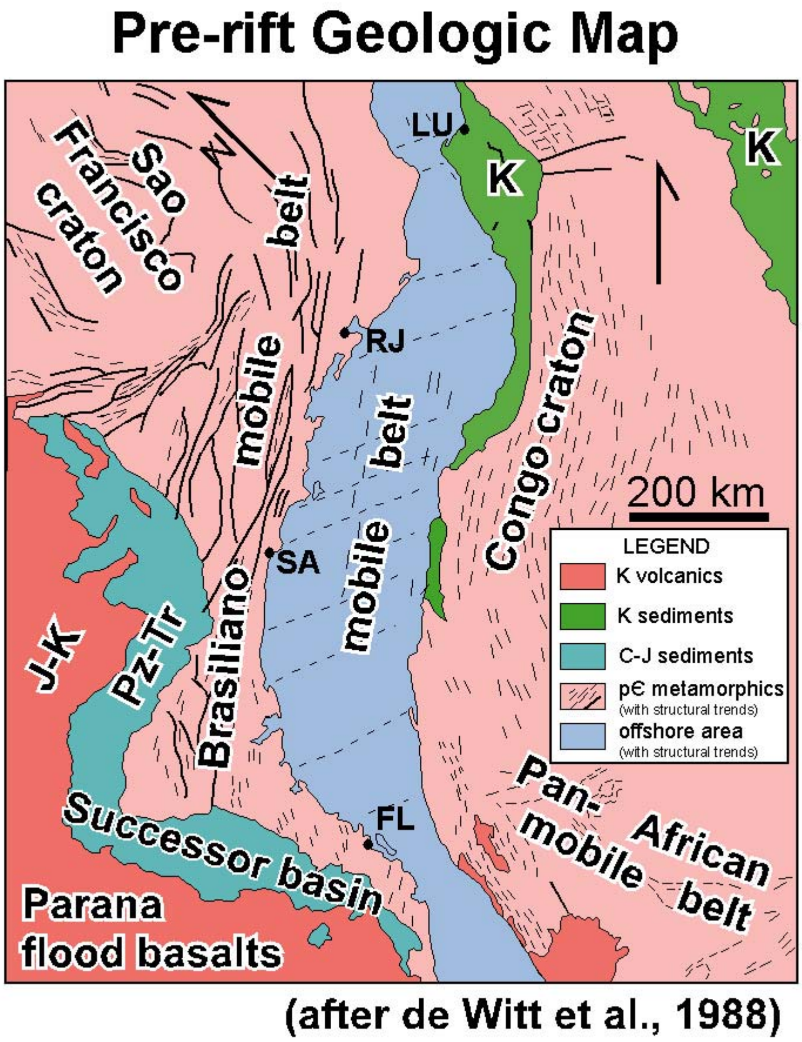
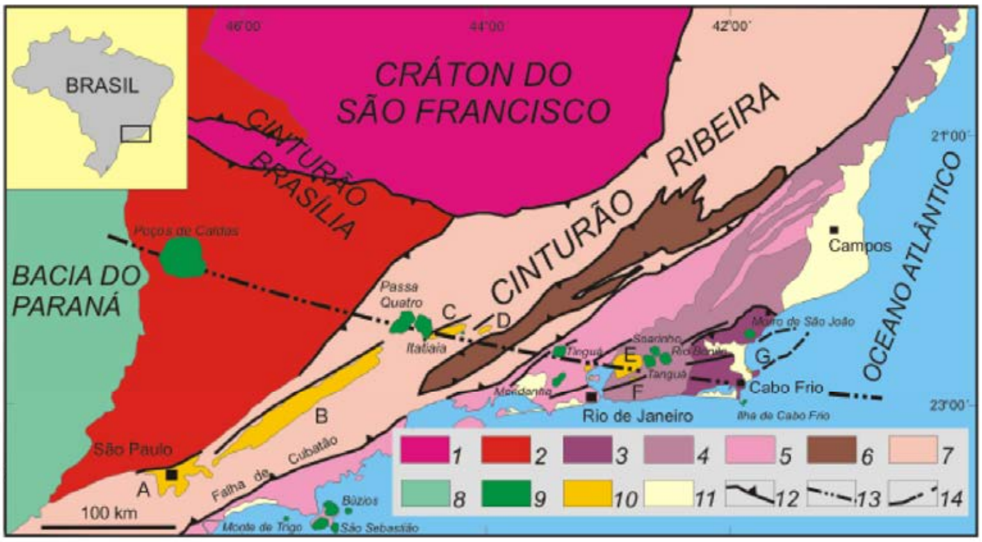


Figure 3-16. *Geological map of SE Brazil and SW Africa, prior to opening of Atlantic (after Meisling et al. 2001). Onshore localities are (from SW to NE): Florianópolis (FL), Santos (SA) and Rio de Janeiro (RJ), in Brazil; Luanda (LU), in Africa.*

Fig. 3 - Mapa tectônico da região sudeste do Brasil - 1) Cráton do São Francisco; 2) Cinturão Brasília; 3) Terreno Cabo Frio; 4) Terreno Oriental - Domínio Costeiro; 5) Terreno Oriental - Arco Magmático Rio Negro; 6) Klippe Paraíba do Sul; 7) Terreno Ocidental; 8) Bacia do Paraná; 9) corpos alcalinos do Cretáceo Superior a Eoceno; 10) bacias do *Rift* Continental do Sudeste do Brasil (RCSB): A - São Paulo; B - Taubaté; C - Resende; D - Volta Redonda; E - Macacu; F - Itaboraí; G - Barra de São João; 11) sedimentos cenozóicos indiferenciados; 12) falhas reversas, nappes; 13) Alinhamento Magmático de Cabo Frio; 14) limites de grabens do RCSB. Fontes: modificado de Riccomini (1989), Ferrari (1990), Mohriak & Barros (1990), Heilbron *et al*. (2000) e Ferrari (2001)



- Tectonic map of southeastern Brazil - 1) São Francisco Craton; 2) Brasília Fold Belt; 3) Cabo Frio Terrain; 4) Oriental Terrain - Costeiro Domain; 5) Oriental Terrain - Rio Negro Magmatic Arc; 6) Paraíba do Sul Klippe; 7) Ocidental Terrain; 8) Paraná Basin; 9) Late Cretaceous to Eocene alkaline bodies; 10) sedimentary basins of the Continental *Rift* of Southeastern Brazil (CRSB): A - São Paulo; B - Taubaté; C - Resende; D - Volta Redonda; E - Macacu; F - Itaboraí; G - Barra de São João; 11) Cenozoic sediments; 12) reverse faults, nappes; 13) Cabo Frio Magmatic Lineament; 14) boundaries of CRSB grabens. After Riccomini (1989), Ferrari (1990), Mohriak & Barros (1990), Heilbron *et al*. (2000) and Ferrari (2001), modified

Figure 3-17. *Geological map of area between São Paulo and Rio de Janeiro (after Riccomini et al. 2004). Detailed caption is next to figure.*

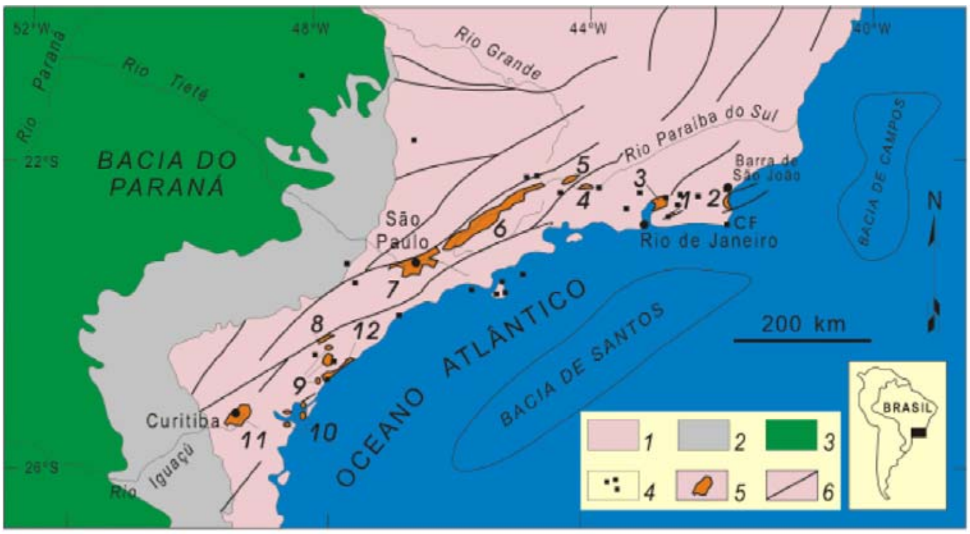


Fig. 1 - Contexto geológico regional do *Rift* Continental do Sudeste do Brasil (RCSB) - 1) embasamento pré-cambriano; 2) rochas sedimentares paleozóicas da Bacia do Paraná; 3) rochas vulcânicas toleíticas eocretáceas da Formação Serra Geral; 4) rochas relacionadas ao magmatismo alcalino mesozóico-cenozóico; 5) bacias cenozóicas do *rift* (1- Bacia de Itaboraí, 2- Gráben de Barra de São João, 3- Bacia do Macacu, 4- Bacia de Volta Redonda, 5- Bacia de Resende, 6- Bacia de Taubaté, 7- Bacia de São Paulo, 8- Gráben de Sete Barras, 9- Formação Pariqüera-Açu, 10- Formação Alexandra e Gráben de Guaraqueçaba, 11- Bacia de Curitiba, 12- Gráben de Cananéia); 6) zonas de cisalhamento pré-cambrianas, em parte reativadas durante o Mesozóico e Cenozóico. Fontes: modificado de Melo *et al*. (1985a), Riccomini *et al*. (1996) e Ferrari & Silva (1997)

- Regional geologic context of the Continental *Rift* of Southeastern Brazil (CRSB) 1) Precambrian basement rocks; 2) Paleozoic sedimentary rocks of the Paraná Basin; 3) Early Cretaceous tholeiitic volcanic rocks of the Serra Geral Formation; 4) Mesozoic to Cenozoic alkaline rocks; 5) Cenozoic basins of the CRSB (1- Itaboraí Basin, 2- Barra de São João Graben, 3- Macacu Basin, 4- Volta Redonda Basin, 5- Resende Basin, 6- Taubaté Basin, 7- São Paulo Basin, 8- Sete Barras Graben, 9- Pariqüera-Açu Formation, 10- Alexandra Formation and Guaraqueçaba Graben, 11- Curitiba Basin, 12- Cananéia Graben); 6) Precambrian shear zones, in part reactivated during the Mesozoic and Cenozoic. After Melo *et al*. (1985a), Riccomini *et al*. (1996) and Ferrari & Silva (1997), modified

Figure 3-18. *Regional context of Tertiary basins (after Riccomini et al. 2004). Detailed caption is beneath figure.*

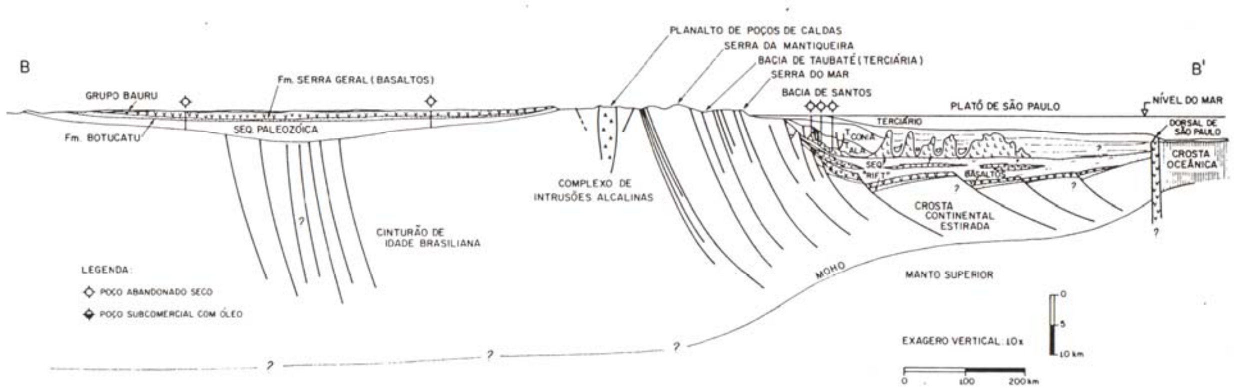


Figure 3-19. *Regional geological section across highlands of SE Brazil, from Parana Basin to Santos Basin (after Macedo 1989). Notice erosional truncation of Palaeozoic strata and continental flood basalts in Parana Basin. Same basalts are at base of rift sequence in Santos Basin. Normal faults through lower crust are hypothetical.*

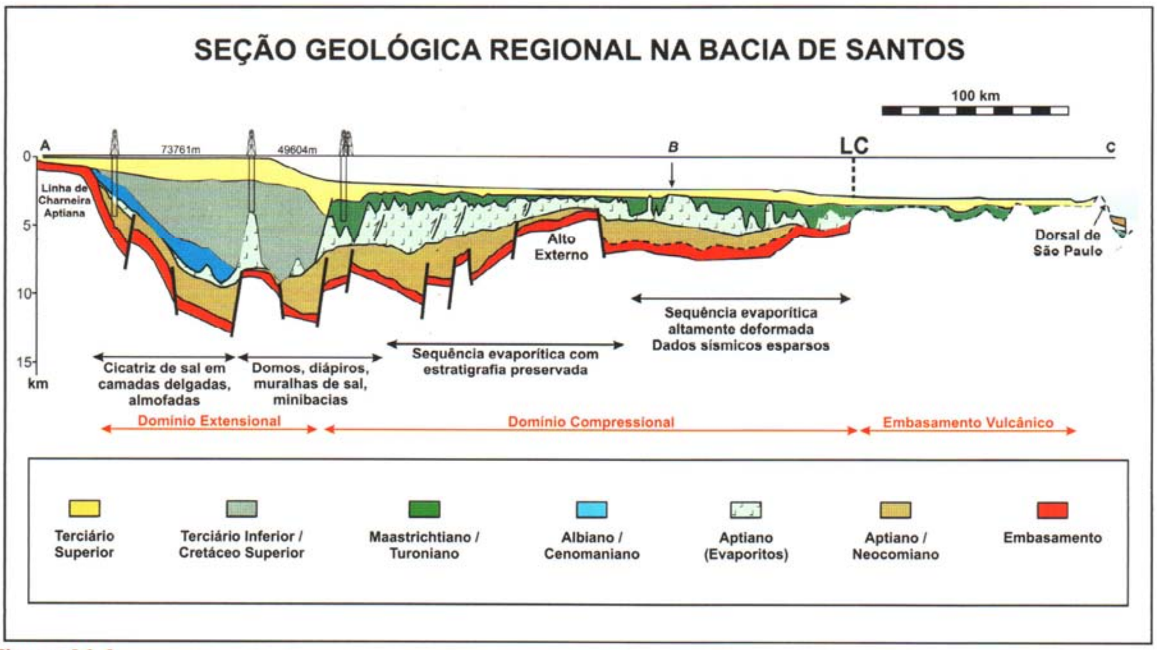


Figura 16.4
Seção geológica regional da parte central da Bacia de Santos, evidenciando os domínios distensivos e compressivos no pacote evaporítico. Localização na Figura 16.6.

Figure 3-20. *Geological section through Santos Basin (after Gamboa et al. 2008). Notice erosional hinge line and thick accumulation of Late Cretaceous clastic sediment under current shelf, which has squeezed Aptian salt seawards.*

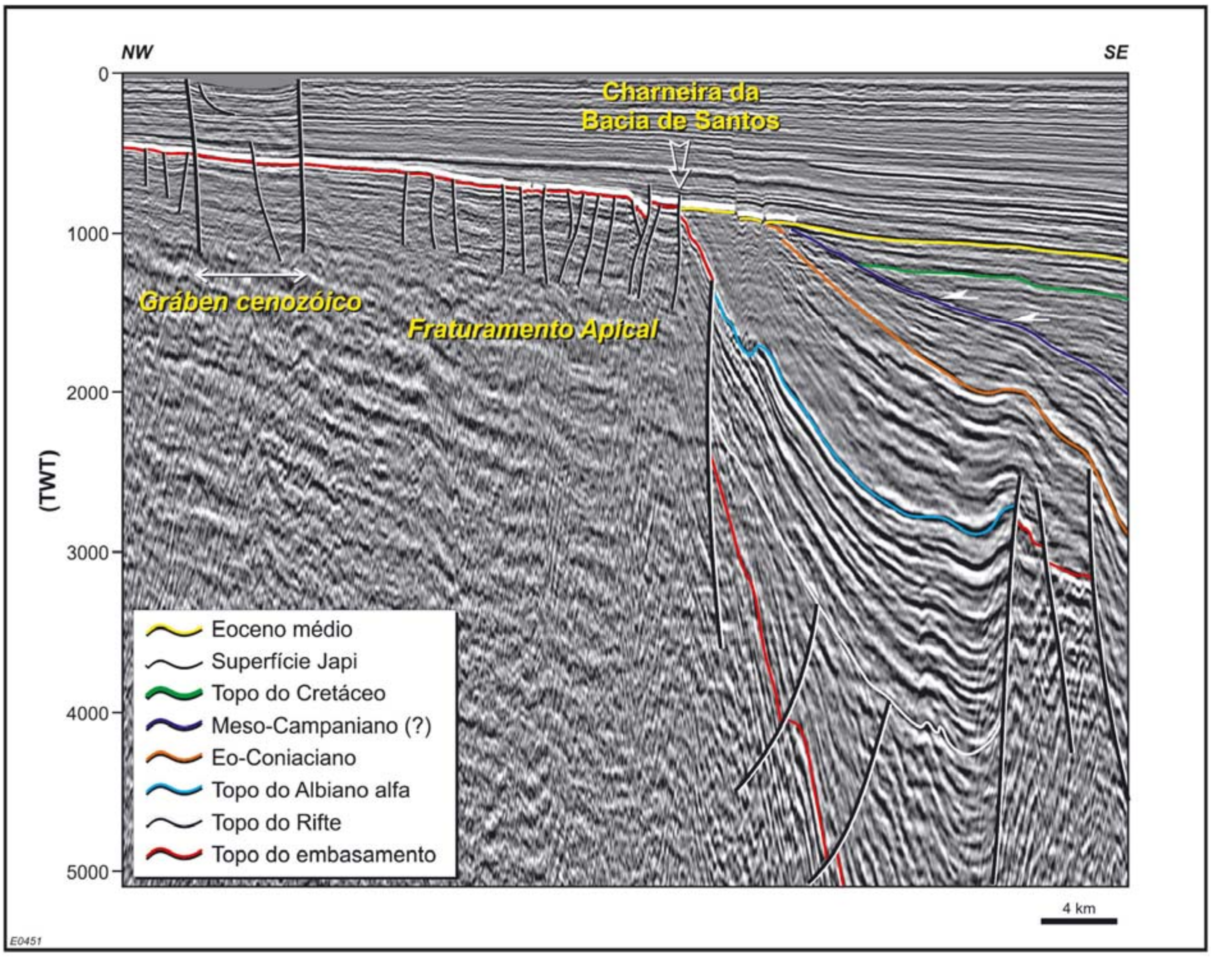


Figure 3-21. *Seismic section across erosional hinge line, Santos Basin (after Zalán & Oliveira 2005). Notice Late Cretaceous strata, onlapping tilted Turonian and older strata, and Tertiary sequence stepping over onto basement, above regional middle Eocene unconformity.*

4. Landscape analysis

4.1 Introduction

The large-scale landforms in the present landscape represent a palimpsest of landforming processes from different climatic and tectonic conditions, not only or mainly the Quaternary. These different processes have left traces in the landscape and given the bedrock characteristic forms and shapes. Analysing and interpreting different landscape elements can be used to understand how landscapes develop over long time and which processes that have been dominant during different time-periods (e.g. Bonow, 2004). To investigate the long-term development of landscapes, the large-scale landforms are best suited for analysis . The denudation surfaces (peneplains) are major and common features in the landscapes on all continents, and also in the study area of NE Brazil (Fig. 4-1). These surfaces are therefore especially important to analyse.

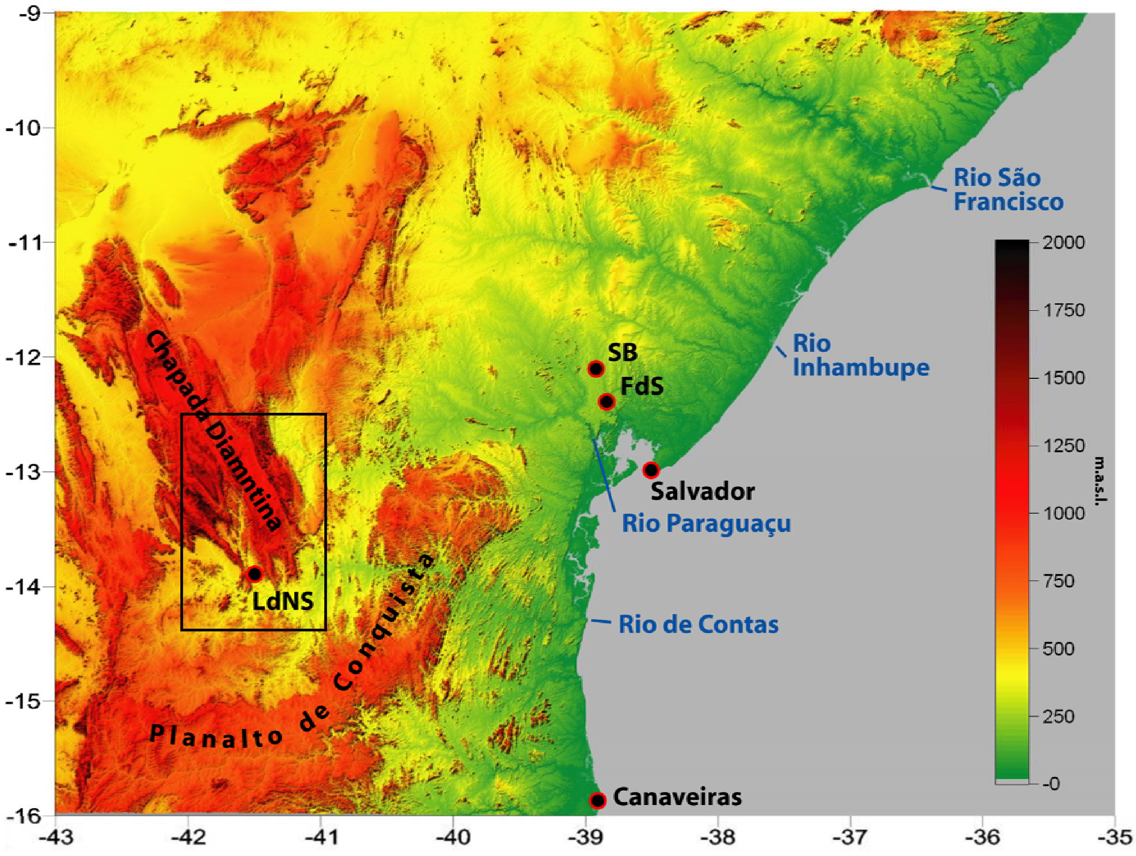


Figure 4-1. *The study area in NE-Brazil. Rectangle shows the location of Fig. 4-7. SB-Santa Bárbara, FdS-Feira de Santana, LdNS- Liveramento de Nossa Senhora.*

4.2 Conceptual model

Analysis of peneplains aims at establishing a relative tectonic event-chronology through identification and mapping of extensive base-level governed surfaces in stepped sequence, that are formed by erosion in climate and/or tectonic setting different from the present. These denudation surfaces, that cut across bedrock of different age and resistance can be arranged in chronological order based on

1) stratigraphical relationships with cover rocks,
2) geometrical relationships between different palaeosurfaces i.e. a) younger surfaces cut across older surfaces, b) a higher step is older than a lower and
3) detailed landforms characteristics, whereby the shape is indicative of processes for the climate in which a surface formed.

In geomorphological analysis, the base-level (the sea) is fundamental, as surfaces eventually always will be graded to that marker. Consequently, and equally important for the geomorphological analysis is that lowered base level (uplift events) causes valley incision and the relief to rejuvenate, while a raised base level (subsidence) causes surfaces to be buried, and thus to be preserved below cover rocks, potentially for long time (Lidmar-Bergström 1982, 1988; Bonow 2004; Bonow et al. 2006).

4.3 Aim within project

The aim with the landscape analysis 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. The landscape study is a step-by-step interpretation of landforms, where the progressive knowledge obtained is incorporated in the final analysis. Details of the mapping are presented in a separate report as part of this project (Bonow 2009).

4.4 Data and methods

The basic elevation data set was the Shuttle Radar Topography Mission (SRTM), with a resolution between data points of 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). Documentation of landforms took place during fieldwork in 2007 along the coast and in the interior highlands of Bahia (cf. Fig. 3-2) (Japsen et al. 2007).

The SRTM elevation data were used to construct a map with 100 m contours, which was used as the base for the surface mapping. From the elevation data, topographical profiles were extracted systematically at every 0.1 degrees in north-south and east-west direction. Along each topographical profile, a 0.2 degree wide corridor was extracted and analysed for maximum and minimum height values and then plotted together (Fig. 4-2).

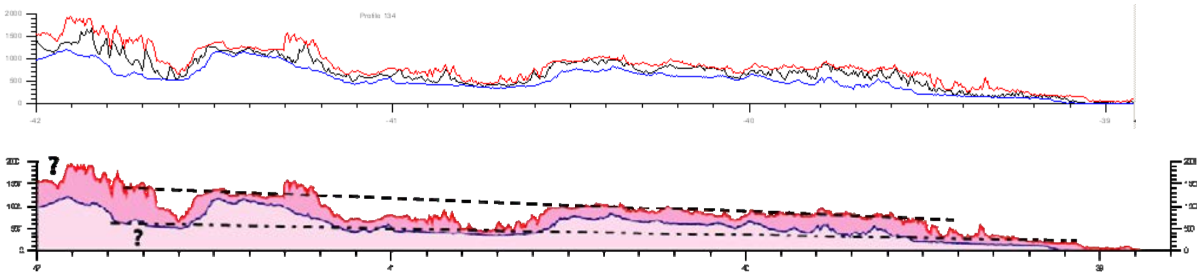


Figure 4-2. *Upper profile: Topography (black line) and maximum and minimum (red and blue respectively) topography within 0.2 degree corridor between 42 and 39*°W along 13.4°S. Such profiles were *constructed for the whole study area along a rectangular grid. Lower profile: The suggested interpretation of the Higher and Lower surface, based on the contour map, is shown. The profiles are thus primarily used to support the mapping, not for interpretation of landscape levels.*

The contour map was analysed together with cross-examination of the profiles to map out the surfaces on the contour map. By mapping the surface levels onto the profiles, these can be used to support the mapping in areas were the surface has been dissected, for example to decide if an isolated plateau is part of a specific surface or not. This method with cross-examination of profiles allows for mapping of inclined surfaces as well as for identification of changes of inclination within surfaces (e.g. faults). The rapid change of inclination in the contours was also used to decide the areal extent for each surface. The consistency of the interpretation along individual lines is checked by tying the topographical lines together in the rectangular grid.

This method of mapping, combining contours and corridor-profiles was developed in Scandinavia and West Greenland (e.g. Lidmar-Bergström 1988, 1996; Bonow et al. 2006). It must be emphasised that it is very important to use the combination of profiles and contour map, because trying to interpret surfaces along single profile lines can not give confidence in landscape levels.

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 (c.f. Japsen et al. 2009).

The mapping resulted in that several areas with extensive coherent levels could be identified, e.g. Chapada Diamantina, Planalto de Conquista and the areas west of the Recôncavo-Tucano-Jatobá basin.

4.5 Main results

The main result from the geomorphological analysis is the map showing three different denudation surfaces (Fig. 4-3). Within the study area, two major denudation surfaces of regional extent has been identified and we will refer to them as the higher surface and the lower surface. Furthermore, a coastal plain of limited extent has been identified. All these surfaces are coherent and in stepped sequence, following the major valleys. The surfaces are developed across rocks of different age and of different resistance, showing that the surfaces originally were graded, at a low position in the landscape, and thus governed by a general base level. Their wide extent is a witness of long time of stable base level conditions available for their formation.

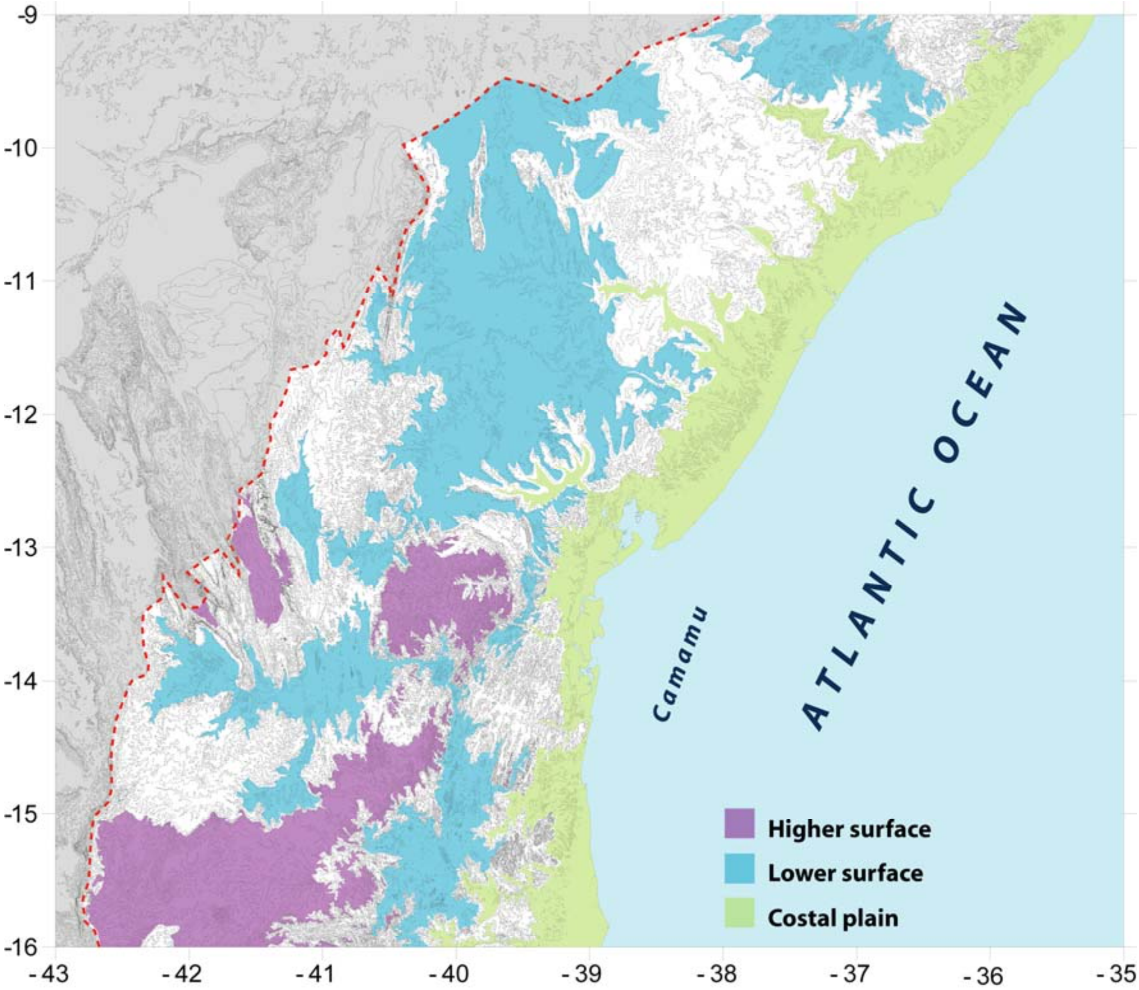


Figure 4-3. *Map showing the interpretation of the two major denudation surfaces, the higher and the lower surface, and the coastal plain in the study area. Red dashed line marks the water divide.*

The higher surface is situated in Chapada Diamantina (c. 1200 m a.s.l.) (Fig. 4-4) and Planalto de Conquista (c. 900 m a.s.l.) (Fig 4-5). Despite this difference in elevation, the surfaces can be correlated because the higher is tilted towards the southeast. It is therefore concluded that they were formed as one coherent surface. The surface cuts across old basement that is deeply weathered and includes Cenozoic laterites over extensive areas (CPRM 2001, 2003), thus constraining its final formation age to the Cenozoic. A winding escarpment, up to 700 m high, usually distinguishes the higher surface from the lower (Figs 4-6, 4-7).

Figure 4-4. *The higher surface in Chapada Diamantina, here at c. 1200 m a.s.l..*

Figure 4-5. *The higher surface with low inselbergs at Planalto de Conquista. The surface is here at about 900 m a.s.l.*

Figure 4-6. *The contact between the higher and the lower surface at Liveramento de Nossa Senhora.*

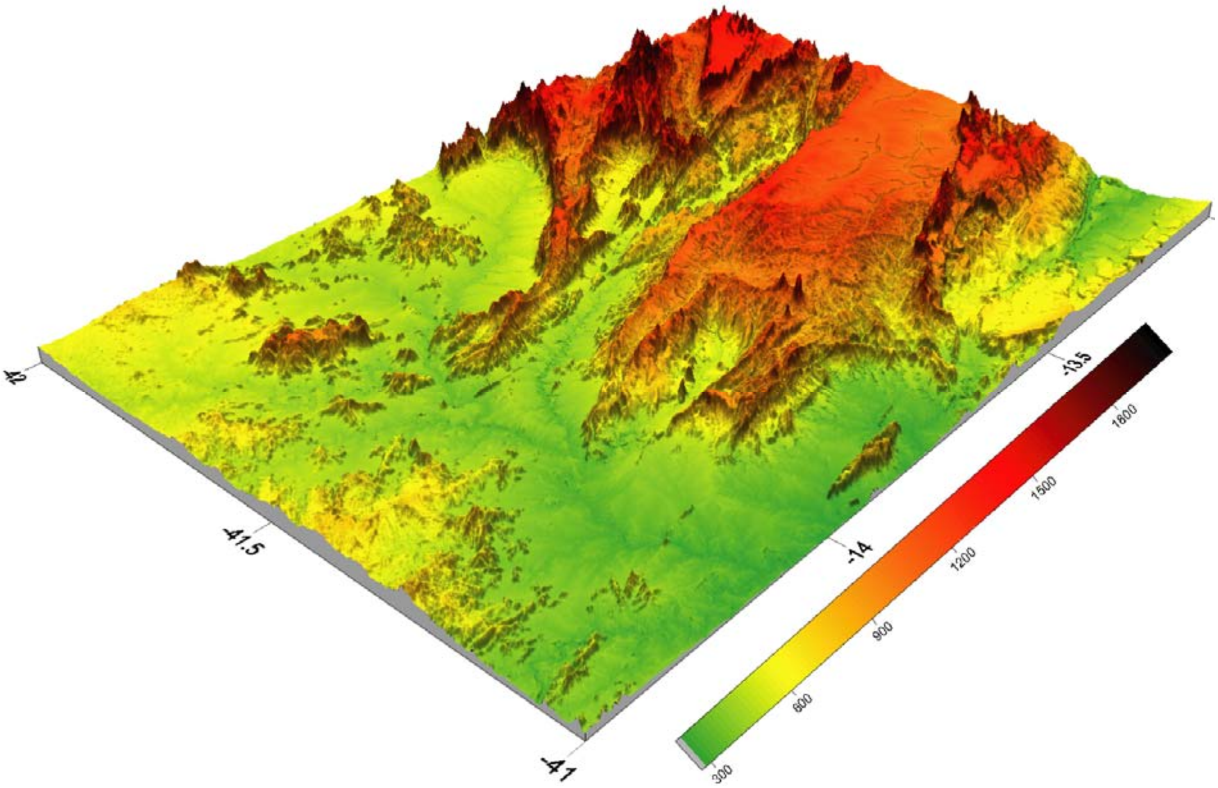


Figure 4-7. *3D model of the Chapada Diamantina area (location in Fig. 4-1). The higher surface(reddish colours) is found at c. 1200 m a.s.l. and only minor valley are incised in the plain. The higher surface is bordered by a winding escarpment towards the lower surface (greenish colours), here at c. 500 m a.s.l..*

The lower surface can be identified from c. 200 m a.s.l. and follows the major valleys as far as 250 km from the coast (Figs 4-8, 4-9). At its upper reaches at c. 500 m a.s.l., the surface ends with an escarpment up to the higher surface. The lower surface cut across both the Aptian sedimentary sequence in the Recôncavo-Tucano Basin and Precambrian basement in the western areas.

The coastal plain is a narrow low-land plain, gently sloping inland. The incision inland follows some of the main rivers and the surface is cut into the Barreiras Formation (Fig 4-10).

Figure 4-8. *The lower surface west of Feira de Santana, at c. 250 m a.s.l. Shallow and wide valleys are incised in the plain.*

Figure 4-9. *The Chapada Diamantina escarpment in contact with the lower surface, here at c 400 m a.s.l..*

Figure 4-10. *The inland incision east of the Tucano Basin is probably recent as witnessed by the preserved surface developed across easily eroded rocks (Marizal) above the river.*

4.6 Conclusions from the landscape analysis and the relative event chronology

Two major denudation surfaces in stepped sequence have formed along the major rivers within the study area in NE Brazil. Both cut across bedrock of different age and different resistance. The mapping has shown that the surfaces follow an inclined plane. These conditions emphasise that they were formed as denudation surfaces that were governed by base level, and graded to low elevations at the time of their formation.

Based on field observations, detailed mapping of the surfaces and of their relationship to the geology, the following relative event chronology is suggested: Post-Aptian denudation led to formation of a regional denudation surface (the now higher surface), which was finallly formed during the Cenozoic. Regional uplift of up to 1 km in the interior resulted in dissection of the higher surface and development of the lower surface towards the new base-level. Based on the geological constraints, the lower surface must be post-Aptian in age, but its geometrical relationship to the higher surface and its wide extent suggests that it developed during the Neogene. Renewed regional uplift (or lowered base level) of a few hundred metres initiated the formation of the coastal plain. The costal plain is post-Barreiras in age, but probably much younger, as witnessed by preserved surfaces in easily eroded sedimentary rocks despite the present rapid dissection of the present landscape.

4.7 Comparison with previous landscape studies

Geomorphological studies regarding general landscape development are few in Brazil. The Brazilian landscapes have usually been looked upon as a result of regional uplift at the time of break-up of the Gondwana (Ab'Sáber 2000 and references therein).

The classical geomorphological work in Brazil of Lester King (King 1956, 1967), defining levels for stepped erosion surfaces, has had a tremendous impact on many studies dealing with various aspects of landscape development, not only in geomorphology but also studies relating, for example palaeoclimate, weathering data and thermochronology, to the stepped landscapes.

In north-east Brazil, King identified four stepped denudation surfaces that he interpreted as low-relief base-level governed erosion surfaces. King regarded the highest surface as the oldest and found that the younger surfaces were formed after break-up of the Gondwana supercontinent in the Cretaceous. The two oldest surfaces were regarded as Mesozoic in age and he named them *Gondwana* or *post-Gondwana*. These surfaces are only preserved in the highest areas in the interior of Brazil.

According to King (1967), the early Cenozoic *Sul-Americana* surface is more frequent than the Gondwana and post-Gondwana surfaces. The Sul-Americana surface of early Cenozoic age is well preserved in the highlands of Chapada Diamantina and Planalto de Conquista. Its age was based on the interpretation that the surface cuts across silicreted sands of presumed early Cenozoic age west of the Rio São Francisco. The *Velhas* cycle was thought to have formed in the late Cenozoic. The youngest cycle was named the *Para-*

guaçu which King (1967) mapped from the coastline up to 400-500 m a.s.l. and this erosional cycle was regarded as a result of recent tilting along the present coastline. However, the surfaces mapped by King (1967) cannot directly be compared with the surfaces mapped in this study (Table 4-1).

Table 4-1: The relationship between the surfaces mapped by King (1967) and the result of mapping in this study

Surface mapped by King (1967)	**Surfaces mapped in this study**
Gondwana Post-Gondwana	Ridges above the Higher Surface
Sul-Americana Velhas	Higher Surface
Paraguaçu	Lower surface Coastal plain

The most recent geomorphological based work in Brazil is published in papers by Jean-Pierre Peulvast and co-authors (e.g. Peulvast and Claudino Sales, 2004; Peulvast et al. 2008 and referenced therein). Peulvast et al. (2008) found evidence for low post-Cenomanian denudation across the Brazilian Northeast (north of 8ºS). The present stepped landscape in that area was found to be the result of a continuously falling base level since Cenomanian times apart from some minor episodic fluctuations, and re-exposed old Mesozoic landscapes in the coastal areas. But Peulvast et al (2008) do not acknowledge the possibility of any significant sedimentary burial of the identified surfaces since their formation. According to Peulvast et al. (2008), the post-Cenomanian uplift caused an inversion of the Cretaceous basins and generated a landscape in which the most elevated landforms correspond either to resistant Mesozoic sedimentary caprock, or to eroded stumps of syn-rift Cretaceous footwall uplands. Peulvast et al. (2008) argued for a stepped landform system dominated by two erosional levels: A low plain between 0 and 300 m a.s.l. and the discontinuous remains of a high plain between 750 and 1100 m a.s.l. The authors found that subsidence in the Cretaceous Araripe Basin ended after the deposition of the Cenomanian Exu Fm that caps Chapada do Araripe. In support of this statement the authors refer to unpublished studies of organic matter in the Albian sediments that suggest that no significant overburden was ever removed by erosion from the exposed upper surface of the Exu caprock (this is however, in contrast with VR values of 0.6 for the Albian strata; Morais Neto et al. 2008b). Peulvast et al. (2008) referred to the increase in denudation rate occurring at 80-60 Ma over much of their study area estimated from apatite fission-track data by Harman et al. (1998), but did not comment on the km-deep exhumation since 80 Ma deduced by Harman et al. (1998) from the same data. The Neogene Barreiras Formation along the coast was found to testify to the last peak of erosion in the hinterland at c. 13 Ma or earlier.

5. Major palaeo-thermal and palaeo-burial episodes identified in this study

5.1 Palaeo-thermal episodes identified from AFTA

5.1.1 Introduction

Apatite fission track analysis (AFTA®) and vitrinite reflectance (VR) data in eight onshore wells and four offshore wells (Figure 5-1) have been employed in this study to define the major palaeo-thermal events that have affected the sedimentary sequences in the Mesozoic rift basins of NE Brazil and the adjacent continental margin. AFTA data in samples from outcrops over the onshore basin margins and hinterland to these basins have also been used to define the timing of major palaeo-thermal episodes and the exhumation history of these regions. At four locations (shown in Figure 5-1), samples were collected over a range of elevations in an attempt to obtain constraints on palaeogeothermal gradients in key palaeo-thermal episodes. In addition, AFTA data in a small number of samples from outcrops in the Serra do Mar north of Rio de Janeiro and from around Rio (Figure 5-2) have been used to investigate the tectonic history of that region.

Full details of all these analyses, including background information on both AFTA and VR, are provided in Geotrack Reports GC990 (onshore) and GC1013 (offshore). Results from wells and outcrops over the onshore region and the inshore region of the offshore shelf define a remarkably consistent thermal history framework, involving a series of cooling episodes, interpreted as representing phases of exhumation. Results from three wells further offshore show very different styles of thermal history, reflecting very different processes. Results from each setting are reviewed in turn, below.

5.1.2 Palaeo-thermal episodes representing exhumation of onshore and inshore regions of NE Brazil

AFTA data in the eight wells and all outcrop samples analysed for this study define a series of regional cooling episodes beginning in the following intervals:

450 to 410 Ma	**Ordovician-Devonian**
320 to 300 Ma	**Carboniferous**
230 to 220 Ma	**Triassic**
180 to 170 Ma	**Jurassic**
~120 Ma	**Aptian**
110 to 105 Ma	**Albian**

80 to 75 Ma	**Campanian**
48 to 45 Ma	**Eocene**
18 to 15 Ma	**Miocene**

These cooling episodes correlate closely with regional unconformities (Figure 5-3), and are interpreted as representing regional exhumation of the basement region. Palaeotemperatures derived from AFTA data in individual samples in each episode are shown in Figure 5-4 (larger versions of each of these maps are provided in Geotrack Report GC990). The earlier (pre-Cretaceous) episodes are recognised only in restricted areas onshore where the effects of more recent events (particularly the Aptian episode) are low enough to preserve evidence of the earlier history. It seems likely that the early episodes probably affected much if not all of the region, at least to some extent. The Albian episode is also only recognised in restricted areas, to the northeast of the main study region and in the Serra do Mar, and also probably represents exhumation. But this event does not seem to have a major effect in the main study area of onshore Bahia.

In contrast to these localised effects, Aptian cooling is recognised in all basement regions analysed in this study, and represents the dominant episode across much of the region. This episode is interpreted as representing a period of major exhumation of these basement margins to the Mesozoic rifts of NE Brazil. In this respect, it is worth noting that interpretation of the AFTA results in terms of regionally synchronous cooling episodes at one particular moment in geological time is certainly an oversimplification of the real history (although it provides a convenient framework in which to consider the results), and this episode in particular may well reflect exhumation over a period of time through the Early Cretaceous. (A lower degree of consistency in estimates of the onset of cooling in this episode compared to others provides some support for this notion.) In this case, the uplift and erosion indicated by this cooling episode would have provided much of the Early Cretaceous basin fill in the Mesozoic rift basins, and was presumably related to the onset of Atlantic rifting.

The Aptian palaeo-thermal episode had no detectable effect on the Mesozoic sedimentary section onshore or offshore. This event does, however, correlate with the major unconformity in the Recôncavo-Tucano-Jatobá rift between the syn-rift (Tithonian to Aptian) section and the overlying post-rift Marizal Formation of Albian age, so the basin sequences probably also underwent some degree of cooling and exhumation at this time, but not such as to have a detectable effect on either AFTA or VR data in the basins.

In all wells analysed from the Recôncavo-Tucano-Jatobá rift basins and the offshore shelf, AFTA and VR data very clearly show that the Mesozoic sequences preserved in these basins today began to cool from their maximum post-depositional palaeotemperatures in the interval 80 to 75 Ma (Campanian). This episode not only dominates the AFTA data from all wells analysed from the Early Cretaceous rift basins, and in outcrop samples across these Basins, but is also recognised throughout the surrounding basement regions as a later stage in the cooling history. Campanian cooling is also particularly strongly expressed in data from the Serra do Mar and around Rio de Janeiro, as discussed in Section 5.1.4.

As with the Aptian event discussed above, the Campanian cooling episode clearly represents a profound cooling event of regional extent. AFTA and VR data from deep wells in the Recôncavo and Tucano Basins as well as the 1-BAS-113 well on the offshore shelf of the Camamu Basin (Figure 5-1) provide very strong evidence that palaeotemperatures in this episode reflect additional burial by 2 to 3 km of post-rift section, under heat flow conditions very close to those of the present day. The close agreement in the onset of cooling in this episode in both basins and adjacent basement terrains suggests similar mechanisms of heating and cooling in both regions. Thus the Campanian is interpreted as a time of profound regional uplift and erosion, in which both the Mesozoic rift basins and the surrounding basement regions underwent regional exhumation.

In NE Brazil, evidence for Eocene cooling (beginning between 48 and 45 Ma) is only identified in AFTA data from deep wells, although this episode is very strongly expressed in outcrop samples from the Serra do Mar (Section 5.1.4). While this episode cannot be resolved in AFTA data from outcrop samples across Bahia or in shallow (< 2 km) well samples, this is probably because Eocene palaeotemperatures were not of sufficient magnitude in these samples to be resolved from those during the Campanian and Miocene (see below) episodes. (Note that in many outcrop samples it is not possible to resolve these two episodes so resolution of Eocene effects is particularly unlikely.) Thus it seems likely that Eocene cooling probably affected at least most of the Bahia region. Again, AFTA data from wells in the Recôncavo and Tucano Basins suggest that Eocene palaeotemperatures reflect additional burial by around 2 to 2.5 km of post-rift section, under heat flow conditions very close to those of the present day, and cooling was due to renewed exhumation of these basin sequences. Although Eocene cooling is not recognised explicitly in AFTA data from the basement regions of Bahia, it appears reasonable to suppose that these regions also underwent renewed exhumation at this time.

Miocene cooling effects are also recognised in all onshore basement regions and basins, as well as the offshore shelf of the Camamu Basin. Almost all data are consistent with an onset of cooling between 18 and 15 Ma, although samples from the Serra do Mar suggest an earlier onset of 25 to 20 Ma (this apparent difference may simply represent a statistical outlier). AFTA data from wells in the Recôncavo and Tucano Basins and the offshore shelf of the Camamu Basin suggest that palaeogeothermal gradients were close to present-day values (see Section 5.1.5) and Miocene palaeotemperatures reflect additional burial by around 1 to 1.5 km of section. And again, a similar explanation of Miocene cooling recognised in samples from adjacent basement terrain seems likely. Therefore, as for both the Campanian and Eocene episodes, Miocene cooling is interpreted as representing regional exhumation, being the final phase of the exhumation history affecting the entire region of NE Brazil which began in the Campanian.

5.1.3 Palaeo-thermal episodes in offshore wells

Whereas all of the events discussed above are interpreted as representing exhumation of onshore and inshore regions, AFTA and VR data from the three wells analysed from further offshore (Figure 5-1) define very different styles of thermal history.

Results from the 1-BAS-88 and 1-BAS-102 wells suggest that burial was more or less continuous, with no episodes of deeper burial and subsequent uplift and erosion detected. The only palaeo-thermal effects identified in these wells appear to be due to contact heating associated with thin intrusives within the Valanginian section of the 1-BAS-88 well and highly localised heating within the Albian section in the 1-BAS-102 some time in the last 20 Myr.

Results from the 1-BAS-129 well also show no effects of deeper burial and subsequent uplift and erosion. However, they do reveal extreme palaeo-thermal effects in the Aptian-Albian section in this well, involving palaeotemperatures >250°C, which are interpreted to reflect pre-115 Ma hydrothermal circulation, probably related to the presence of numerous intrusives identified in the vicinity of this well on seismic sections. Palaeogene units in this well were affected by an unrelated episode of hot fluid flow during the Middle Eocene (49-45 Ma), the effects of which have produced local heating in the shallower section. Both of these fluid-related episodes are very clearly expressed in the diagenetic history of sedimentary units from this well, as discussed in Geotrack Report GC1013A.

The timing of the earlier of these two episodes correlates with the Aptian event recognised in the onshore region. This may be coincidental, or may reflect a common linkage of events in both locations to rifting of the Atlantic margin. The coincidence in timing between the later episode and Eocene cooling recognised onshore (48-45 Ma) suggests a common link, and it seems likely that the hot fluid circulation responsible for the effects identified from AFTA and VR in the 1-BAS-129 well was initiated in some way by the uplift and erosion recognised onshore (discussed in detail in a later Section).

5.1.4 Palaeo-thermal events recognised in the Serra do Mar and around Rio de Janeiro

AFTA data in fifteen samples from locations in the Serra do Mar and around Rio de Janeiro shown in Figure 5-2 define five cooling episodes which began in the following episodes:

170 to 120 Ma	**Late Jurassic - Early Cretaceous**
110 to 105 Ma	**Albian**
80 to 75 Ma	**Campanian**
55 to 45 Ma	**Eocene**
25 to 20 Ma	**Late Oligocene - Early Miocene**

The timing of these events shows a very close match to the episodes recognised in NE Brazil (Section 5.1.2). The correlation between the Latest Jurassic-Early Cretaceous episode (cooling beginning between 170 and 120 Ma) identified from AFTA data in samples from the highest elevations in the Serra do Mar and around Rio de Janeiro and the Aptian episode in NE Brazil (cooling beginning at ~120 Ma) is less strong than for other episodes. But it seems reasonable to assume a common timing of ~120 Ma (Aptian) for the onset of cooling in both areas, given the regional nature of cooling at this time (Figure 5-4).

The Albian episode (cooling beginning at 110 to 105 Ma) identified in samples from the Serra do Mar correlates well with the mid-Cretaceous cooling (cooling beginning at 110 to 90 Ma) identified in AFTA from the northeast of the main study area in samples originally from the Turner et al. (2008) study. Combining timing constraints from both region suggests that cooling interval of 110 to 105 Ma (Albian) can be applied to both regions. But in contrast to the Aptian episode (above), evidence for the Albian episode is not present in samples from the main outcrop dataset from NE Brazil (Figure 5-4).

The timing of both the Campanian and Eocene cooling episodes in the Serra do Mar show a very close match to the corresponding events identified in NE Brazil, suggesting that these indeed represent synchronous cooling episodes reflecting exhumation of truly regional extent. However, as illustrated by the comparison of timing constraints for the onset of cooling identified from AFTA in samples from these regions in Figure 5-5, while Campanian cooling is recognised in samples from all regions, Eocene cooling is completely absent from samples around Teresopolis and from the floor of the Guanabara Graben (Figure 5-2). This, together with a lack of systematic variation of palaeotemperatures with elevation in samples form each area (Geotrack Report GC990, Section 12) suggests that major tectonic offsets exist in this area (consistent with the presence of major lineaments evident in the topography).

In contrast to the events discussed so far, the timing of the most recent episode of cooling identified in the Serra do mar, at between 25 and 20 Ma, is earlier than the corresponding cooling episode in NE Brazil (18 to 15 Ma, Section 5.1.2). Whether this represents a real difference or whether it simply represents the presence of statistical outliers is unclear. In subsequent discussion, we discuss the evolution of the region in terms of a common Miocene event across the whole region. But more complex scenarios should be borne in mind.

5.1.5 Magnitude of section removed during exhumation from AFTA

General principles of estimating removed section from palaeo-thermal constraints
Where palaeotemperatures can be defined from AFTA and/or VR data over a range of elevations (in outcrop) or depths (in wells), the rate of increase with depth through the section allows definition of the range of palaeogeothermal gradients that can explain the data. Extrapolation of fitted palaeogeothermal gradients from the corresponding unconformity surface to an appropriate value of palaeo-surface temperature then allows estimation of the amount of additional section that is required, above that which is preserved at the present day, to explain those palaeotemperatures.

Estimating amounts of additional burial in this way (also referred to as “removed section”, since it is no longer present) is subject to a number of critical assumptions. These are explained in detail in Geotrack Reports GC990 and GC1013, and we focus on the major points here. The most critical assumption is that the palaeogeothermal gradient was linear throughout the entire section at the time of maximum palaeotemperatures. This assumption may be invalid if non-burial-related heating (e.g. confined fluid flow) or major differences in lithology produce severely non-linear palaeotemperature profiles, which can result in linear extrapolation overestimating the amount of removed section. For this reason, the values quoted here should be viewed as upper limits to the total amount of section removed. Selection of an appropriate surface temperature is also critical.

Another crucial factor in considering amounts of removed section is that where multiple phases of exhumation occur within the interval represented by a single unconformity, as is the case here, the history between the separate episodes is not constrained (since the AFTA data constrain only the palaeotemperature peak, and not the prior history during heating to that peak). Therefore, in this study it is not clear what proportion of the total amount of section deposited above the preserved Early Cretaceous section was removed between the onset of cooling in the Campanian episode and the onset of any reburial leading to the Eocene peak. Similar comments apply for the period between the onset of Eocene and Miocene exhumation. Therefore this type of analysis should strictly be viewed as providing estimates of the amount of additional section that is present at each palaeothermal maximum, whereas the amount of any reburial between each palaeothermal peak is not constrained by the AFTA data.

Results from basement terrains in this study

Unfortunately, all the elevation sections in basement regions analysed for this study (i.e. the four shown in Figure 5-1 plus two areas in Figure 5-2) show a lack of consistency in palaeotemperatures characterising individual palaeo-thermal episodes, and it has not proven possible to obtain estimates of palaeogeothermal gradients from these datasets. In the Serra do Mar, the lack of consistency is interpreted as due to the presence of tectonic offsets, with discrete blocks having undergone differing amounts of exhumation in individual episodes. Faults capable of producing such tectonic offsets are evident as lineaments in the landscape (Section 3.3, Fig. 3-15) so such an interpretation seems reasonable. While a similar interpretation is possible in basement areas of NE Brazil, the landscape here shows no evidence of any major faults that could produce the required offsets (Section 4, Fig. 4-3, 4-7), and a more likely explanation here is the difficulty in resolving individual cooling episodes from AFTA, particularly at lower temperatures (<80°C), in samples which have undergone up to eight (or more) discrete phases of cooling.

While no explicit estimates of palaeogeothermal gradients are possible, Table 5-1 provides a summary of the amounts of addition burial required to produce specific palaeotemperatures for a range of possible palaeogeothermal gradients. From these values it is clear that for any reasonable value of palaeogeothermal gradient, palaeotemperatures in excess of 60°C in samples now at outcrop represent burial by a kilometre of more of section that has been subsequently eroded. Given that samples from the highest elevations in both NE Brazil and the Serra do Mar show palaeotemperatures of the order of 50°C in the Miocene, it is clear that a significant amount of section must have been eroded from these areas within the last 25 Myr. Campanian palaeotemperatures in both areas are higher, implying much higher amounts of section has been removed over the last 80 Myr.

Results from wells in this study

In contrast to the basement regions discussed above, AFTA and VR data from three wells in the Tucano Basin described in Geotrack Report GC990 provide extremely tight constraints on the range of viable palaeogeothermal gradients in the three key palaeo-thermal episodes.

As illustrated in Figure 5-6, the allowed range of palaeogeothermal gradients for the Campanian episode in all three wells is tightly constrained around the present-day thermal gradient of 15°C/km (derived from the AFTA data and published information from Meister, 1973), and values much in excess of this can clearly be ruled out. Values for the later episodes are less well constrained, but are also highly consistent with the present-day value and these results leave little scope for any variation of basal heat flow since at least the Campanian.

Similarly, in offshore well 1-BAS-113, the range of Campanian palaeogeothermal gradients is very tightly constrained around the present-day gradient of 24.9°C/km in this well (derived from corrected BHT values in this well, as described in Geotrack Report GC1013). While the range of allowed Miocene palaeo-gradients is broader, a constant heat flow scenario again provides a reliable description of the results from this well.

Results from the 6-MGP-34 well in the Recôncavo Basin are less tightly constrained that in the wells discussed above (due to a combination of palaeotemperature constraints being available over a narrower range of depths, and to most of the AFTA samples being totally annealed in the Campanian episode). Palaeotemperatures in the three key episodes are consistent with palaeogeothermal gradients in the range 20 to 25°C/km (Figure 5-6). This range also overlaps with the present-day thermal gradient in this well of ~20°C/km estimated from the AFTA data, although this value is not well constrained in detail (Geotrack report GC990). Results from the 1-AO-1 well allow only broad constraints. But in general, all available constraints on palaeogeothermal gradients are consistent with constant palaeogeothermal gradients across the region since the onset of Campanian cooling, suggesting that exhumation was the dominant cooling process.

Figure 5-7 shows the correlated values of palaeogeothermal gradient and removed section allowed by palaeotemperature constraints from these wells. These plots reflect the fact that a given set of palaeotemperature constraints are consistent with a range of palaeogeothermal gradients, with low gradients extrapolating to higher amounts of removed section and higher gradients requiring lesser amounts of section. The hyperbolic ellipsoidal regions in Figure 5-7 define the range of values of both parameters that are consistent with the palaeotemperature constraints for each episode in the six wells, within 95% confidence limits (i.e. ±2 sigma uncertainties). Figure 5-8 provides a direct comparison of constraints on Campanian, Eocene and Miocene palaeogeothermal gradients in the six wells.

Thus, based on a palaeogeothermal gradient of 15°C/km, estimates of the amounts of additional section required to explain the Campanian, Eocene and Miocene palaeotemperatures in the three Tucano Basin wells from Figures 5-7 and 5-8 are highly consistent, viz:

Well	Campanian	Eocene	Miocene
1-BRN-1-BA	2800-3400 m	2350-3050 m	1250-1750 m
1-FPO-1-BA	3350-3750 m	2350-2750 m	1350-1950 m
1-FVM-1-BA	3100-3600 m	1100-2400 m	900-1700 m

Using 22.5°C/km for the Recôncavo Basin wells, corresponding values are:

Well	Campanian	Eocene	Miocene
6-MGP-34-BA	2450-2950 m	1750-2200 m	1400-1900 m
1-AO-1-BA	2450-2925 m	0-4250 m	1100-1750 m

While for a palaeogeothermal gradient of 25°C/km for offshore well 1-BAS-113, the corresponding values are:

Well	Campanian	Eocene	Miocene
1-BAS-113	1950-2150 m	-	850-1250 m

While it is clear that there is a high level of consistency between results from the three Tucano Basin wells (1-BRN-1, 1-FPO-1 and 1-FVM-1), there is also a clear difference between these and both the Recôncavo Basin wells (6-MGP-34 and 1-AO-1) and offshore well 1-BAS-113. In particular, constraints on the Campanian episode, being the most tightly constrained, show a strong suggestion of a progressive shift as illustrated in Figure 5-8 from lower gradients and higher values of removed section in the Tucano Basin, through intermediate values in the Recôncavo basin to higher gradients and lower amounts of section removed in the offshore region, as summarised below:

Region	Palaeogeothermal gradient (°C/km)	Campanian	Eocene	Miocene
Tucano Basin	15	3300 m	2200 m	1300 m
Recôncavo Basin	22.5	2750 m	1900 m	1500 m
Offshore	25	2000 m	1200 m?	1000 m

All indications from this study are that the magnitude of these three cooling episodes is of similar magnitude across the Tucano and Recôncavo Basins in the vicinity of the sampled wells, and that any regional variation is large scale. Therefore we regarded the values listed above as providing a generalised representation of amounts of removed section within the vicinity of the wells analysed in each of the three settings.

One outstanding question in the light of these comments is whether Eocene exhumation affected the offshore region. The similarity of results from the two Basins to those in offshore well 1-BAS-113 suggests a similar overall history should apply, and we therefore have estimated that around 1200 m of additional section were present at the onset of Eocene cooling, based on the relative positions of the three fields in Figure 5-8 for the other two episodes. This figure of 1200 m is very close to the amount of additional section present during the Miocene (1000 m), and this probably explains the lack of resolution of a discrete Eocene episode in the 1-BAS-113 well.

The results discussed here therefore suggest a pattern of decreasing amounts of palaeo-burial from north (Tucano Basin) to south across the region in each episode, together with a corresponding increase in basal heat flow (palaeogeothermal gradient). Comparison of the resulting estimates of additional burial with independent values estimated from sonic velocities are presented in the next section.

5.2 Palaeo-burial recognised from sonic velocities

5.2.1 Data and method

The magnitude of exhumation has been estimated from burial anomalies evaluated from sonic data for the Mesozoic succession in 18 onshore and offshore wells and for the Proterozoic succession in 1 onshore well, NE Brazil covering the Almada, Camamu, Recôncavo, Sanfranciscana and Tucano Basins) (Japsen 2009). The burial anomaly is the difference between the present-day burial depth of a rock and its maximum burial estimated as the depth corresponding to normal compaction for the measured velocity predicted by a normal velocity-depth trend for the lithology in question; here we will only refer to the absolute value of the burial anomaly. The magnitude of exhumation since maximum burial is the sum of the burial anomaly and the post-exhumational burial.

Burial anomalies has been estimated for the drilled succession in each well and they are primarily based on (1) a comparison between the sonic data for high-velocity sandstones and a slightly revised baselines for pure sandstone (relative to those of Japsen et al. 2007b) and (2) by a comparison between the sonic data for low-velocity shales and a new baseline for organic-rich shales defined for the Morro do Barro and Rio de Contas Formations. Furthermore, the interpretation was supported by a comparison between the sonic data and the baseline for pure shale (Japsen 2000).

The estimation of the burial anomaly was based on depth-shifting all three baselines by the same amount until a match is obtained between the baselines and velocity-depth data-points for the corresponding lithologies. The benefit of this qualitative approach is that whereas the velocity-depth trend for one of the lithologies may be difficult to identify from the sonic data, the comparison of the sonic data for two or more lithologies with the respective baseline effectively limits the range of the possible burial anomalies. The interpretation of the data for the sandstone units relies on identification of high-velocity units with pure sand and the estimated burial anomaly may thus in some cases only be considered as a lower limit.

5.2.2 Main results

Estimates of the section removed relative to the sediments in the Early Cretaceous rift basins are (see Table 5-2; Fig. 5-9):

Tucano Basin
2.5 ± 0.6 km for one well (1-FPO-1) with two other wells only yielded lower limits of 1.5 and 1.8 km, respectively (1-BRN-1, 1-FVM-1).

Recôncavo Basin,
2.5 ± 0.8 km for one well (6-MGP-34).

Camamu Basin
Inshore, north-west: about 2.0 km for two wells (1-BAS-84, -113).
Inshore, south-west: about 1.4 to 1.7 km with estimates ranging from 1.1 ± 0.9 to 1.9 ± 0.5 km for five wells (1-BAS-21, -64, -74, -97, -107).
Deep-water: The drilled section is at maximum burial today in one well (1-BAS-129).

Almada Basin
Inshore, exhumed: variations between 1.1 ± 0.7 to 2.9 ± 0.9 km (1-BAS-71, -77,-79).
Inshore, maximum burial: the drilled sections in two wells are found to be at maximum burial today (1-BAS-88, -118).
Deep-water: The drilled section is at maximum burial today in one well (1-BAS-102)

Sanfranciscana Basin
A tentative estimate of the section removed relative to Proterozoic shale drilled in western Bahia: about 5 km for one well (FLU-1).

5.2.3 Constraints on the age and thickness of the section removed at the post-Algodões unconformity in the inshore areas

In the inshore parts of the south-western Camamu Basin, a section of up to 2 km was removed at an unconformity above the Albian–Cenomanian Algodões Fm (c. 400 m preserved) and below the preserved parts of the Urucutuca Fm which is not older than Campanian in this area. This suggests that the exhumation (and hence maximum burial) occurred at the mid-Campanian unconformity which is recognized across the Almada and Camamu Basins. This interpretation is furthermore, in agreement with the Campanian cooling event identified from AFTA data the western part of Bahia and in offshore well 1-BAS-113 (cf. Geotrack onshore and offshore reports 990 & 1013). The section removed at the mid-Campanian unconformity in this part of the Camamu Basin was thus partly a Turonian–mid-Campanian sequence in the lower part of the Urucutuca Fm (probably c. 1 km prior to exhumation) and partly an upper part of the Algodões Fm.

5.2.4 Constraints on the age and thickness of the section removed in the Recôncavo-Tucano Basins

In the onshore Recôncavo and Tucano Basins, the youngest Mesozoic sediments belong to the Aptian Marizal Fm that rests on rift sediments above a major Aptian unconformity. The section removed above the Marizal Fm is estimated to c 2.5 km with an upper limit around 3 km based on the sonic data in two wells. This magnitude of exhumation onshore is comparable to the exhumation offshore that reaches 2.0 to 2.5 km. The section removed thus corresponds to the accumulated thicknesses of an upper part of the Aptian Marizal Fm (equivalent to the uppermost parts of the Taipus-Mirim Fm), an Albian–Cenomanian sequence (equivalent to the Algodões Fm) and a Turonian–mid-Campanian sequence (equivalent to the Urucutuca Fm below the mid-Campanian unconformity).

5.2.5 Wells with drilled sections at maximum burial depth

In the inshore parts of the Almada Basin, the section drilled (including the Palaeogene sediments) are however, now at maximum burial in the inshore well 1-BAS-88 (supported by AFTA data; Geotrack onshore report 1013) and in well 1-BAS-118 further offshore. These wells have a significant Cenozoic section preserved in contrast to other wells along the coast; Palaeocene sediments have been found 700 and 900 m below sea bed in these wells, respectively. This indicates that the wells have experienced a different tectonic history than most of the coastal zone that has allowed the preservation of mainly Palaeogene strata relatively near the coast (Fig. 5- 9). Since the sediments in well 1-BAS-88 are at maximum burial today, only an upper limit of 1.6 km (= the amount of section above the unconformity) can be estimated of the magnitude of exhumation at the Campanian unconformity in this well. But this upper limit agrees well with the 1.1 km exhumation estimated for the near-by well 1-BAS-79. The sediments in the deep-sea well 1-BAS-129 are also at maximum burial today, but there is a marked Campanian unconformity in the drilled section between Palaeocene sediments at 2979 m MD and the Albian–Cenomanian Algodões Fm at 3156 m MD (105 m preserved). The upper limit for erosion at this unconformity is thus its depth below sea bed (the post-exhumational burial), 1.2 km.

5.2.6 Comparison of results based on sonic and AFTA data

The estimated magnitudes of exhumation since the Campanian based on the palaeothermal indicators (AFTA and VR, Section 5.1) are in very good agreement with those based on sonic velocity data that are sensitive to changes in burial (effective stress) (Section 5.2). The estimates for the Recôncavo-Tucano Basins are c. 2.5 km based on sonic data whereas the estimates based on thermal data are 2.75 to 3.3 km in the same area. The sonic estimate for the Camamu Basin (BAS-113) is 2.2 km whereas that based on thermal data is 2.0 km. This agreement between results that are obtained from totally independent physical parameters underlines the consistency of the results presented here. Furthermore, while non-linear thermal gradients may potentially lead to overestimation of the estimates based on thermal data and estimates based on sonic data may in some cases be considered as minimum values since the method primarily rely on identification of very pure sand units that may not be present in a drilled section, the consistency of results from the two approaches suggests that the estimates can be regarded as reliable.

5.3 Reconstructed thermal and burial/uplift histories

5.3.1 General considerations

It should be stressed that it is not possible, using the tools employed in this study, to reconstruct the full detail of the thermal history or the burial and exhumation history of the rock units analysed. AFTA and VR data define only the magnitude of the dominant palaeo-thermal peaks with confidence, and converting this information to burial history constraints is fraught with uncertainty. Sonic velocities define only the maximum burial situation, and not the subsequent history. Therefore there is a wide variety of reconstructions that are consistent with a particular dataset. For this reason, in presenting reconstructed thermal histories and burial/exhumation histories, we focus on stressing the general nature of the history, rather than the detailed evolution.

As an example of this, basement regions in NE Brazil underwent a major cooling episode in the Aptian (~120 Ma), and then underwent a further cooling episode in the Campanian (at ~77 Ma), together with the sedimentary fill of the Mesozoic rift basins. Based on results presented here and in Geotrack Report GC990, both these cooling episodes are interpreted as representing exhumation. This raises the question of how much section was removed during the phase of exhumation that began at ~120 Ma, and how much section (if any) was redeposited between then and the recommencement of exhumation in the Campanian. AFTA data only define the palaeotemperatures of individual samples at each palaeo-thermal peak, and not the history in between.

Rather than trying to show the full range of reconstructions that are possible on this basis, we have focussed on showing the overall style of cooling or exhumation in this Section. Further insights into the history between individual phases of exhumation may be derived from integration with geological information, and this aspect of the study is pursued in Section 6.

5.3.2 Onshore and inshore wells

The preferred thermal history reconstructions for representative wells from the Tucano and Recôncavo Basins and the inshore area are shown in Figure 5-10, while corresponding burial-exhumation history reconstructions are shown in Figure 5-11. These Figures are taken from the discussions of the results in the individual wells in Geotrack Reports GC990 and GC1013, where full details can be found. These reconstructions all involve progressive burial of the preserved Early Cretaceous sediments (plus Late Jurassic in places) by between 2 and 3 km of additional section deposited between the age of the youngest preserved section (~110 Ma in the Tucano Basin and slightly earlier in the Recôncavo Basin and offshore) and 80 to 75 Ma, when exhumation begins. The additional section is removed in three phases beginning between 80 and 75 Ma, between 48 and 45 Ma and between 18 and 15 Ma. All reconstructions are based on constant geothermal gradients. While a range of other options can be put forward, as discussed in Section 5.1 the results from these areas show no evidence to suggest any significant variation in basal heat flow over the last 80 Myr.

In all these reconstructions, we have included some degree of reburial between each episode of exhumation. However, as explained in Section 5.3.1 this is unconstrained and a range of alternative scenarios are also possible, ranging from one in which no intervening reburial took place to the other extreme in which all additional section is totally removed in each episode. Since the overall implications of the range of scenarios for the maturation histories of source rocks within these basins are similar, we do not pursue this issue here. Further discussion of how these reconstructions can be made more realistic is provided in Section 6, where these reconstructions are integrated with geological constraints.

5.3.3 Basement regions of NE Brazil

Figures 5-12 and 5-13 provide a summary of the general pattern of thermal histories for outcrop samples in various regions of NE Brazil. Temperature scales are shown with a corresponding depth scale using a thermal gradient of 25°C/km for basement areas. Thus, for a constant heat flow scenario, these Figures also illustrate the variation in exhumation histories across the region.

It should be stressed that the histories between each dominant cooling episode are not constrained, so neither the total amount of cooling that occurred between individual episodes nor the amount of re-heating to the next palaeo-thermal peak, can be defined. The histories in Figures 5-10 and 5-11 are drawn using an episodic cooling/heating model, with a moderate degree of reheating to each palaeo-thermal peak. But as explained in Section 5.3.1, this is only one of many options.

In addition to this factor, it should also be stressed that the exhumation histories depicted in these Figures are hugely uncertain because of a lack of information on thermal gradients across the region. For all these reasons, it is not possible to determine precise amounts of removed section, and the values shown in Figures 5-10 and 5-11 should be viewed as providing a general guide to the amounts of additional section present during key episodes, rather than in any way attempting to define the complete history. Histories of individual samples within each area will differ due to differences in elevation, as well as variation in the magnitude of individual episodes, but the histories shown here provide a schematic representation of the variation in thermal history styles across the area.

One striking feature that emerges from Figure 5-12 is the marked difference in the histories between the eastern margin of the Tucano Basin and the western flank of the Recôncavo Basin. Whereas the former region cooled below ~110°C in the ~Aptian event, samples from the western region have remained below 110°C since the Carboniferous. Another key difference is apparent in Figure 5-13 is the dominance of Jurassic cooling in the region in the southwest (samples 84 to 95), whereas samples in the other two areas cooled below 110°C in earlier episodes.

5.3.4 Offshore wells

The preferred thermal history reconstructions for the three offshore wells analysed in Geotrack report GC1013 are shown in Figure 5-14, and the corresponding burial-exhumation history reconstructions are shown in Figure 5-15. These Figures are taken from the discussions of the results in the individual wells in Geotrack Report GC1013, where full details can be found. The reconstructions for the 1-BAS-88 and 1-BAS-102 wells are both based on constant geothermal gradients and no additional burial, with only localised heating effects, attributed to the movement of hot fluids, identified in each well. Units throughout the section intersected in each well are therefore at their maximum burial depths at the present day.

All sedimentary units intersected in the 1-BAS-129 well are also interpreted to be at their maximum post-depositional burial depths (Figure 5-14), but in this well, the reconstructed thermal history (Figure 5-15) displays the effects of two pervasive heating effects, each interpreted as representing hot fluid movements. The earlier event, which must have taken place very early in the depositional history of the section, prior to 115 Ma, is interpreted as due to pervasive hydrothermal circulation throughout much of the section, probably related to the presence of numerous intrusives identified on seismic sections. Palaeogene units in this well were affected by an unrelated episode of hot fluid flow during the Middle Eocene, the effects of which have produced local heating in the shallower section.

5.3.5 Serra do Mar and Rio de Janeiro

Figure 5-16 shows palaeotemperatures derived from AFTA in outcrop samples from three locations in the Serra do Mar and around Rio de Janeiro (Figure 5-2) plotted against sample elevation. Figure 5-17 provide summaries of the general pattern of thermal histories for selected samples from these locations. Temperature scales in these plots are shown with a corresponding depth scale using a thermal gradient of 25°C/km, so for a constant heat flow scenario, these Figures also illustrate the variation in exhumation histories across the region.

As for the basement regions of NE Brazil shown in Figures 5-11 and 5-12, it is again emphasised that the histories between each dominant cooling episode are not constrained, so neither the total amount of cooling that occurred between individual episodes nor the amount of re-heating to the next palaeo-thermal peak, can be defined. In addition, since no information on thermal gradients in the region is available, the exhumation histories are highly uncertain, and should be viewed as providing a generalised depiction of the overall history, rather than an accurate description of the denudation history.

Note from Section 5.1.4, the timing of the most recent major cooling episode identified by AFTA from the Serra do Mar alone is between 25 and 20 Ma, whereas the combined dataset from the whole study suggest a rather later timing between 18 and 15 Ma (Section 5.1.2). In the following discussion we will restrict discussion of this episode to “Miocene cooling”, with the understanding that there is some uncertainty surround the precise timing, as a result of this being the last (and lowest temperature event) in a series of cooling episodes that have affected this region. The most important outcomes from the study of these samples are:

- Samples at or close to the present-day surface in the highland regions of the Serra do Mar around Petropolis (e.g. GC990-11, 13, -257), Teresopolis (e.g. GC990-50, -51), as well as around Rio de Janeiro (GC990-2, -7), cooled from palaeotemperatures around 50 or 60°C in the Miocene cooling episode. This implies that in the Early Miocene (or possibly Middle Miocene?), these rocks were buried by up to 1 km or more of section, which has subsequently been eroded. Since these rocks are now near the elevation of the regional planation surface, this suggests that this surface was buried by some thickness of section at the onset of Miocene cooling.

- Miocene and Eocene palaeotemperatures in samples from Petropolis show a marked offset in Figure 5-16, suggesting that a major tectonic offset exists between samples GC990-11 and samples GC990-257 and -13, such that the two latter samples have undergone a much larger degree of Miocene cooling than sample GC990-11. In contrast, both Miocene and Eocene palaeotemperatures in samples GC990-8, -9, -10 and -11 show a very rapid increase with decreasing elevation, suggesting a high palaeogeothermal gradient. But in the light of data from the highest elevations (above), we suspect these apparent high gradients are due to further offsets in a reverse sense to the higher elevations, such that sample GC990-11, for example, has undergone less net exhumation than sample GC990-8 at close to sea level.

- Miocene and Eocene palaeotemperatures in samples from Rio de Janeiro also show an erratic variation with elevation, suggesting further tectonic offsets in this region.

- Samples from the highest elevations generally preserve evidence for earlier cooling epsiodes (e.g. the 170-120 Ma palaeotemperatures, interpreted as representing the regional Aptian cooling episode as explained in Section 5.1.4, in samples GC990-3 (Rio) and GC990-20 (Teresopolis).

- Miocene and Campanian palaeotemperatures in samples from around Teresopolis show little change over an elevation range of ~2 km, and Miocene palaeotemperatures suggest reversals in the expected trend of increase with depth within the section, as e.g. between samples GC990-52 and -53 and between GC990-258 and -56 (Figure 15-16). In the light of above comments, we regard this as evidence of further tectonic offsets between samples in this section.

- Perhaps the strongest feature of these data overall is the complete absence of palaeotemperatures characterising the Eocene episode in samples from the graben region or in samples from around Teresopolis. The disappearance of this episode over a distance of around 25 km between Petropolis and Teresopolis is unexplained at present, and further work is required to shed light on this aspect of the results. This is particularly surprising since Eocene cooling is recognised in NE Brazil (Section 5.1.2) and appears to represent a regional episode of uplift and erosion. The most likely explanation is simply that the effects of the Eocene episode were less pronounced around Teresopolis, and cannot be resolved from Miocene palaeotemperatures.

- AFTA from sample GC990-255, collected in the centre of the graben (Figures 5-2, 5-17) show no evidence of any Miocene cooling. This is consistent with the setting of this sample within the Guanabara graben, an area of Cenozoic subsidence. Sample GC990-256, locate some way to the north (along the edge of the graben, south of Petropolis), does require Miocene cooling, suggesting that this location is still within the region affected by uplift of the Serra do Mar. Samples GC990-260 and -261, from the Palaeogene hot spring deposit within the Itaboraí Basin, both show Miocene cooling, which most likely represents the influence of hot fluids at this location, although some degree of Eocene and Oligocene burial and subsequent Miocene exhumation may be possible at this location.

Overall, as indicated in Figure 5-17, AFTA data in the samples collected around the Serra do Mar define a complex exhumation history involving multiple episodes from Early Cretaceous times onwards, but dominated by major episodes in Albian, Campanian, Eocene (in parts) and Miocene times. Further analyses in this area are required before the full detail of the history becomes clear.

Integration of this information with geological evidence is discussed in Section 6.3.

5.4 Comparison with previous exhumation studies

5.4.1 Exhumation history of the Recôncavo-Tucano and Camamu Basins

Magnavita *et al*. (1994) discussed the burial and exhumation history of the Recôncavo and Tucano basins, reporting that the depth to the top of the oil window (defined by a vitrinite reflectance R_o level of 0.6%) is relatively shallow across the Recôncavo Basin, reaching a maximum depth of 1.6 km (below mean sea level) in the centre of the basin (Figure 5-18). In contrast, across much of the Tucano Basin the top of the oil window is distinctly deeper, reaching a maximum of 3.2 km in the centre of the basin, although source rocks on the western border are mature to within 400 m of the surface.

Magnavita *et al*. (1994) suggested that for an assumed geothermal gradient of 30ºC/km, an R_o level of 0.6% should be reached at a depth of ~3 km, so the much shallower oil window in the Recôncavo Basin requires either that heat flow was higher during rifting and the subsequent opening of the South Atlantic, or that the sedimentary section in the basin has been more deeply buried and subsequently exhumed. Magnavita *et al*. (1994) estimated that at least 1750 m of section had been eroded at the location of the Rio do Bu oilfield, based on VR data (see 5-18 for location). Davison (1987) estimated a minimum of 1 km of exhumation from the surface porosity of synrift shales in the middle of the Recôncavo Basin.

Surface outcrop patterns are also indicative of large-scale removal of post-rift strata from the Recôncavo and South Tucano basins, as early synrift strata crop out throughout the basin, and only a limited cover of postrift strata is preserved; e.g. the Marizal Formation with a maximum thickness of 400 m (Fig. 3-2). Magnavita *et al*. (1994) thus concluded that the Recôncavo Basin had been deeply exhumed, with the main phase of uplift represented by the regional unconformity between the Aptian Marizal Formation and the underlying synrift section. They also suggested a later period of regional uplift and erosion, based on the presence of remnants of post-rift Marizal Formation above the level of the adjacent basement margins, although the exact age of this episode could not be defined.

The results of our study contrast with the conclusions of Magnavita et al. (1994) in a number of important ways. One important difference is that our study suggests that the centre of the Tucano Basin has undergone a similar or slightly greater degree of exhumation compared to the Recôncavo Basin (e.g. Figure 5-8, Section 5.3.1). In this context, the difference in the depth to the top of the oil window in the two basins can be understood in terms of the very different thermal gradients in the two Basins, with an extremely low gradient of 15°C/km in the centre of the Tucano Basin compared to around between 20 and 25°C/km in the Recôncavo Basin. Comparison of the map of the depth to the top of the oil window from Magnavita et al. (1994) with the map of present-day thermal gradients across the area from Meister (1973) emphasises this point (Figure 5-18), remembering that the results of this study suggest that basal heat flow has not changed significantly over at least the last 80 Myr.

Another major difference in our study is the timing and extent of the main phase of post-rift exhumation. Magnavita et al. (1994) advocated the sub-Marizal Fm unconformity as representing the main episode of uplift and erosion in the Recôncavo Basin, and that uplift and erosion was restricted to the basin system. But our results clearly show that any effects of this unconformity were minor, and the main phase of exhumation began in the Campanian, affecting not only the basins but also the surrounding basement terrain. This clearly shows the benefits of the data-driven approach adopted for this study and the importance of not only investigating the exhumation of basin sediments but also the surrounding basement flanks. Magnavita et al. (1994) were more accurate in defining a period of post-Cretaceous uplift and erosion on the basis of the present disposition of remnants of the post-rift sequence at relatively high elevations above the basin margins, and our results confirm that this phase of uplift and erosion continued through into Miocene times in three major phases.

Magnavita et al (1994) suggested that preservation of thin sandstones of presumed Devonian age at many localities outside the basin margins represented remnants of a widespread shallow basin which linked the RTJ Rift with the Palaeozoic age Parnaíba Basin farther north, and suggested that a pre-Devonian basement peneplain had been re-exhumed. The earlier episodes of deeper burial and subsequent exhumation through the Late Palaeozoic defined by our AFTA results from NE Brazil support this conclusion.

Scotchman and Chiossi (2008) analysed vitrinite reflectance data from wells in the Camamu shelf and found high maturities at relatively shallow depths. Extrapolation of the maturity trends indicated a range of deeper burial between 1.2 and 2.7 km across the shelf area. This result is in good agreement with those presented here (cf. Table 5-2).

5.4.2 Previous thermochronological studies in NE Brazil

A number of thermochronological studies of regions of NE Brazil have been published in recent years. Harman *et al*. 1998 reported apatite fission-track (AFT) data from outcrops on the São Francisco Craton west of the RTJ Rift, within the rift and from the basement block east of the rift. AFT ages in these samples are discussed in Section 11 of Geotrack Report GC990, and are broadly consistent with our own results. Harman *et al.* 1998 derived thermal histories from their data indicating two main phases of cooling, the first coeval with continental breakup in the Early Cretaceous (c. 130 Ma) and the second broadly coeval with a change in relative plate motion in the Late Cretaceous (60 to 80 Ma). Harman *et al.* 1998 suggest a total cooling to the present-day on the Craton of 50 to 70ºC since 130 Ma, whereas the cooling along the coast since 80 Ma is 70 to 100ºC. According to these authors a cooling of 100ºC corresponds to 6-7 km of denudation for a geothermal gradient of 15ºC/km, which is reduced to 3–4 km if a gradient of 30°C/km is used. These conclusions are broadly compatible with the histories suggested here, although the results of this study provide considerably more detail, particularly on the timing of individual phases of exhumation (benefitting significantly from the availability of samples from exploration wells in the Mesozoic rift basins).

More recently, Turner et al. (2008) reported AFTA data in samples from the Recôncavo and Tucano basins and surrounding basement margins, and compared the resulting thermal histories (and the corresponding thermal history implications) with those from the conjugate margin of Africa. These results were interpreted in terms of two major cooling episodes which began in the intervals 110 to 100 Ma and 40 to 10 Ma. Results from some of the samples from the Turner et al. (2000) study have been integrated into this study (Section 11, Geotrack Report GC990), and these results have been reassessed in the light of the larger dataset now available. This suggests that the presence of multiple cooling episodes was not fully appreciated in the Turner et al. (2008) study.

One notable outcome of the Turner et al study is that AFTA data from the Rio Muni-1 well and outcrop samples from Equatorial Guinea define four major episodes of cooling in West Africa, beginning in the intervals 112 to 90 Ma, 85 to 70 Ma, 45 to 35 Ma and 15 to 10 Ma. While minor differences exist, these four episodes show a remarkably close match to those identified in NE Brazil in this study, suggesting that the exhumation episodes identified in this study are controlled by processes acting on a plate-wide scale, rather than representing a response to local influences.

Most recently, Morais-Neto et al. (2008a) published AFTA data from the Borborema plateau of NE Brazil, to the northeast of the region studied in this report. These data were interpreted in terms of two dominant episodes of cooling, in the intervals 100 to 90 Ma and 20 to 0 Ma, while an intermediate event in the interval 65 to 50 Ma was also suggested. Further reassessment of these data in the light of the results of this study again suggests that the effects of multiple episodes may not have been fully resolved, although the dominant cooling episode appears to be well defined and shows a close correlation with the earlier event identified in the Turner et al (2008) study. But overall, it is likely that further reassessment of these data may result in a rather more complex history than the two-event scenario favoured by Morais-Neto et al. (2008a).

Table 5-1. Relationship between additional burial and palaeotemperature for different palaeogeothermal gradients

	Additional burial (km) required to achieve each palaeotemperature in samples at outcrop, for specified values of palaeogeothermal gradient (surface temperature = 20°C)			
Maximum palaeotemperature	20°C/km	30°C/km	40°C/km	50°C/km
50°C	1.5	1.0	0.75	0.6
60°C	2.0	1.33	1.0	0.8
70°C	2.5	1.67	1.25	1.0
80°C	3.0	2.0	1.5	1.2
90°C	3.5	2.33	1.75	1.4
100°C	4.0	2.67	2.0	1.6
110°C	4.5	3.0	2.25	1.8
120°C	5.0	3.33	2.5	2.0

Table 5-2. Estimates of burial anomaly for the pre-Campanian section in individual wells and the corresponding amount of removed section. The estimate is based on comparison between the normal velocity-depth trends for pure sandstone, shale and organic-rich shale and sonic log data for the relevant intervals. Depths below sea bed / ground level.

Basin	Well	Formation below unconformity		Burial anomaly*	Post-exhumational burial	Section removed **	
		Name	Thick (km)	(km)	(km)	Thick (km)	Formations
Tuc	1-BRN-1	Mrz	0.1	1.5 – 3.5	0	1.5 – 3.5	Mrz-younger
WB	1-FLU-1	Prot	1.0	5.0 ± 0.5	0	5.0 ± 0.8	Cmb-Cret
Tuc	1-FPO-1	Mrz	0.3	2.5 ± 0.3	0	2.5 ± 0.6	Mrz-younger
Tuc	1-FVM-1	Mrz	0.1	1.8 ± 0.6	0	min 1.8	Mrz-younger
Rec	6-MGP-34	SSb	0.6	2.5 ± 0.5	0	2.5 ± 0.8	SSb-younger
Cam	BAS-021	Alg	0.4	1.9 ± 0.2	0	1.9 ± 0.5	Alg-Uruc
Cam	BAS-064	Alg	0.4	1.4 ± 0.4	0	1.4 ± 0.7	Alg-Uruc
Alm	BAS-071	RdC	1.4	2.5 ± 0.6	0.4	2.9 ± 0.9	(RdC) Tm-Uruc
Cam	BAS-074	Alg	0.4	1.4 ± 0.4	0	1.4 ± 0.7	Alg-Uruc
Alm	BAS-077	Alg	0.0	0.7 ± 0.4	0.8	1.5 ± 0.7	Alg-Uruc
Alm	BAS-079	Alg	0.0	0.7 ± 0.4	0.4	1.1 ± 0.7	Alg-Uruc
Cam	BAS-084	RdC	2.0	2.0 ± 0.4	0.4	2.4 ± 0.7	(RdC) TM-Uruc
Alm	BAS-088	TM	0.0	0 ± 0.2	1.6	(<1.6)***	(TM-Uruc)
Cam	BAS-097	Alg	0.4	1.6 ± 0.2	0.1	1.7 ± 0.5	Alg-Uruc
Alm	BAS-102	-	-	0 ± 0.2	-	0	-
Cam	BAS-107	Alg	0.3	0.8 ± 0.6	0.3	1.1 ± 0.9	Alg-Uruc
Cam	BAS-113	RdC	0.1	2.2 ± 0.2	0.1	2.3 ± 0.5	RdC-Uruc
Alm	BAS-118	TM	0.8	0 ± 0.4	(1.3)	(<1.3)***	(TM-Uruc)
Cam	BAS-129	Alg	0.1	0 ± 0.2	(1.2)	(<1.2)***	(Alg-Uruc)

*) Magnitude of the burial anomaly (positive numbers). Uncertainty given for the match between the datapoints and the baselines.

**) Allowing for the uncertainty of the baselines.

***) Since the Mesozoic sediments are at maximum burial today, any exhumation on the Late Cretaceous unconformity must have a smaller magnitude than the depth to the unconformity (see Fig. 4-2). min: minimum.

Alg: Algodões Fm; Alm: Almada; Cam: Camamu; Cmb: Cambrian; Cret: Cretaceous; Mrz: Marizal Fm; Prot: Proterozoic; RdC: Rec: Recôncavo; Rio de Contas Fm; TM: Taipus-Mirim Fm; Tuc: Tucano; SSb: São Sebastião Fm; Uruc: Urucutuca Fm; WB: West Bahia.

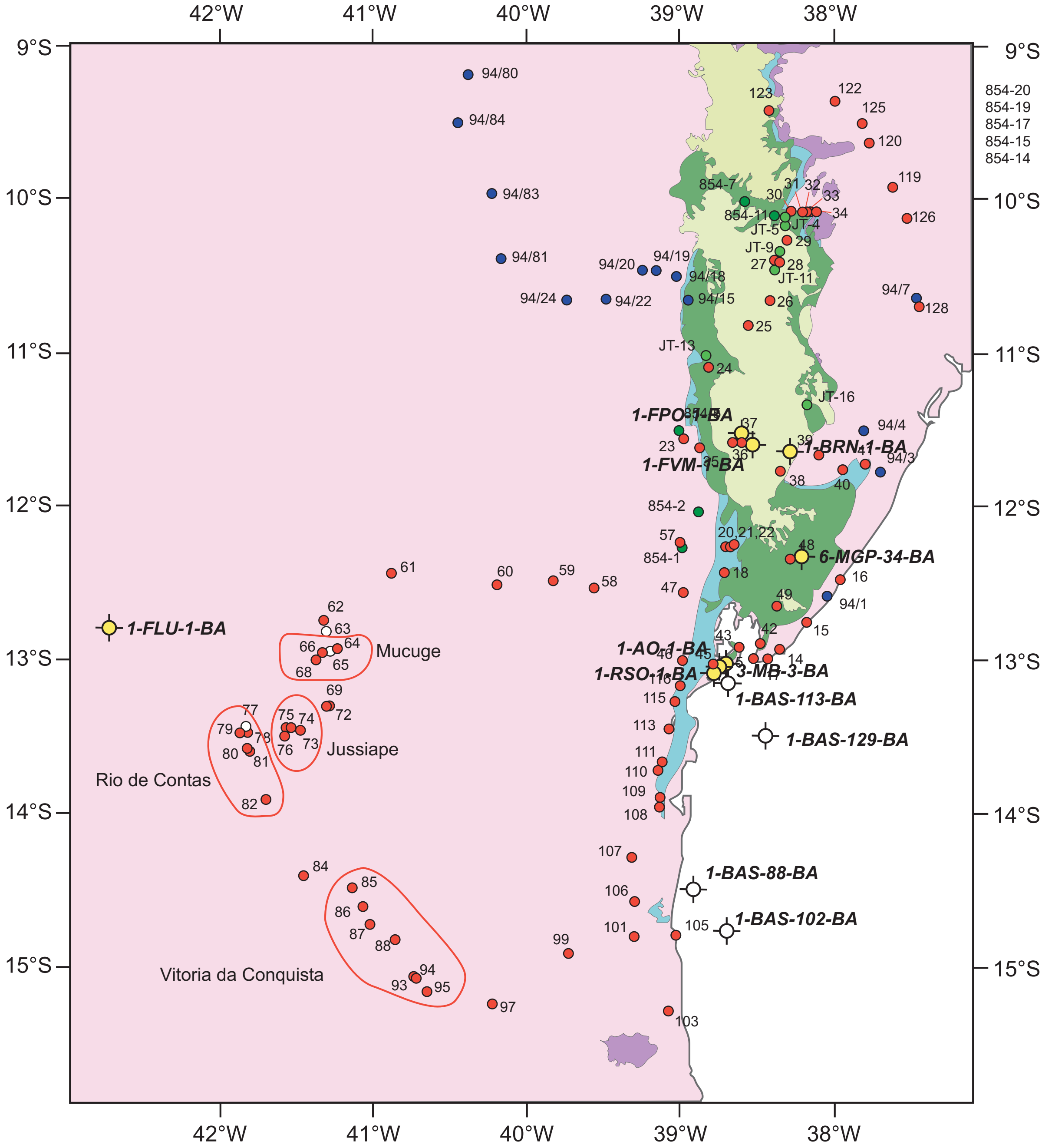


Figure 5-1. *Location map showing* ***offshore and onshore wells plus outcrop samples from Bahia*** *for which AFTA data are discussed in this Section. Samples shown with green symbols refer to published data from Turner et al. (2008). Those shown with 854 prefixes have been reinterpreted for this study and details are included in Tables 11.2 and 11.3. Samples shown with blue symbols are from Harman et al. (1998), and have not been converted to quantitative thermal history constraints. Locations of four elevation sections discussed from the Highland region in the southwest are also shown (red outlines). Compare with Figure 3.2 for a key to geological units and detail of the basement regions*

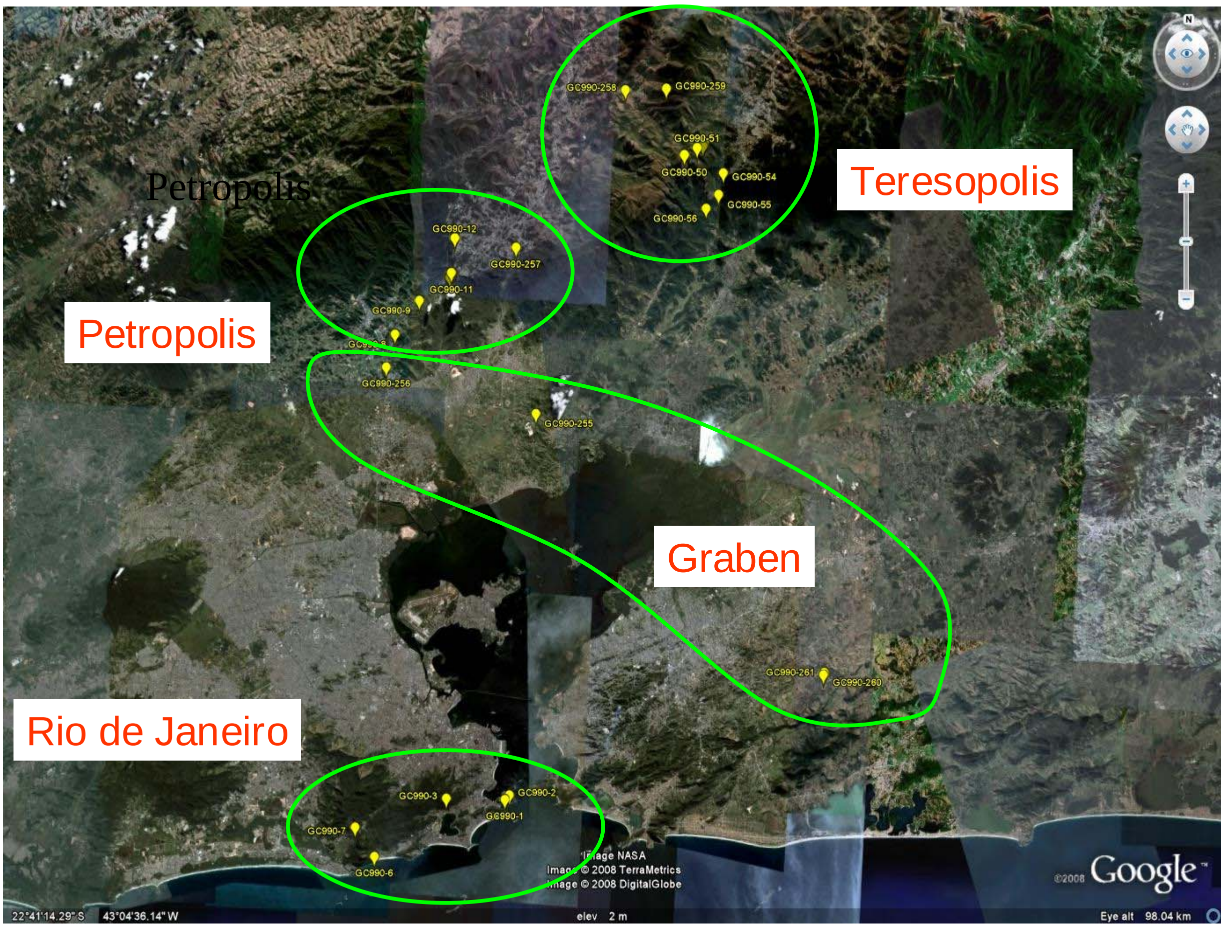


Figure 5-2. *Location map showing samples from the Serra do Mar and around Rio de Janeiro discussed in this Section, indicating the four regions discussed in the text.*

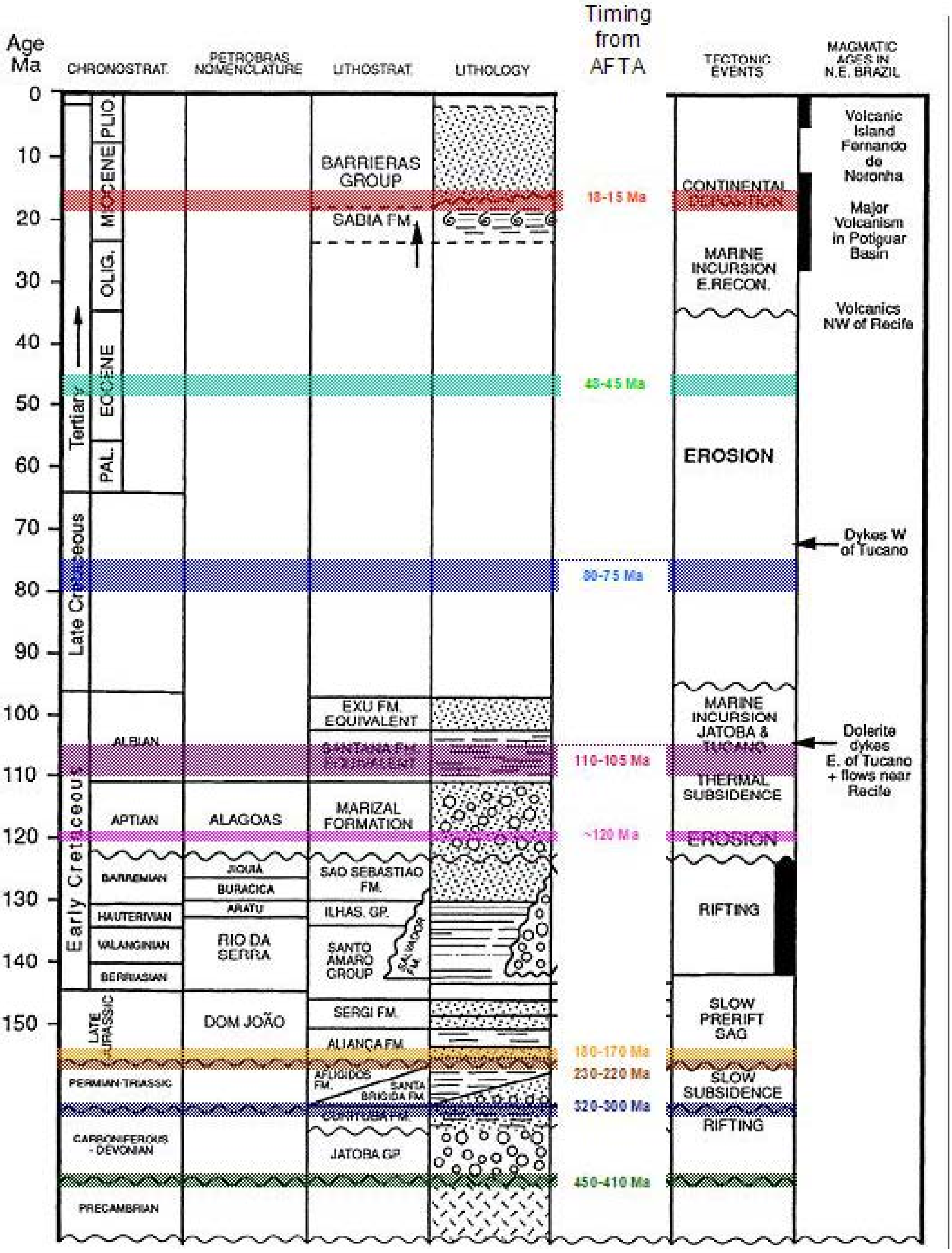


Figure 5-3. *Regional cooling episodes (Section 5.1.2) indicated on the stratigraphic column and geological history of the Recôncavo-Tucano-Jatobá Rift from Magnavita et al. (1994). See also Table 3-1 for constraints on the main unconformities and the revised stratigraphic charts for the Almada, Camamu and Recôncavo basin in Appendix A.*

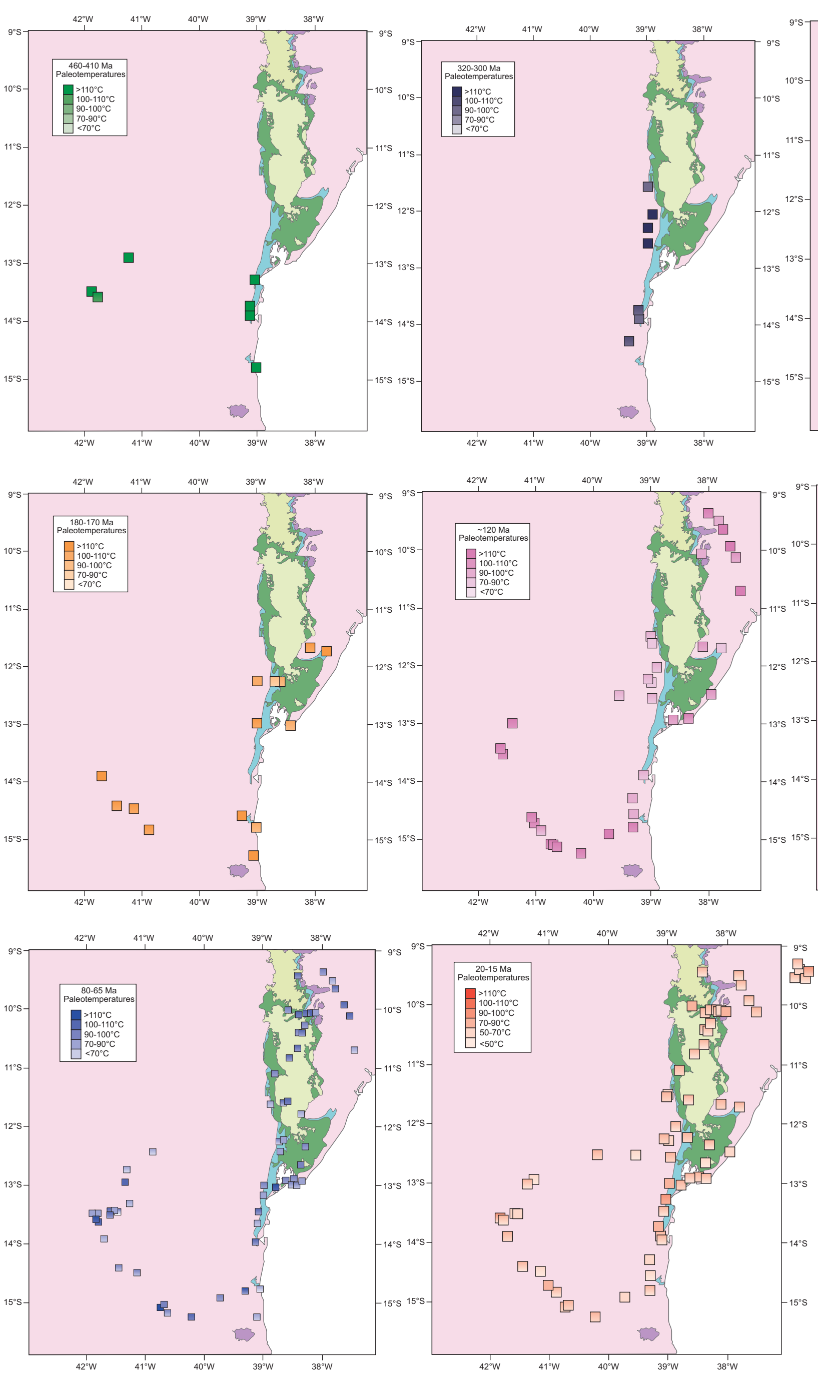


Figure 5-4. *Maps of palaeotemperatures derived from AFTA data from individual samples in eight palaeo-thermal episodes identified in Geotrack Report GC990, where larger versions of each map can be found.*

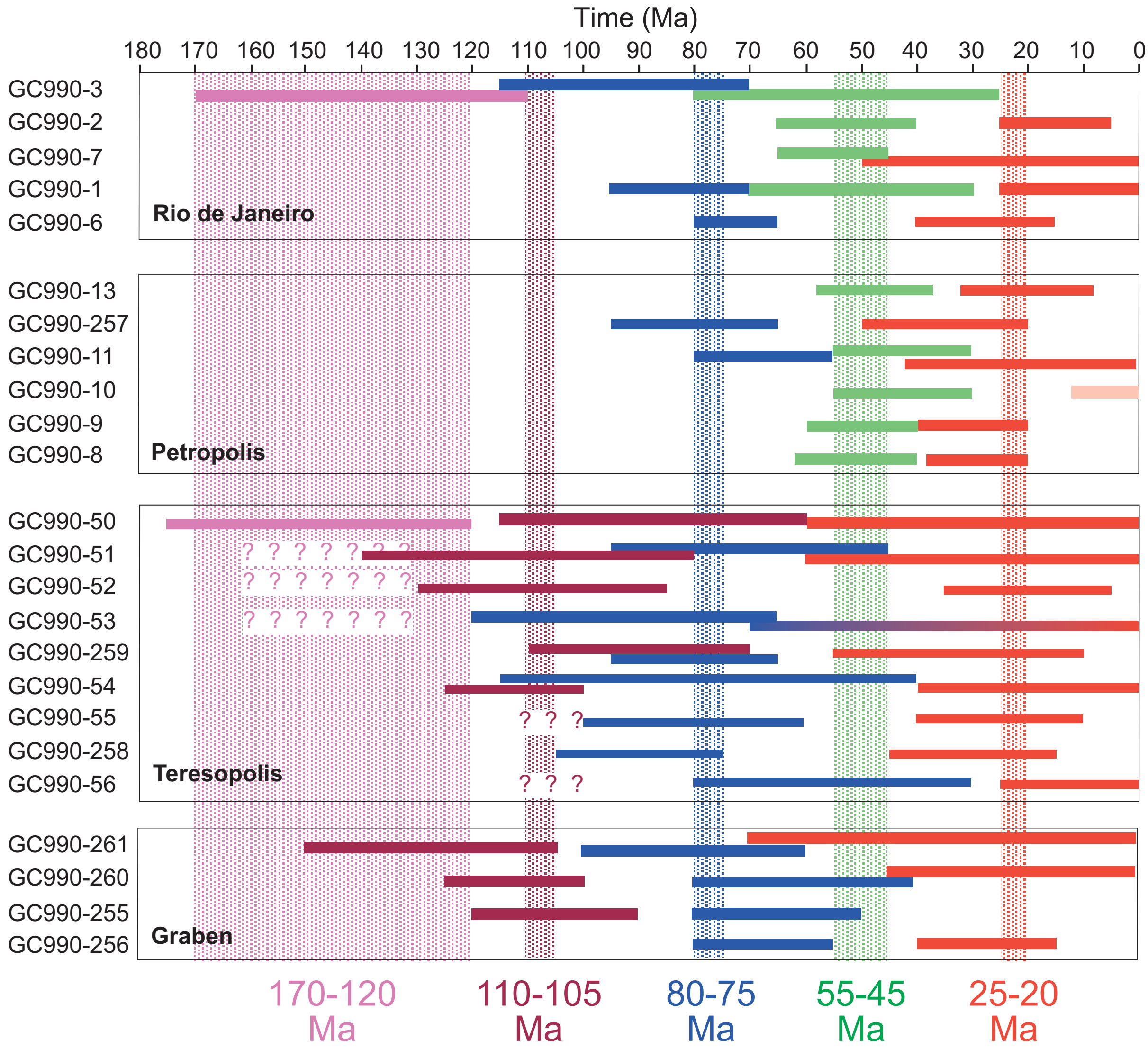


Figure 5-5. *Timing constraints from AFTA data in* ***outcrop samples from the Serra do Mar region****. Samples at each location are plotted in terms of elevation above sea level. If the palaeo-thermal effects identified in the AFTA data from these samples represent syn-chronous cooling episodes, then all results can be explained in terms of five post-depositional cooling episodes, involving cooling which began in the intervals shown at the bottom of the Figure*

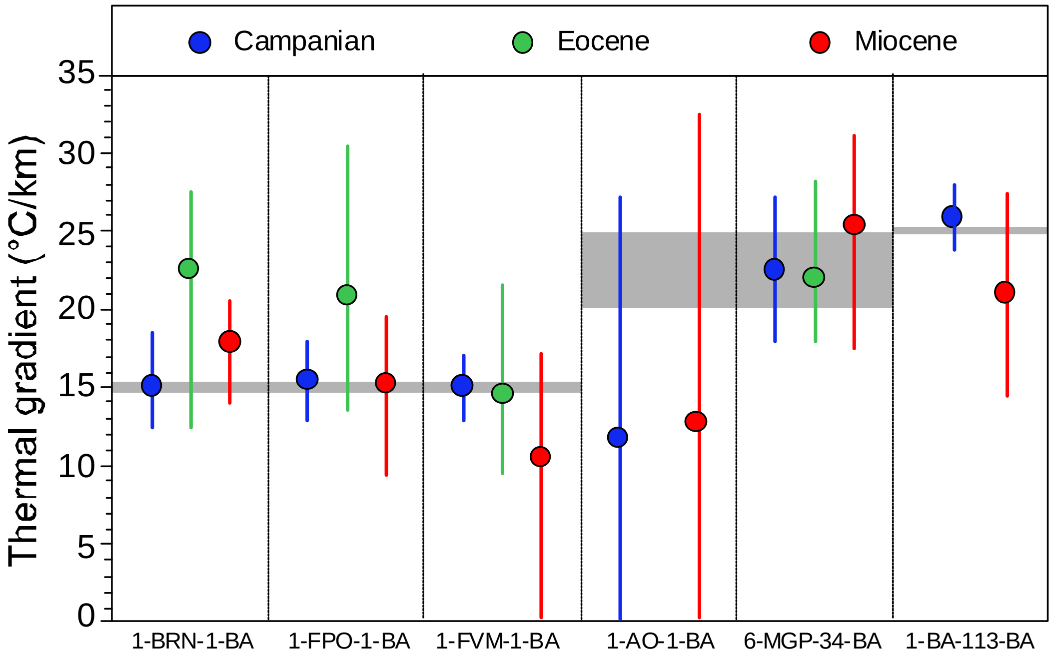


Figure 5-6. *Comparison of present-day thermal gradients (grey shaded boxes) with palaeogeothermal gradients obtained in this study in three episodes from five wells (from Table 13.1), plus constraints on Campanian and Miocene values from the 1-BAS-113 well from Geotrack Report #1013. These results suggest little or no change in basal heat flow over at least the last 80 Myr.*

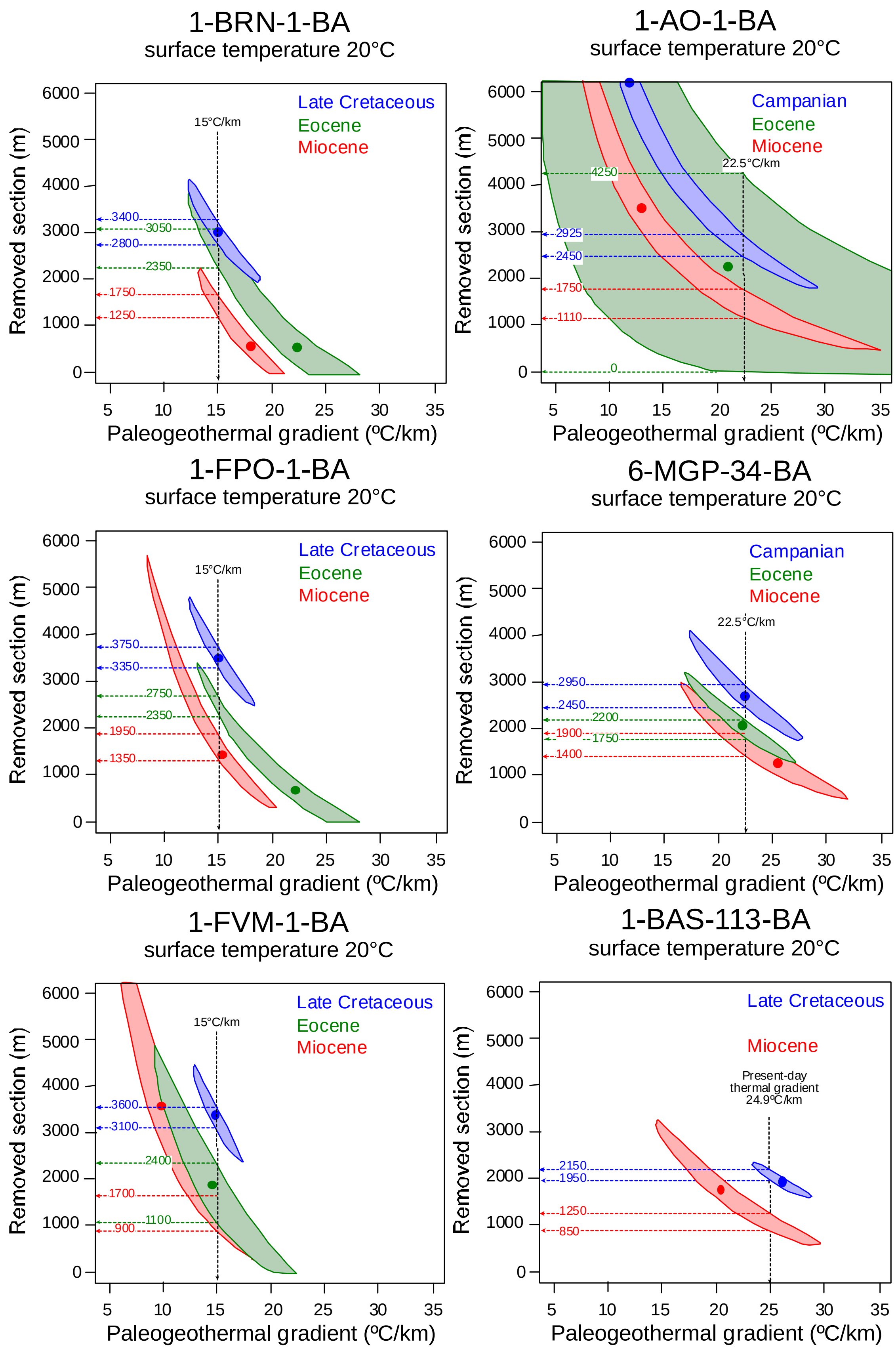


Figure 5-7. *Comparison of constraints on 3 episodes in 6 wells. See text for discussion.*

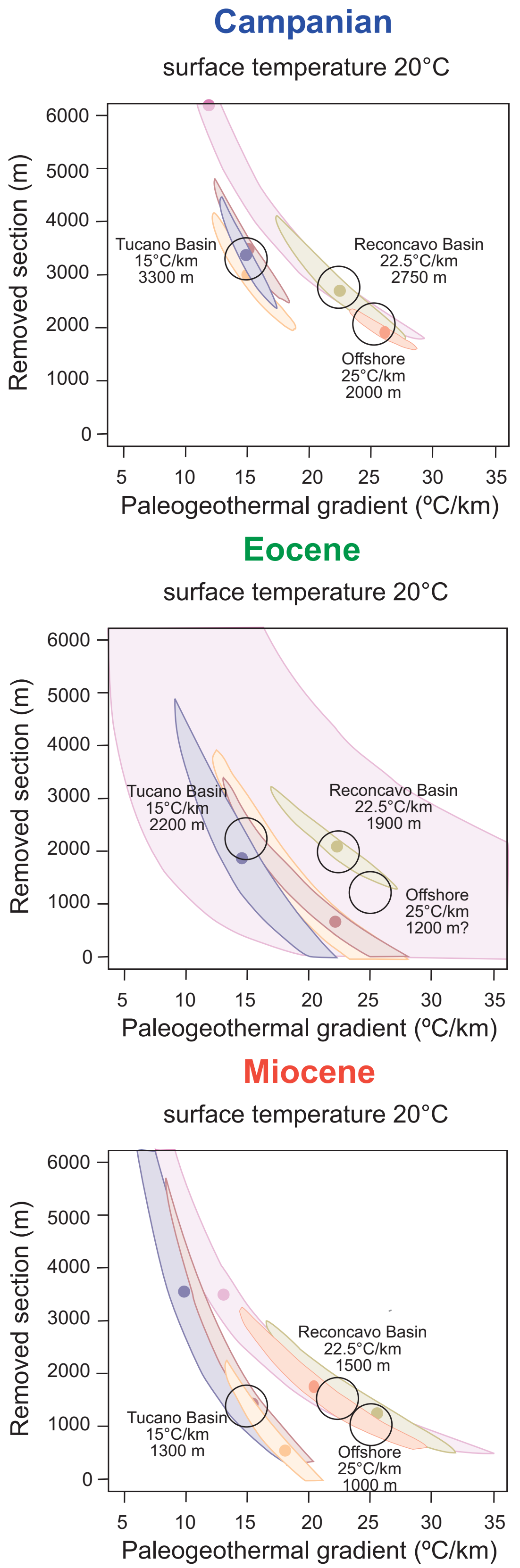


Figure 5-8. *Comparison of constraints on 3 episodes in 6 wells with suggested interpretation showing a regular progression across the area. See text for discussion.*

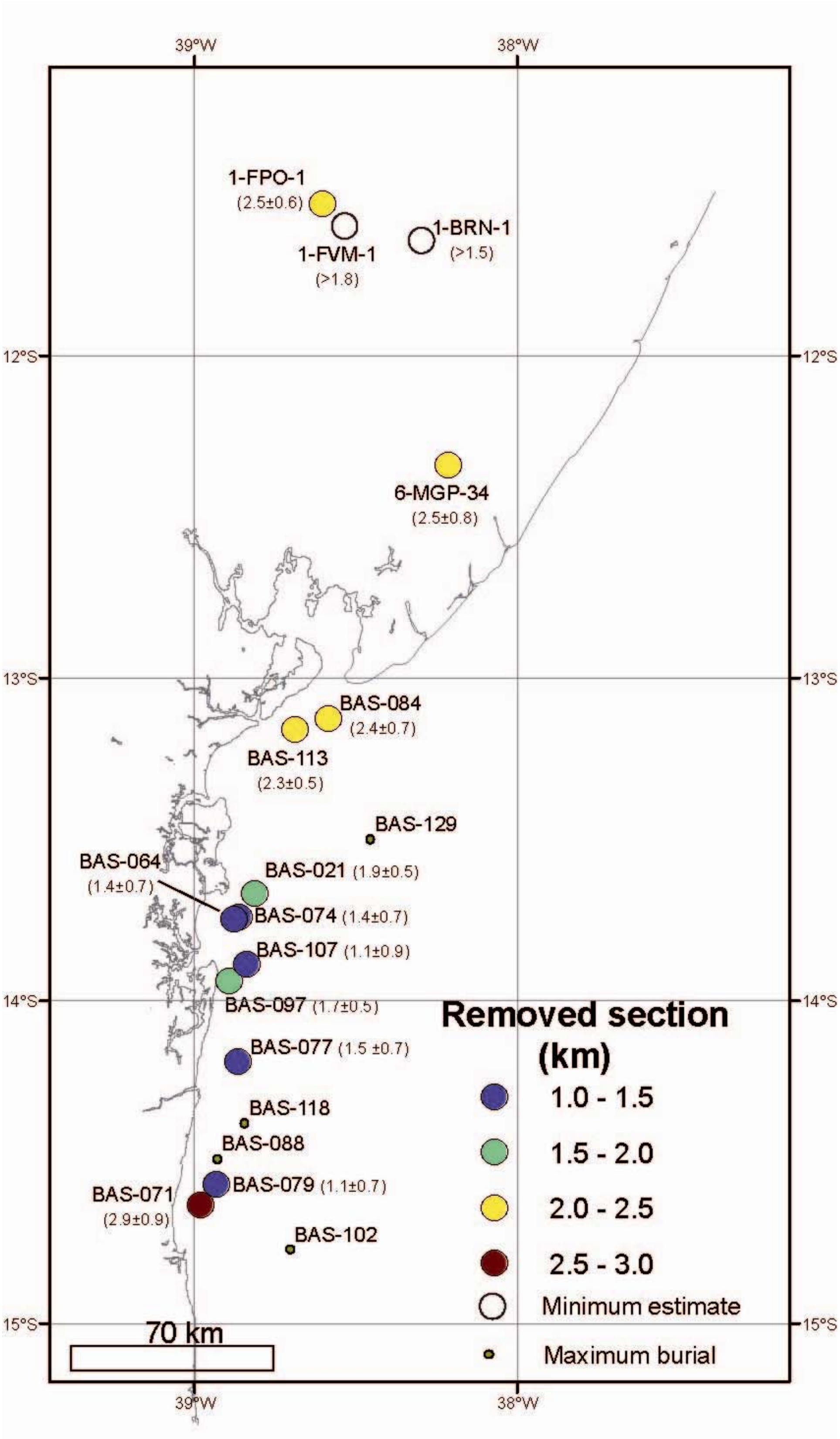


Figure 5-9. *Map of the estimated amount of section removed since maximum burial in the Late Cretaceous based on sonic data in onshore and offshore wells, NE Brazil.*

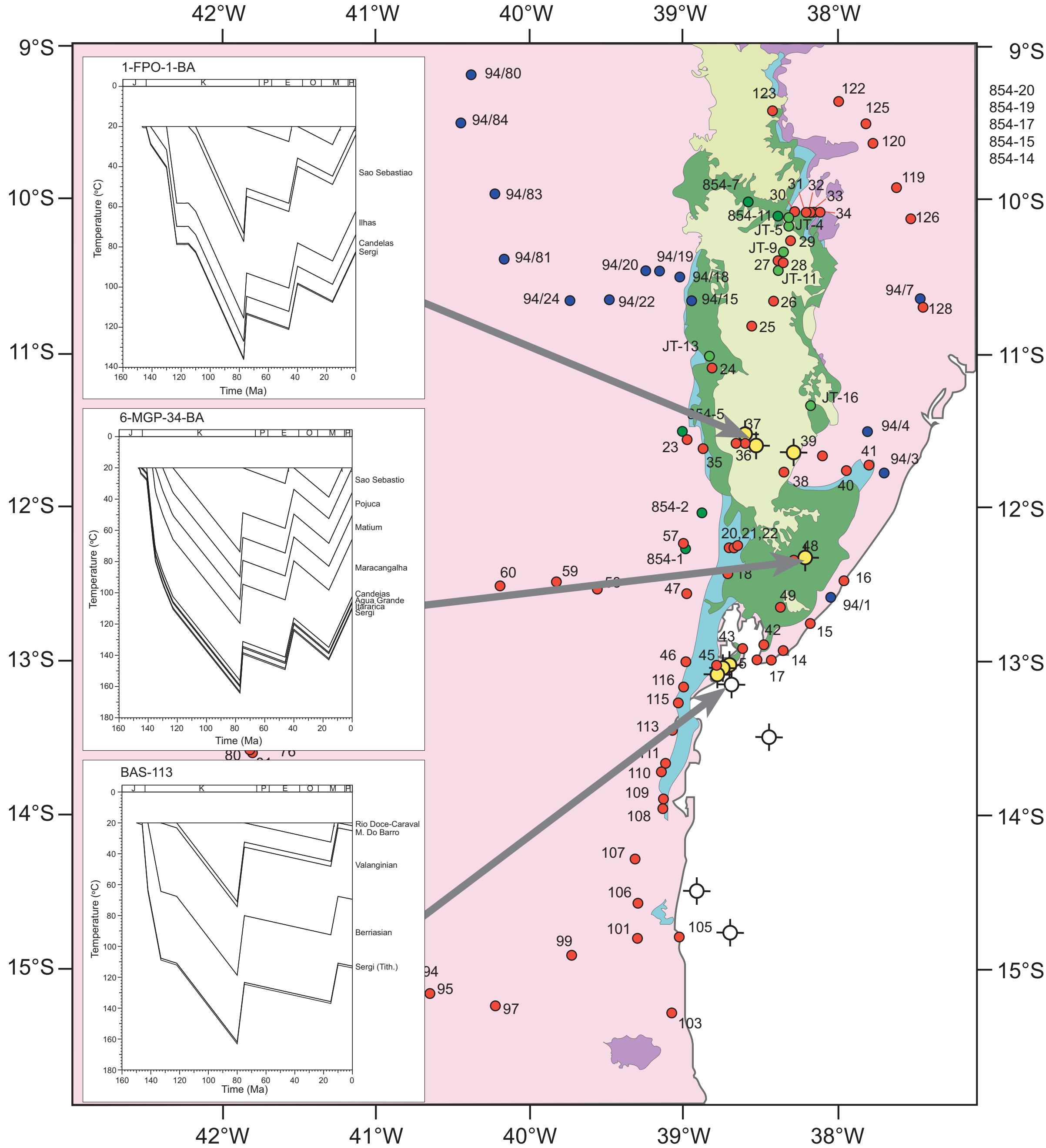


Figure 5-10. : *Reconstructed thermal histories in three representative wells from the Tucano Basin (1-FPO-1), Recôncavo Basin (6-MGP-34) and inshore region (1-BAS-113). These reconstructions are taken from the discussions of the results from each well in Geotrack reports GC990 and GC1013, where full details are provided. While some aspects of these reconstructions remain uncertain, the magnitude of the palaeo-thermal maximum and the subsequent palaeo-thermal peaks are well defined. See text for further details.*

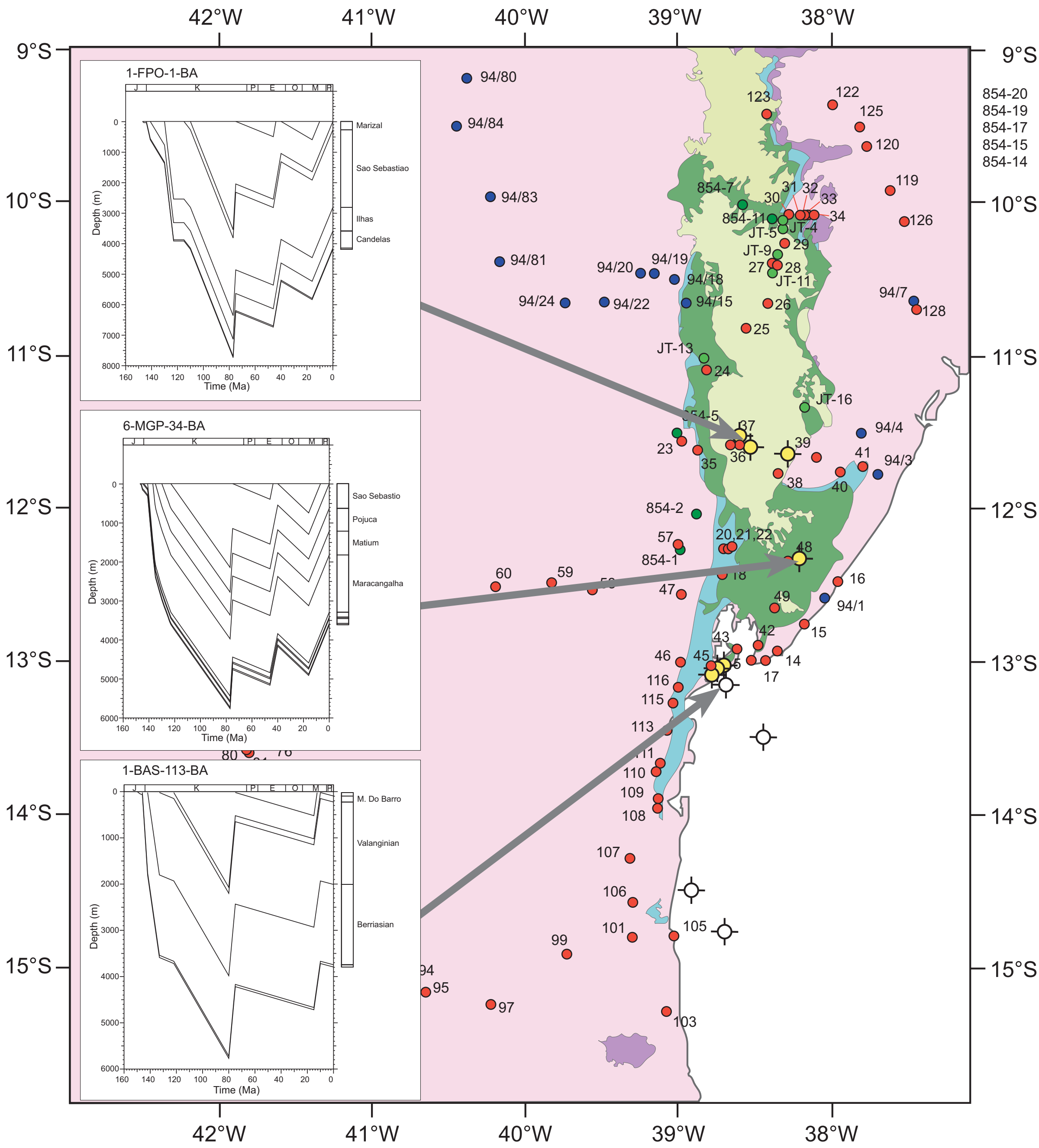


Figure 5-11. *Reconstructed burial - exhumation histories in three representative wells from the Tucano Basin (1-FPO-1), Recôncavo Basin (6-MGP-34) and inshore region (1-BAS-113). These reconstructions are taken from the discussions of the results from each well in Geotrack reports GC990 and GC1013, where full details are provided. It is emphasised that many aspects of these reconstructions are uncertain. See text for further details.*

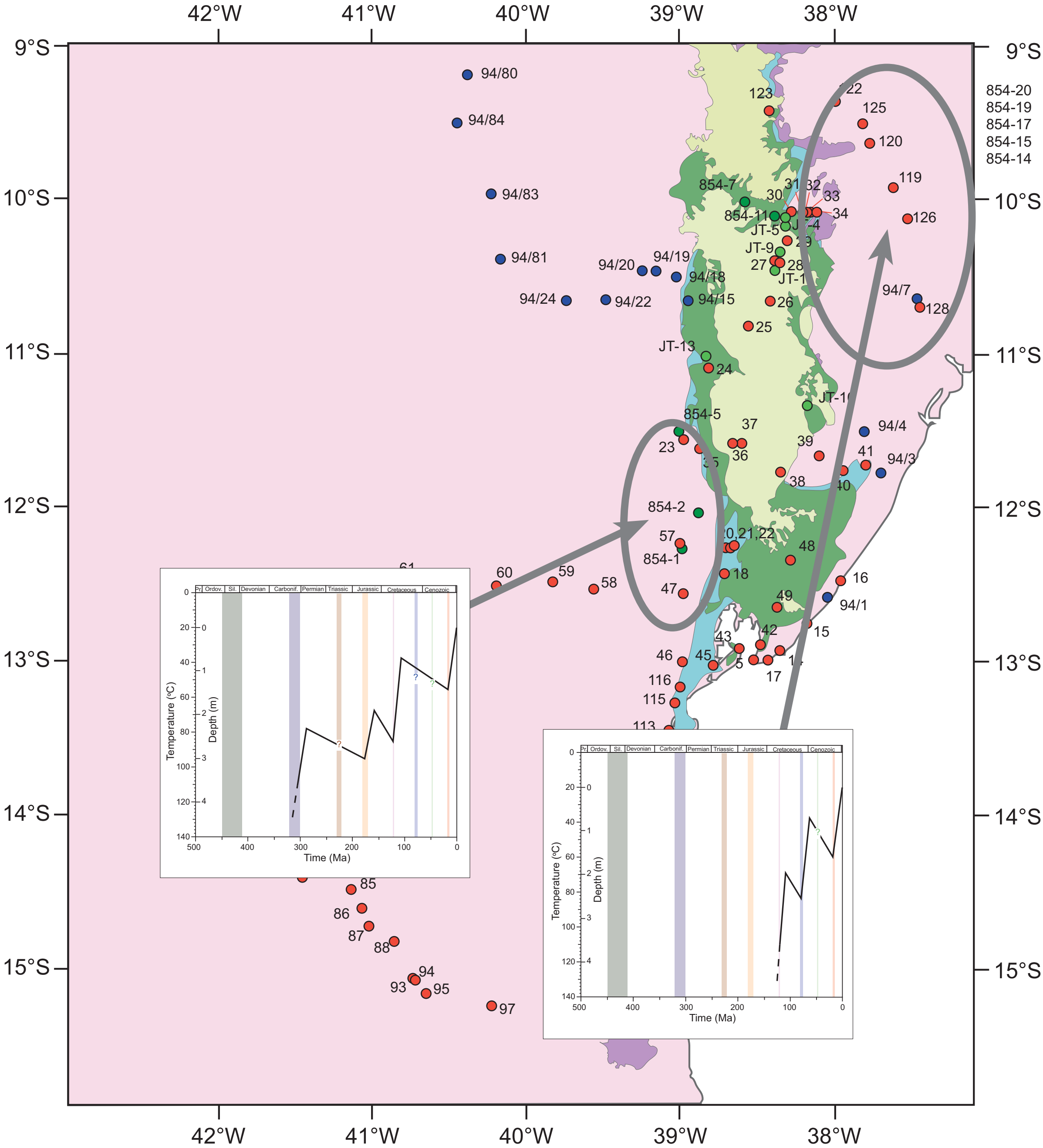


Figure 5-12. *Generalised pattern of thermal histories for outcrop samples in two regions of NE Brazil. Vertical coloured bars denote the timing of major regional cooling episodes identified in this study, from Geotrack Report GC990. The temperature scale is shown with a corresponding depth scale using a thermal gradient of 25°C/km for basement areas although this is speculative, particularly given the present-day thermal gradients of 15°C/km in the Tucano Basin (see text). Histories of individual samples within each are will differ due to differences in elevation, but the histories shown here provide a schematic representation of the variation in thermal history styles across the area. Note the difference in the histories between the two areas shown here, with much earlier cooling below 110°C in the west.*

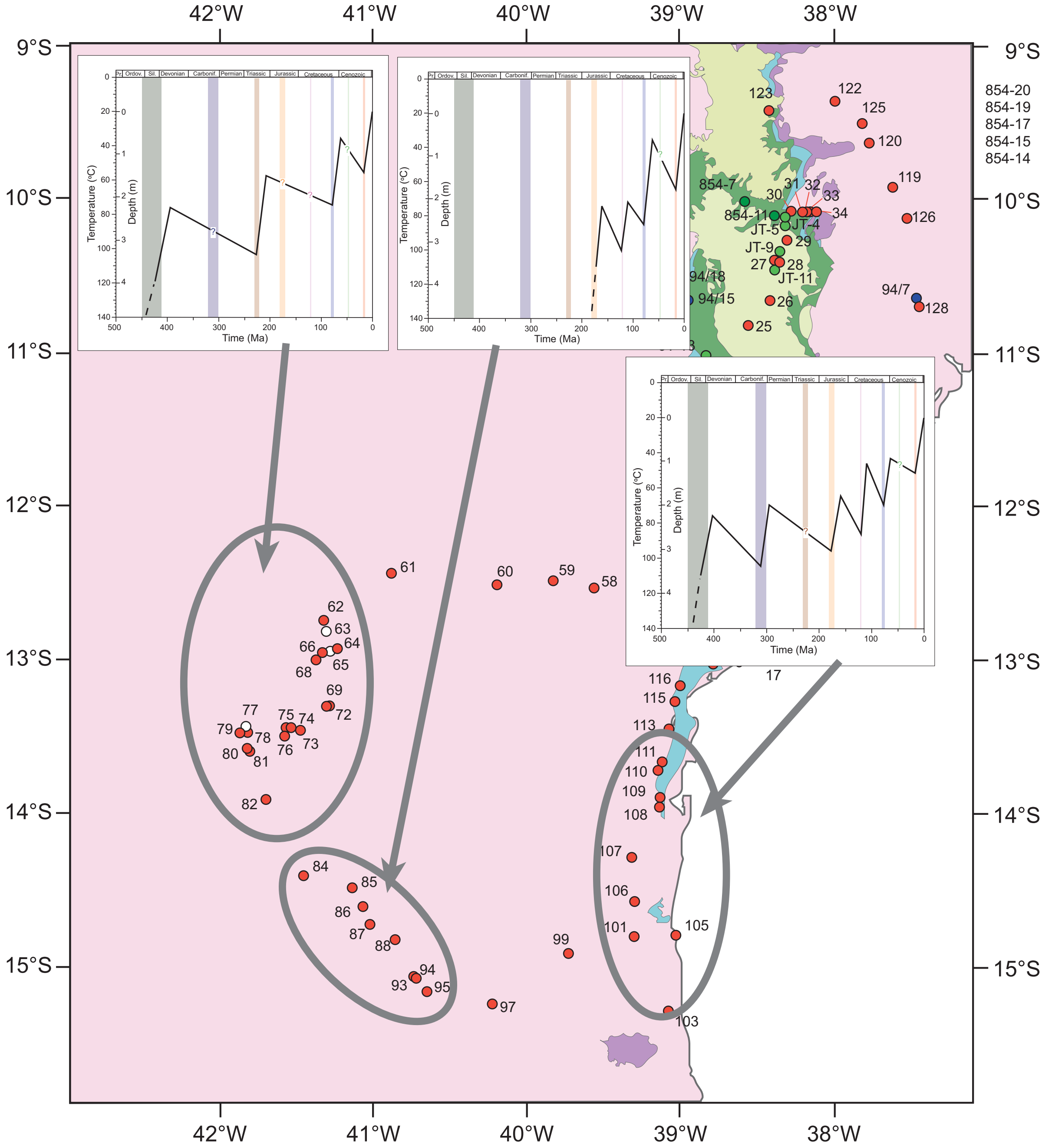


Figure 5-13. *Generalised pattern of thermal histories for outcrop samples in three more regions of NE Brazil. Vertical coloured bars again denote the timing of major regional cooling episodes identified in this study, from Geotrack Report GC990. The temperature scale is shown with a corresponding depth scale using a thermal gradient of 25°C/km for all three basement terrains. Histories of individual samples within each are will differ due to differences in elevation, but the histories shown here provide a schematic representation of the variation in thermal history styles across the area. Note the dominance of Jurassic cooling in the region in the southwest (samples 84 to 95), whereas samples in the other two areas cooled below 110°C in earlier episodes.*

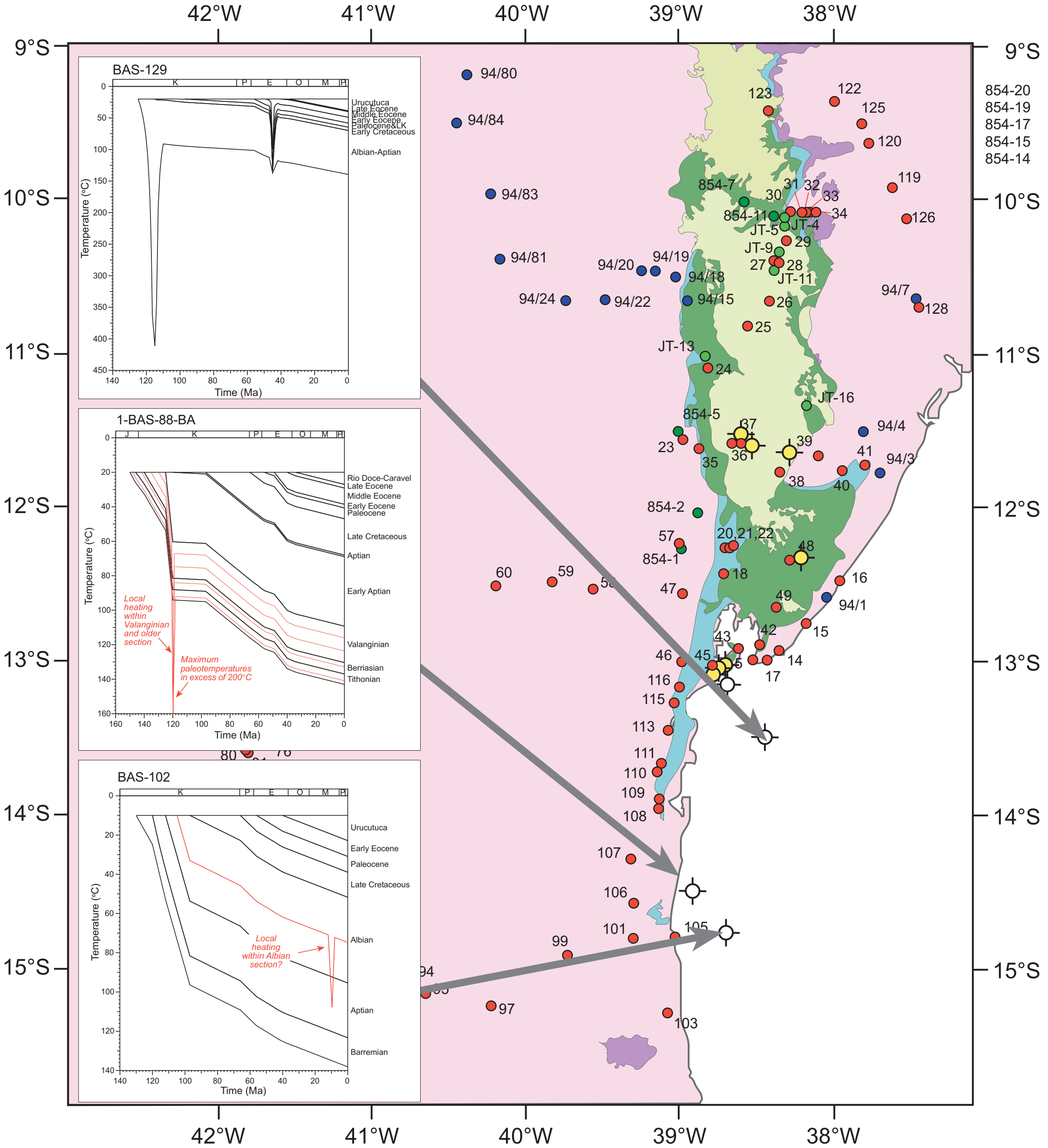


Figure 5-14. *Reconstructed thermal histories in three offshore wells, taken from the discussions of the results from each well in Geotrack Report GC1013, where full details are provided. While some aspects of these reconstructions remain uncertain, the magnitude of the palaeo-thermal maximum and the subsequent palaeo-thermal peaks are well defined. See text for further details.*

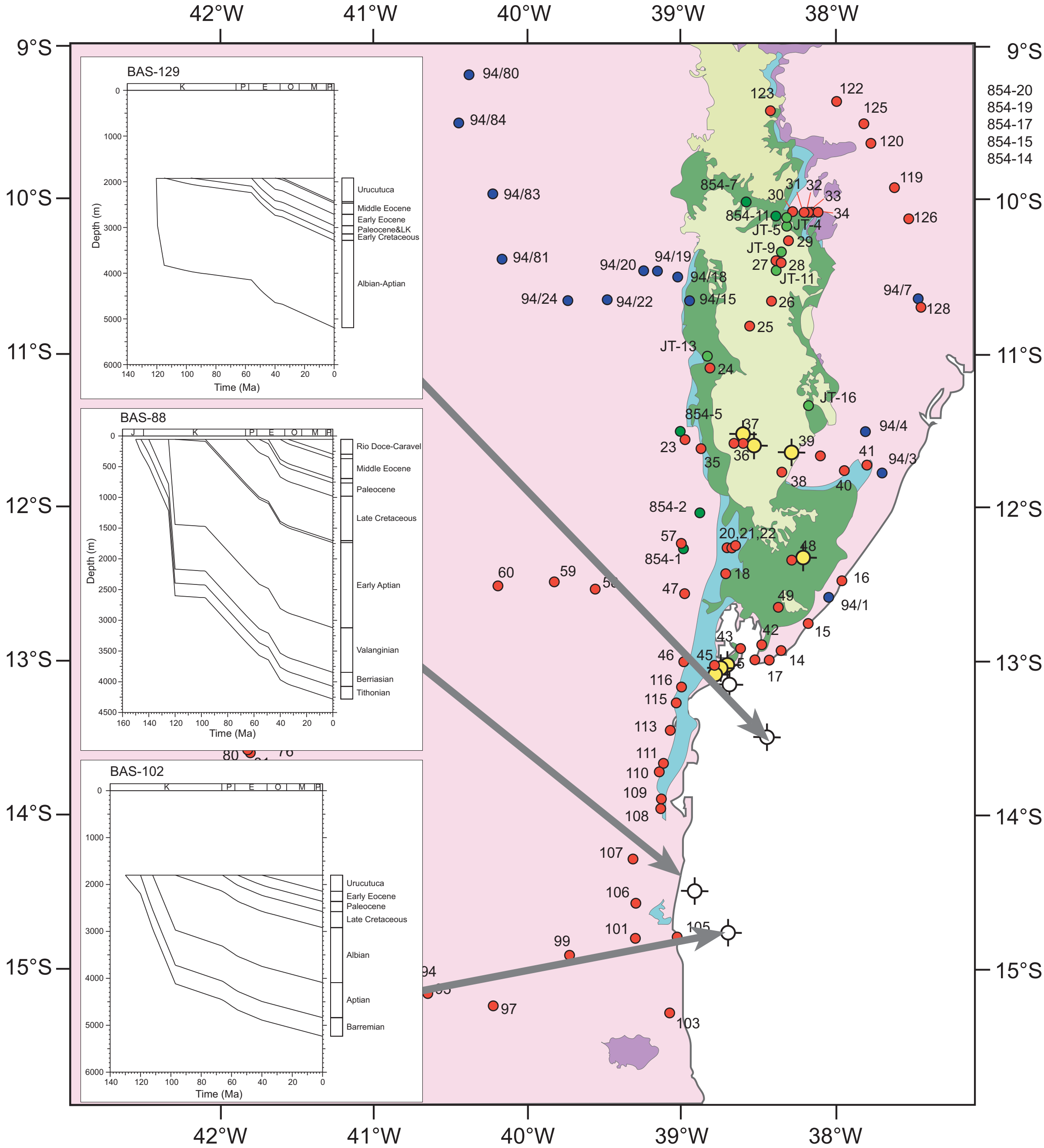


Figure 5-15. *Reconstructed burial histories in three offshore wells, taken from the discussions of the results from each well in Geotrack Report GC1013, where full details are provided. In all three wells, AFTA and VR data suggest that all sedimentary units are currently at their maximum burial depths. See text for further details.*

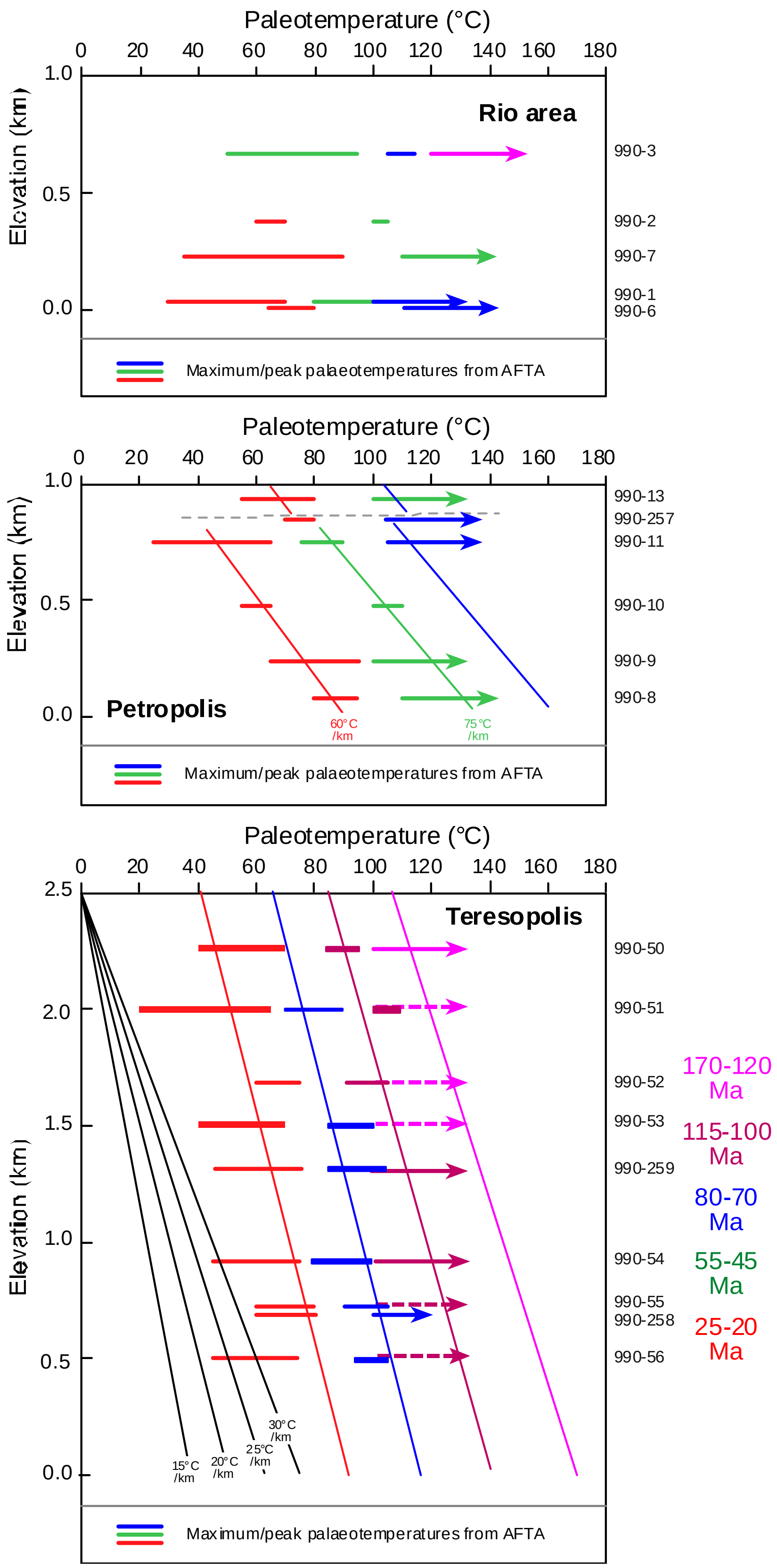


Figure 5.16. *Palaeotemperatures derived from AFTA for samples from the Serra do Mar region (Figure 15.2) plotted against elevation (a.s.l.). Profiles are drawn for illustration only. See text for discussion.*

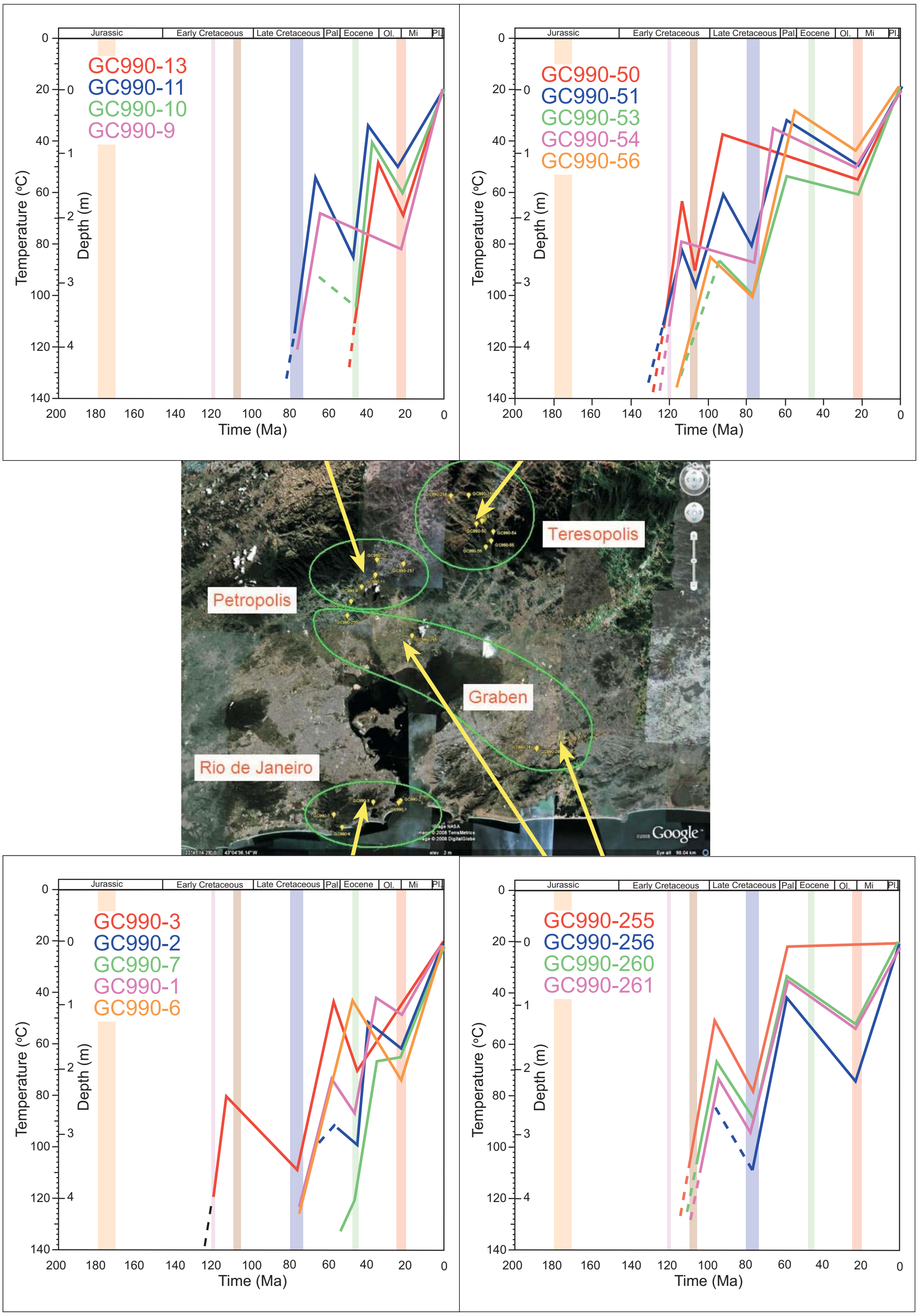


Figure 5-17. *Generalised pattern of thermal histories derived from AFTA data in selected outcrop samples from the Serra do Mar. Vertical coloured bars again denote the timing of major regional cooling episodes identified in this study, from Geotrack Report GC990. The temperature scale is shown with a corresponding depth scale using a thermal gradient of 25°C/km, although this remains uncertain. Sample numbers are arranged in order of elevation (a.s.l.). Note the lack of coherent variation with sample elevation within each region.*

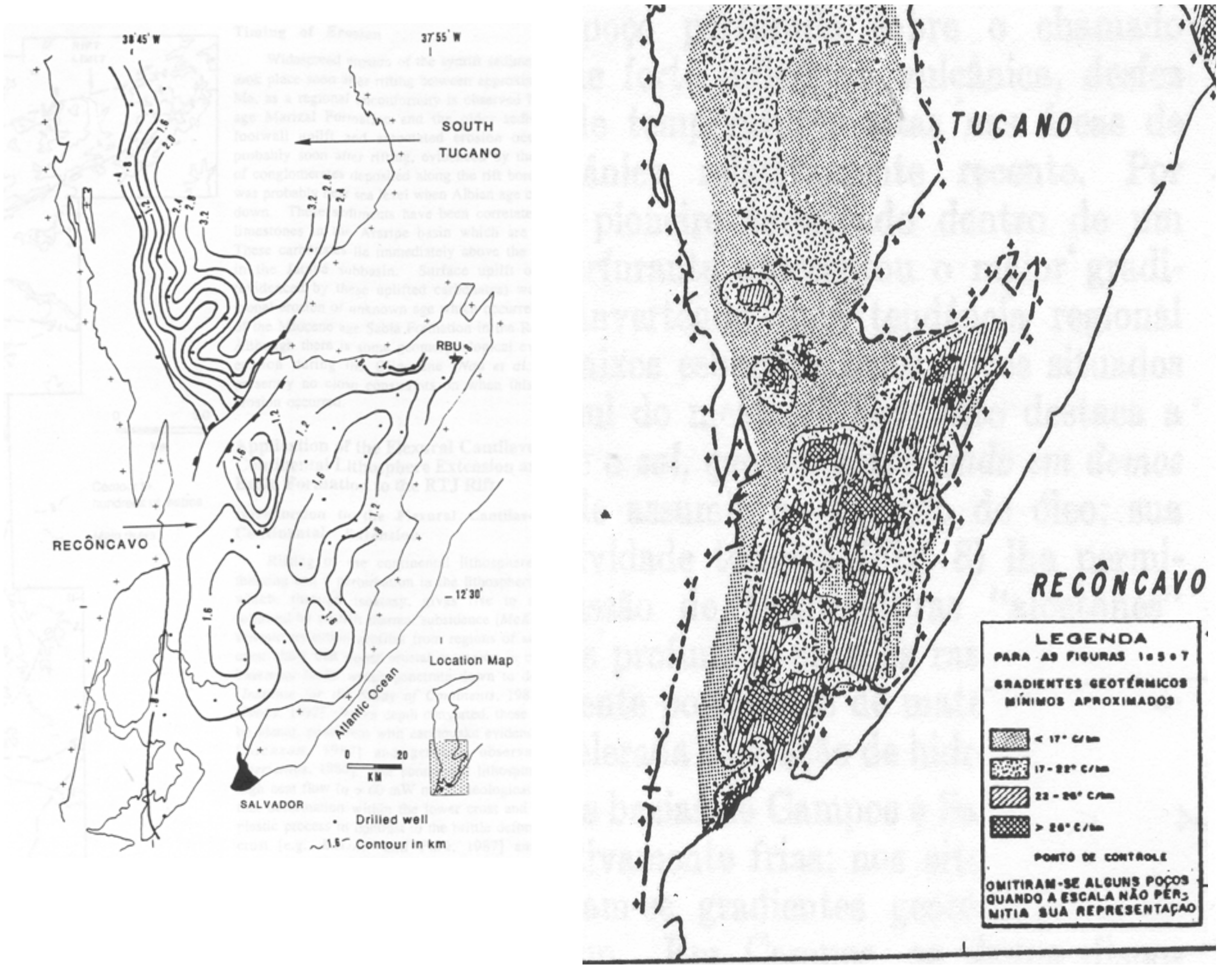


Figure 5-18. *Comparison of depth to top of oil window Recôncavo and South Tucano basins (left) from Magnavita et al. (1994) and thermal gradients across the same area from Meister (1973). The close similarity between the two maps emphasises the primary control of maturity exerted by thermal gradients across this region, with generally similar amounts of exhumation across the whole region.*

6. Integration of burial and exhumation history with denudation chronology and the stratigraphic record

6.1 Comparison of onshore and offshore records

6.1.1 Correlation between offshore unconformities and cooling events from AFTA data

The sedimentary deposits of the Almada and Camamu Basins records almost 150 Myr of geological development including several pronounced unconformities, and deposits may thus serve as a mirror image of what happened onshore. Three of the major offshore unconformities correlate closely with the events of cooling and exhumation established from the AFTA data onshore and in the inshore Camamu well 1-BAS-113. The correlation is best for the Almada Basin, probably because the sedimentary succession in the Camamu Basin is strongly affected by major land slides (see Section 3.2). The stratigraphic chart for the Almada Basin (Gontijo et al. 2007; see Appendix A) indicates

- an mid-Campanian unconformity between 80 and 75 Ma, exactly the interval for the onset of cooling from the AFTA data.
- a mid-Eocene unconformity between 47 and 45 Ma corresponding to the onset of cooling from the AFTA data between 48 and 45 Ma, and
- a mid-Miocene unconformity between 16 and 12 Ma which is slightly shifted relative to the onset of cooling from the AFTA data between 18 and 15 Ma. There is overlap between these intervals, but the slightly younger timing from biostratigraphic data may also reflect limited coverage of Neogene samples.

6.1.2 The cover eroded during the Campanian event

A section of up to 2 km was removed at the Campanian unconformity along the south-western margin of the Camamu Basin based on sonic data from a number of wells (see Section 5.2). The unconformity is above the Albian–Cenomanian Algodões Fm (c. 400 m preserved) and below the preserved parts of the Urucutuca Fm which is not older than Campanian in this area. The section removed was thus partly a Turonian–mid-Campanian sequence in the lower part of the Urucutuca Fm (probably c. 1 km prior to exhumation) and partly an upper part of the Algodões Fm. In the Recôncavo-Tucano Basins, the Aptian Marizal Fm was buried below a cover of 2.5–3 km prior to the Campanian event. This section corresponds to the accumulated thicknesses of an upper part of the Aptian Marizal Fm (equivalent to the uppermost parts of the Taipus-Mirim Fm), an Albian–Cenomanian sequence (equivalent to the Algodões Fm) and a Turonian–mid-Campanian sequence (equivalent to the Urucutuca Fm below the mid-Campanian unconformity).

The highlands in the interior of the study area, Chapada Diamantina and Planalto de Conquista, were buried below a rock column that can loosely be estimated to 2 km based on the AFTA data (see Section 5.1.5). Since a palaeothermal event recorded by the AFTA data represents a heating followed by cooling, it is likely that sediments were deposited over these areas prior to the Campanian cooling event. This interpretation seems geological plausible because the highlands are situated about mid-way between the Cretaceous deposits in the rifts along the margin and the extensive Cretaceous cover in the Sanfranciscana Basin in western Bahia (Figs 3-4, 3-5). Post-rift sediments *sensu strictu* were probably only deposited in some distance from the rift, and the distance between Chapada Diamantina and the rift system is considerable (c. 250 km) compared to the width of the onshore rift (c. 100 km). Note that the age of the Upper Cretaceous sediments in the Sanfranciscana Basin spans the entire Late Cretaceous (Campos & Dardenne 1997a, b), and that this area thus was unaffected by exhumation during the Campanian.

6.1.3 The cover eroded during the Eocene and Miocene events

The magnitude of the Eocene exhumation was limited in the inshore parts of the Almada and SW Camamu Basins, where Palaeocene–Oligocene and possibly Campanian strata are preserved above the main unconformity and the Palaeogene section is almost at seabed; e.g. wells 1-BAS-77, -79 and -107 (Fig. 5-9). The Mesozoic sediments are not at maximum burial in these wells according to the analysis of the sonic data (Table 5-2), but the sonic data do not allow us to discriminate whether this is the case for the Palaeogene sediments. The shallow burial of the Palaeogene succession indicates that it could have been buried below a section that is now removed. If this is the case, the burial probably continued into the Neogene when both onshore and inshore areas were affected by Miocene exhumation as documented by the AFTA data (e.g. 1-BAS-113; Geotrack onshore and offshore reports 990, 1013). The magnitude of any Eocene exhumation (as identified in AFTA data in samples from deep wells in the Recôncavo-Tucano Basins) was not sufficient to remove the Palaeocene strata in these wells. Likely implications of these observations are thus

- that the exhumation following the Cenomanian event was completed during the Late Cretaceous along the western margins of the Almada and Camamu Basins, both onshore and offshore;
- that Palaeogene burial took place in the Almada and Camamu Basins, both onshore and offshore and that the palaeothermal peak at c. 16 Ma identified in AFTA data in outcrop samples along the coast represents maximum Cenozoic burial prior to Miocene exhumation (see Fig. 5-4).

However, in the Recôncavo Basin any Palaeogene deposits were removed prior to the Neogene (probably by Eocene exhumation) because the Lower Miocene Sabiá Fm rests on Early Cretaceous rift sediments in this area (Petri 1972).

The mid-Eocene unconformity is however, prominent in most of the Almada and Camamu Basins and the e.g. in well 1-BAS-129, Eocene strata overlies the large slide that formed between Late Cretaceous and mid Eocene times (Cobbold 2008a, b). A possible inference from the results presented here is thus that a major part of the sliding was initiated by the Eocene uplift event that affected the Recôncavo and southern Tucano Basins. Significant uplift onshore may have caused tilting of the margin and thus provoked mass failure. It is interesting that there are no major slides in the Almada Basin where much of the Palaeogene succession is preserved along the western margin of the basin and thus indicating that Eocene uplift and exhumation had limited effect.

6.2 Neogene uplift of Serra do Mar constrained by AFTA data

As discussed in Section 5.3.5, AFTA data from the Serra do Mar reveal a series of cooling episodes which are interpreted as representing a progressive history of exhumation, with dominant episodes in the Albian, Campanian, Eocene and Miocene. While exact amounts of exhumation in each episode are not clear, for any realistic value of thermal gradient (say 20 to 50°C/km), at least 2 km of section, and possibly much more, must have been removed from the sampled sections since the Albian.

Most importantly, samples close to the planation surface at high elevations in the Serra do Mar today were at palaeotemperatures around 60°C or more in the Miocene, suggesting that they were buried by possibly 1 km or more of section prior to the commencement of the Miocene cooling episode. Since these samples are at lesser depths from the planation surface today, this shows that rocks now at the level of the planation surface must have been themselves buried by hundreds of metres of section when Miocene exhumation began. This, in turn shows that the planation surfaces are very recent features or are very recently reexposed, in either way produced or reproduced as a result of the Miocene phase of exhumation – i.e. they are post-Miocene surfaces or are older surfaces that have been brought back to the surface by Miocene exhumation.

This has a further corollary that the present-day topography must post-date the onset of Miocene exhumation. If we take the timing of 25 to 20 Ma derived from AFTA data alone, this implies that uplift of the mountains is Miocene or younger (and if we extend the timing from the entire study of 18 to 15 Ma to the Serra do Mar, then uplift of the mountains must be post-15 Ma or post-Middle Miocene).

This description is highly consistent with the section through the Serra do Mar drawn by Zalan and Oliveira (2005), as shown in Figure 3-15, with the southern face of the Serra do Mar representing an uplifted fault Scarp. In this Figure the red line represents the planation surface created by Miocene exhumation, as described above. This Figure also highlights the presence of numerous lineaments that could represent faults capable of explaining the tectonic offsets inferred from the palaeotemperature-elevation profiles in this region.

The history outlined here is also highly consistent with the tectonic evolution of the region summarised in Section 3.3 and outlined in more detail by Cobbold et al. (2001), involving three phases of post-rift tectonic reactivation in Late Cretaceous, Eocene and Miocene times. The consistency between this description, based purely on geological evidence, and the thermal and exhumation history framework derived from AFTA data in this study provides strong support for the conclusions reached in this section. Note also the reference to “recent block faulting following peneplanation” from Section 3.3, which also supports the interpretations presented here.

Integrating the AFTA data with this geological evidence shows that the episode of tectonism expressed by the present-day landscape in this region is simply the most recent in a long series of tectonic episodes.

6.3 Integration of landscape studies and exhumation histories across Brazil

6.3.1 Fundamental observations and outstanding questions

The Brazilian landscapes have often been looked upon as a result of uplift related to the break-up of the Gondwana (e.g. Zonneveld 1993; Ab'Sáber 2000 and references therein). We challenge this view and present observations to support that the present landscape mainly reflects periods of burial, uplift and erosion during the Cenozoic.

Prior to the Campanian uplift event, the present land surface was buried below a 2 to 3 km thick rock column that most likely included a continuous cover of Cretaceous sediments as we have argued in the preceding Chapter. A simple, but important implication of this result is that the present landscape was shaped during the Cenozoic and thus long after rifting.

The geomorphological analysis has also demonstrated that the landscape is young (Chapter 4). The analysis has identified two Cenozoic peneplains, the higher and the lower surface (HS and LS), and has led to the conclusion that these surfaces were formed by incision along major rivers and thus that their formation was governed by erosion relative to a general base level. The lower surface developed subsequent to uplift of the higher surface. To narrow down when these peneplains formed during the Cenozoic we must constrain the model by available geological data about when the peneplains may have been exposed at the surface of the earth. In particular, as there are no dated Cenozoic deposits on the plateaux within the study area, we will include observations from similar plateaux in Borborema and Minas Gerais, north and south of the study area (cf. Fig. 3-6). Below we summarize the observations presented in the previous chapters that may constrain the age for the formation of the higher and the lower surface.

The main question for understanding the landscape development in eastern Brazil, is to estimate the age for the formation of the higher surface and in particular to find out if it was formed before or after the Miocene cooling event that started between 18 and 15 Ma prior to which, AFTA data from vertical profiles in the interior show that the plateau areas were buried below a rock column of several hundred metres. If the higher surface is Palaeogene in age and thus existed prior to the Miocene event, then the cover must have been Cenozoic sediments; if the surface was not formed until Neogene times, after the Miocene event, then the cover may have been early Miocene and older rocks, including Precambrian basement. At the end of this Section we summarize the implications of geological models with and without Miocene reburial of the higher surface, alternatives A and B, respectively (Figs 6-1, 6-2).

6.3.2 Constraints within the study area in eastern Bahia

Cenozoic sediments

- Lower Miocene Sabiá Fm (marine) (Viana et al. 1971; Petri 1972). Within the Recôncavo Basin and near well 6-MGP-34; Fig. 3-7. Marine transgression at the Oligocene-Miocene transition is known from several locations along the coasts of South America (Schobbenhaus & Brito Neves 2007).
- Neogene Barreiras Fm (continental) along the coast, but also into the south-western part of the Tucano Basin and the basement areas west of the rift; Figs 3-2, 3-7. Pliocene (Fig. A-1, Silva et al. 2007). According to Arai (2006) the Barreiras Fm can be subdivided into an upper and a lower unit, of mainly Middle Miocene and Pliocene age, respectively.
- Palaeogene sediments at seabed along the western margins of the Almada and Camamu Basins above a rift section that was more deeply buried prior to the Campanian event (e.g. 1-BAS-77; see Fig. 5-9). In these inshore areas the Late Cretaceous exhumation was completed prior to the Palaeocene.

Cenozoic weathering history

- Cenozoic laterites are preserved below the HS in Chapada Diamantina and Planalto de Conquista according to geological map of Bahia; Fig. 3-2 (CPRM 2001, 2003).

Regional planation surfaces

- The higher surface (HS) cuts across Precambrian rocks that are deeply weathered and includes Cenozoic laterites over extensive areas (CPRM 2001, 2003), thus constraining its final formation age to the Cenozoic The HS is tilted towards the southeast.
- The LS was formed at the expense of the HS by erosion along major rivers after an event that lifted the HS by 500-700 m.
- The lower surface (LS) cuts across Precambrian basement and Lower Cretaceous sediments in the RTJ Rift. The Sabiá outlier is found in trenches below the level of the LS.
- The Barreiras Fm is most likely deposited on the LS, but not on the HS.
- The LS is tilted towards the east and the LS is currently being destructed by incision along major rivers after an event that lifted both the LS and HS by some hundred metres in the interior. This process lead to the formation of a coastal plain by incision below the LS. The LS was deformed during the latest Cenozoic along km-scale compressive structures within the RTJ Rift (Fig. 3-7).

Cenozoic burial and exhumation history

- Exhumation after the Campanian event as documented from AFTA data in outcrop and well samples across the entire study onshore area and the inshore 1-BAS113 well; supported by sonic data in wells along most of the western margin of the Almada and Camamu Basins. Greater depth of burial in the onshore areas 2–3.5 km. Age of removed section within the RTJ Rift was Aptian to Campanian; the section removed over the interior highlands was partly Cretaceous sediments (cf. Fig. 3-4).

- Exhumation after the Eocene event as documented from AFTA in deep wells in the RTJ Rift. Greater depth of burial c. 2 km.
- Exhumation after the Miocene event as documented from AFTA data from outcrop and well samples across the entire onshore study area including the highlands, the RTJ Rift and the inshore 1-BAS113 well. Greater depth of burial in the RTJ Rift 1-1.5 km. Miocene palaeotemperatures in the highlands and along the scarps separating the HS from the LS may be explained by a several hundred metres thick cover above the HS. This indicates the presence of a continuous cover across the plateaux (extending across the RTJ Rift) prior to Miocene cooling.

6.3.3 Constraints from outside the study area

No mapping have been undertaken within this project to document that the plateaux north and south of the study area correlate with the higher surface in the study area. The plateaus in all three areas, do however, share the same characteristics such as elevation and escarpments between a higher and a lower regional surface (cf. Figs 3-8, 3-9). Furthermore, plateaux across north-east Brazil are characterized by lateritic covers with thick weathering profiles (e.g. CPRM 2001, 2003).

Constraints from the plateaus in western Bahia (Sanfranciscana Basin)

Upper Cretaceous sediments and planation surfaces (up to 1 km a.s.l.)

- A regional planation surface cuts across Maastrichtian and older sandstone; Figs 3-4, 3-5 (Campos & Dardenne 1997a, b). This surface most likely correlates with the HS further east.
- Late Cenozoic Chapadâo Fm, '*coberturas eluvionares*' found above 800 m a.s.l. on extensive plateaux ('*chapadas*') (Campos & Dardenne 1997a, b).

Constraints from the Borborema Plateau north-east of the study area

Cenozoic sediments in plateau areas (up to 1 km a.s.l.)

- Palaeogene Serra do Martins Fm (64-25 Ma), continuous cover on plateaux; Fig. 3-9 (Morais Neto 2008a).

Cenozoic weathering history in plateau areas

- C. 28 Ma, peak of weathering ages (Guia Lima 2008).
- 28–15 Ma, gap in the weathering ages (Guia Lima 2008). Due to erosion (cf. Vasconcelos & Carmo 2008) or due to protective cover in late Oligocene to mid-Miocene times?

Cenozoic burial and exhumation history

- Post-30 Ma, post-depositional heating of Serra do Martins Fm to above 60°C (Morais Neto 2008a). This thermal history represents a continuation of the results from the highlands within the study area.

Constraints from Chapada do Araripe north of the study area

Upper Cretaceous sediments in plateau areas (up to 1 km a.s.l.)

- Albian–Cenomanian Exu Fm (post-rift sequence) constitutes the main stratigraphic unit below the plateau surface

Cenozoic burial and exhumation history

- two main episodes of cooling estimated from AFTA data, one in the Late Cretaceous and one after 40 Ma; caused by regional exhumation that also affected the plateau surface (Morais Neto et al. 2006).

Constraints from the plateau areas in Minas Gerais south of the study area

Cenozoic sediments on the plateau areas near Belo Horizonte (c. 900 m a.s.l.)

- Eocene Fonseca Fm in downfaulted position below the Chapada de Canga Fm; Fig. 3-8 (Sant'Anna et al. 1997).
- post-Eocene Chapada de Canga Fm, continuous cover on plateaus.

Cenozoic weathering history

- 50 to 40 Ma (Eocene), peak of weathering ages (Spiers et al. 2006).
- 30–15 Ma, gap in weathering ages (Vasconcelos & Carmo 2008). Due to erosion or due to protective cover in late Oligocene to mid-Miocene times?

Cenozoic burial and exhumation history

- 90–95°C during the Campanian event (within 170-65 Ma range), sample GC990-4, Diamantina, located c. 250 km north of Belo Horizonte.
- 50-70°C post-30 Ma, sample GC990-4. This thermal history represents a continuation of the results from the highlands within the study area.

Constraints from Serra do Mar, south-east Brazil

Cenozoic sediments

- Palaeocene to Miocene deposits in the Continental Rift of South East Brazil including the Itaboraí and Taubaté Basins; see Figs 3-17, -18 (e.g. Riccomini et al. 2008).

Cenozoic burial and exhumation history

- Exhumation after the Eocene event documented from AFTA data across the area – apart from the Teresopolis profile; Figs 5-15 and 5-16.
- Exhumation after the Miocene event documented from AFTA data over the entire area – apart from one sample at the graben floor (GC990-255).
- Tectonic exhumation after the Miocene event due to block uplift along major faults separating the mountains from the graben. A cover of c. 1 km removed from above the summits, but the present graben floor is close to the surface that was dissected and uplifted during the Miocene event. Hardly any scarp retreat since uplift because the main rivers are draining along the back side of the mountains. This interpretation explains that the draining system was changed at the beginning of the Miocene as suggested by Cobbold et al. (2001) based on an almost identical model for this area (see Section 3.3).

6.3.4 Alternative A: No reburial since maximum burial

Removal of the post-rift succession since maximum burial of the rift sediments in the Late Cretaceous took place in three steps during the Campanian, Eocene and Miocene events without any major reburial between these events. Formation of the HS (and the LS) consequently occurred after the Miocene event and both surfaces are thus of Neogene age (Figs 6-1, 6-2). Model A involves the following sequence of events:

1. U1 uplift event in the Campanian after maximum burial of rift sediments, 2-3 km thick cover across the study area.
2. U2 uplift event in the Eocene (documented in the Recôncavo-Tucano Basins and in Serra do Mar).
3. U3 uplift event in the Miocene (starting between 18 and 15 Ma).
4. HS formed by erosion to base level.
5. Ux uplift event at an unknown time after the Miocene event leading to uplift of the HS.
6. LS formed by river incision to the new base level.
7. U4 uplift event in the Quaternary(?) leading to incision below the LS and the formation of the coastal plain. Maximum uplift in the interior. Gentle folding of Barreiras Fm and the LS within the Tucano Basin.

Model A does not match with

- the existence of Palaeogene planation surfaces north and south of the study area documented by the presence of the Palaeogene sediments of the Serra do Martins and Fonseca Fms on the Borborema Plateau and on the plateaus in Minas Gerais. Palaeogene weathering ages on these plateaus also support that the plateau surfaces were exposed during the Palaeogene;
- the gap in the weathering record between c. 30 and 15 Ma for the plateau north and south of the study area (suggesting an Upper Oligocene–Lower Miocene cover on a Palaeogene surface);
- the deposition of the Lower Miocene Sabiá Fm over Lower Cretaceous sediments in the Recôncavo Basin because model A implies that 1-1.5 km of Cretaceous sediments at the location of the Sabiá Fm were not removed until after the Miocene event;
- the need to introduce a additional Neogene uplift event for which there is no supporting evidence (Ux, after U3 and before U4);
- the short time available for the formation of these regional erosion surfaces. Both surfaces would be formed between 18 Ma and possibly 2 Ma (between U3 and U4), leaving about 7 million years available for the formation of each surface. For comparison, the regional planation surface in West Greenland was formed during c. 20 million years (Japsen et al. 2006). Having said that, it is, however, difficult to compare areas with different climatic and tectonic conditions;
- the presence of Palaeogene sediments at seabed along the western margin of the Almada and Camamu Basins above a rift section that was more deeply buried prior to the Campanian event (suggesting completion of the Campanian exhumation prior to the Cenozoic).

6.3.5 Alternative B: Miocene reburial prior to last phase of exhumation

Removal of the post-rift succession since maximum burial of the rift sediments in the Late Cretaceous generally took place in two steps during the Campanian and Eocene event and was completed prior to the Oligocene–Miocene transition at c. 25 Ma (across most of the Camamu and Almada Basins the exhumation was completed prior to the Cenozoic) (Figs 6-1, 6-2). Late Oligocene to Early Miocene reburial took place across the study area, but these sediments were almost completely removed after the Miocene uplift event. The Palaeogene HS was formed after the Campanian uplift events – and probably even after the Eocene event – and before the reburial around 30 Ma as well as before the Miocene uplift. The LS was formed after the Miocene event and is thus of Neogene age. Model B involves the following sequence of events:

1. U1 uplift event in the Campanian after maximum burial of rift sediments, 2-3 km thick cover across the study area.
2. U2 uplift event in the Eocene (documented in Recôncavo-Tucano Basins and in Serra do Mar).
3. HS formed by erosion to base level prior to c. 30 Ma.
4. Deposition of an Upper Oligocene–Lower Miocene cover on the HS across the entire study area, including continental deposits in the hinterland and marine transgression of the coastal zone.
5. U3 uplift event in the Miocene lifting the HS and removing the most of the cover.
6. LS formed by river incision to the new base level.
7. U4 uplift event in the Quaternary(?) leading to incision below the LS and the formation of the coastal plain. Maximum uplift in interior. Gentle folding of Barreiras Fm and the LS within the Tucano Basin.

Model B does match with
- the existence of Palaeogene planation surfaces north and south of the study area (see above),
- the gap in the weathering record between c. 30 and 15 Ma for the plateau north and south of the study area by halting the weathering processes under a Upper Oligocene–Lower Miocene cover,
- the deposition of the Lower Miocene Sabiá Fm on a Palaeogene plain that may have been the equivalent to what is now preserved as the HS further inland
- the three post-rift uplift events known from the AFTA data,
- a reasonable time for the formation of the regional erosion surfaces. The HS was formed over at least c. 15 million years, between 45 (or earlier) and 30 Ma. The LS was formed over c. 15 million years, between 18 and maybe 2 Ma,
- the completion of the Late Cretaceous exhumation prior to the Palaeocene in the inshore areas where Palaeogene burial took place.

6.3.6 Available evidence is best explained if the higer surface is Palaeogene and was buried during the Miocene

The above discussion clearly points towards model B as the theory that most successfully can explain all available data. We thus conclude that the higher surface that defines the plateaux in the interior highlands were formed during the Palaeogene after the Campanian and most likely after the Eocene event, but prior to reburial in the late Oligocene–Early Miocene. The higher surface is thus most likely of Eocene–Oligocene age.

This conclusion raises the questions of the origin and independent evidence for the existence of an extensive Upper Oligocene–Lower Miocene cover within the study area (see Fig. 6-3).

In the interior, such a cover – which must have been several hundred metres thick according to the AFTA data – might be equivalent to the Serra do Martins (north), Chapadão (west) and Chapada de Canga (south) Fms that overlies the plateau surfaces there. These deposits are all non-fossiliferous, continental sediments that cover the plateaux and the preserved thickness of the Serra do Martins Fm is up to 100 m. The possibility of post-30 Ma reburial of the Palaeogene plateau surface has been documented by AFTA data for the Serra do Martins Fm on the Borborema Plateau (Morais Neto 2008a). An intriguing aspect of this model is to identify the unknown source of these sediments, but that aspect is not specific to this model, but a fundamental problem in Cenozoic geology of Brazil. The only new dimension added here, is that the cover must have been thicker that it is today.

The late Cenozoic burial history is more complex along the coast than in the interior because here we find deposits of the Lower Miocene marine Sabia Fm, the Neogene continental Barreiras Fm and the Neogene Rio Doce Fm in the coastal environment. The reburial prior to the Miocene event may thus have been made up by contributions from several sedimentary units.

The presence of the Sabiá Fm is important for understanding the Neogene development of the Recôncavo Basin and the coastal zone. According to the model presented here, the Sabiá Fm was deposited after transgression over a Palaeogene plain prior to the Miocene event, but today the deposits are found in deep trenches below the LS. The preservation of these deposits until the present can only be explained by some degree of down-faulting (probably during the Miocene event).

If we base our analysis on the existence and Early Miocene age of the Sabiá Fm, then all the Miocene heating seen in the AFTA data in the Recôncavo 6-MGP-34 well is due to Neogene reburial because the Sabiá Fm rests on Lower Cretaceous sediments (Petri 1972). The cover removed may thus have been partly Sabiá Fm, partly Rio Doce Fm and partly the Miocene unit of the Barreiras Fm (Barreiras Inferior, Arai 2006). The Barreiras Fm preserved today was deposited on the LS (Fig. 3-7), and as the LS was formed after the Miocene event, then these occurrences of the Barreiras Fm must belong to the Barreiras Superior (e.g. of Pliocene age).

6.4 Possible development along an onshore-offshore profile

A possible development along an onshore-offshore profile across Chapada Diamantina and the Camamu Basin is shown in Figure 6-4 based on the arguments presented in the preceding Section. The development is illustrated by four sketches at Present, 16, 35? and 77 Ma, respectively:

- 77 Ma, Campanian maximum burial of the rift sediments; the Cretaceous cover most likely extended over the interior highlands and into the Sanfranciscana basin in the western Bahia. The plateau surface of Chapada Diamantina was buried below a c. 2 km thick rock column at that time according to the AFTA data presented here.

- 35? Ma. Palaeogene peneplain with deep weathering profiles and laterites developed after Campanian and Eocene uplift and long exposure at the surface. The age of the higher surface is not well constrained in the study area, but similar plateau surfaces north and south of the study area were exposed during the Palaeogene according to stratigraphic data (Sant'Anna et al. 1997; Morais Neto et al. 2008a) as well as according to geochronological constraints on deep weathering (Spier et al. 2006; Lima 2008). Major sliding offshore happened between the late Aptian and the middle Eocene (Cobbold et al. 2008a,b) and is here assumed to have taken place between the Campanian and the Eocene uplift events, possibly with a major movement during the Eocene event that affected the onshore areas strongly. Post-rift sediments that are preserved within the in the inshore part of the Camamu Basin today, may also have been down-faulted during the Eocene event.

- 16 Ma, Miocene burial of the interior highlands and of the coastal zone. AFTA data along the present-day escarpments between the higher and the lower surface show that the plateau surface (HS) was buried below a cover that was several hundred meters thick prior to the Miocene cooling event. As plateaux in the region were exposed during the Palaeogene, this cover must have been of late Oligocene–early Miocene age. In the coastal region the present surface was buried by c. 1 km during the same time. This cover may thus have been partly Sabiá Fm, partly Rio Doce Fm and partly the Miocene unit of the Barreiras Fm (Barreiras Inferior, Arai 2006). The Sabiá Fm rests on Lower Cretaceous sediments (Petri 1972) so any Palaeogene sediments in the Camamu-Recôncavo area are likely to have been removed prior to the Miocene.

- Present, reexposure of the Palaeogene plateau surface (HS) and formation of the lower surface (HS) after Miocene uplift. Weathered basement and laterites are preserved on the plateaux, but not on the LS that was formed by incision below the HS. Removal of much of the late Oligocene–early Miocene cover in the coastal zone and continued subsidence in the deep sea that must have acted as a by-pass zone relative to the eroded material from the onshore and inshore areas (alternatively altered drainage patterns may lead to the deposition of these sediments elsewhere along the coast).

Constraints on the age of the Lower Surface (LS) Younger than the Miocene uplift event

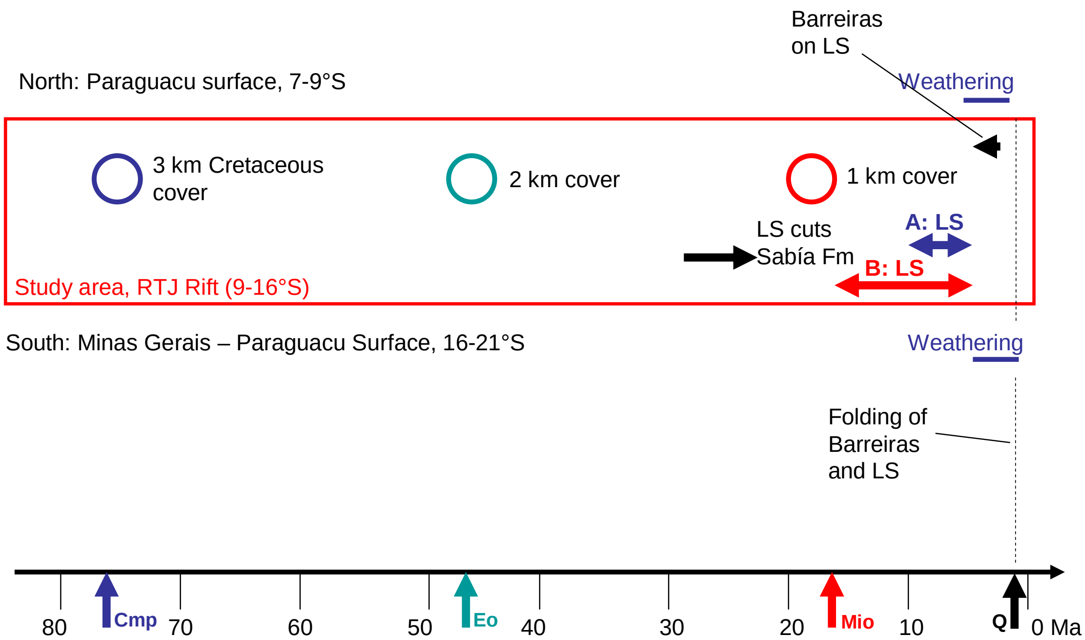


Figure 6-1. *Constraints on the age of the lower surface (LS) shown relative to geological observations over time as summarized in Section 6.3. The upper part of the figure shows the constraints for the area north of the study area, the middle part (marked by a red rectangle) shows the constraints for the study area (the RTJ Rift) and the lower part the constraints for the area to the south. The Paraguaçu surface (King 1967) is mainly equivalent to the LS. Circles indicate estimates for the thickness of the cover above the HS prior to uplift events based on AFTA data (vertical arrows along time scale); blue: Campanian, green: Eocene, red: Miocene, pink fill: Cenozoic cover. Black vertical arrow marks Quaternary uplift identified from field observations and mapping of landforms. Blue lines indicate duration of weathering. Black horizontal arrows indicate constraints on the age of the LS from stratigraphic data. Double arrows indicate the time interval available for the formation of the LS; blue: model A, red: model B.*

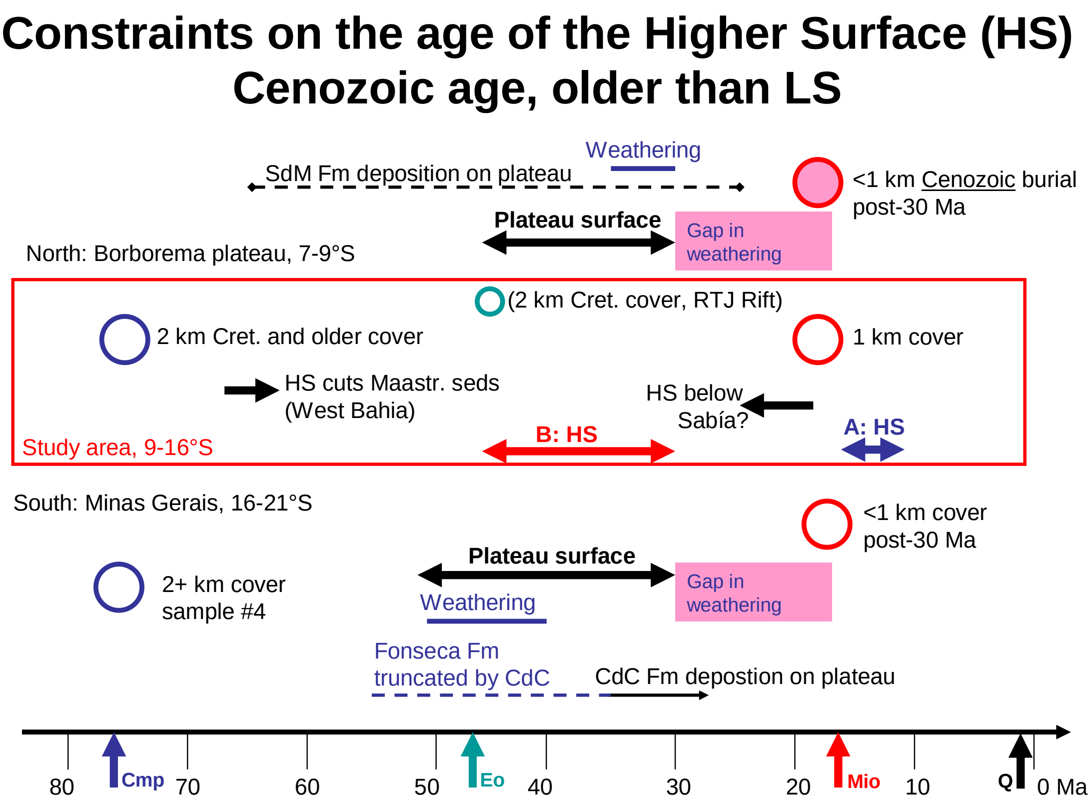


Figure 6-2. *Constraints on the age of the higher Surface (HS) shown relative to geological observations over time as summarized in section 6.3. The upper part of the figure shows the constraints for the Borborema plateau north of the study area, the middle part (marked by a red rectangle) shows the constraints for the study area and the lower part the constraints for the plateaux in Minas Gerais. Circles indicate estimates for the thickness of the cover above the HS prior to uplift events based on AFTA data (vertical arrows along time scale); blue: Campanian, green: Eocene, red: Miocene, pink fill: Cenozoic cover. Black vertical arrow marks Quaternary uplift identified from field observations and mapping of landforms. Blue lines indicate duration of weathering, pink double arrows indicate gaps in the weathering record. Arrows indicate constraints on the age of the HS from stratigraphic data. Double arrows indicate the time interval available for the formation of the HS; blue: model A, red: model B. CdC: Chapada de Canga Fm, SdM: Serra do Martins Fm. Dashed lines indicate uncertain constraints on the timing.*

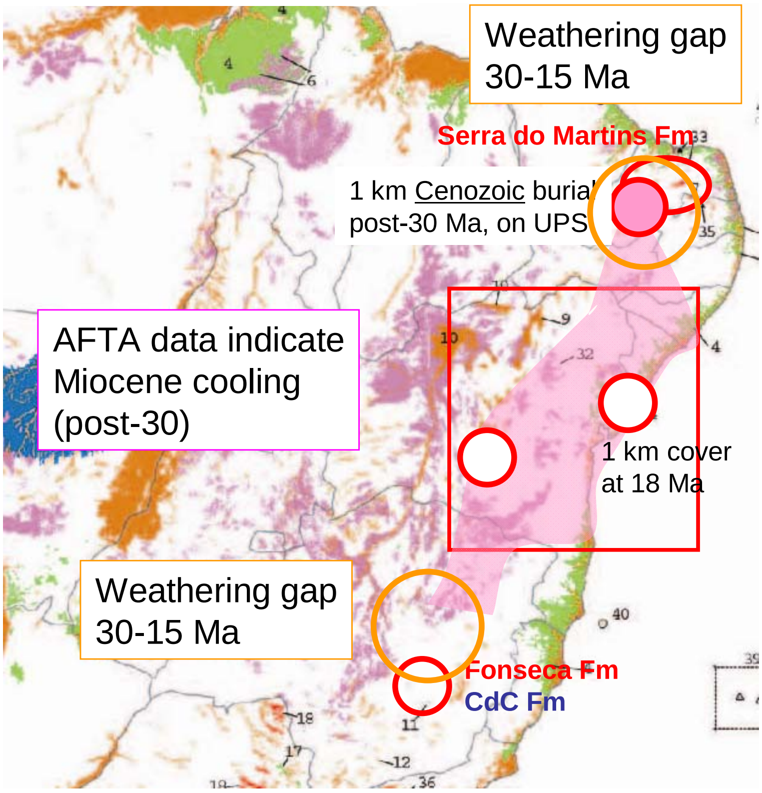


Figure 6-3. *Map of observations that indicate Neogene reburial of the higher Surface that was formed during the Palaeogene following the arguments given for model B in section 6.3 (detail of map in Fig. 3-6). Purple zone across the study area (red box) and to the north and south of it marks an area where AFTA data indicate significant Miocene cooling (locally post-30 Ma) corresponding to a significant cover above the Palaeogene plateaux. This is in agreement with the gap in the weathering record observed for the plateaux in Borborema and Minas Gerais (Vasconcelos & Carmo 2008, Guia Lima 2008). Such a cover might be equivalent to the Serra do Martins (north), Chapadão (west) and Chapada de Canga (south) Fms that overlies the plateau surfaces there.*

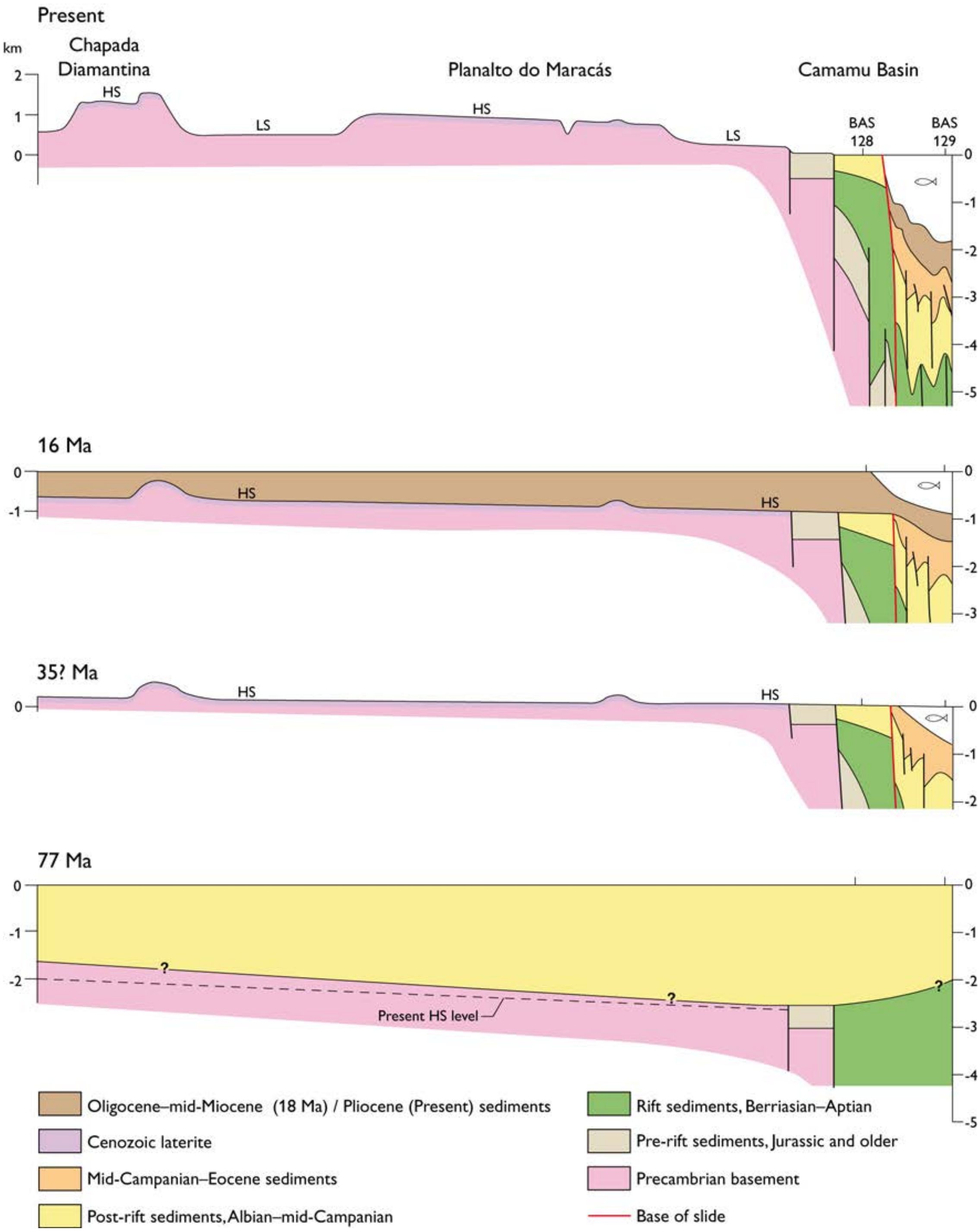


Figure 6-4. *Possible development along an onshore-offshore profile across Chapada Diamantina and the Camamu Basin. Based on the topographic profile shown in Figure 4-2, the schematic geological cross section shown in figure 11.22 in Menezes and da Silva. (2008) and available well data.*

Present, reexposure of the Palaeogene plateau surface (HS) and formation of the lower surface (HS) after Miocene uplift. Continued subsidence in the deep-water part of the Camamu Basin.

16 Ma, Miocene burial of the interior highlands and of the coastal zone. Whereas the cover over the highlands may have been continental deposits comparable to the Serra do

Martins and Chapada de Canga Fms, the cover in the coastal region may have been partly Sabiá Fm, partly Rio Doce Fm and partly the Miocene unit of the Barreiras Fm (Barreiras Inferior, Arai 2006).

35? Ma. Palaeogene peneplain with deep weathering profiles and laterites developed after Campanian and Eocene uplift and long exposure at the surface. Major sliding offshore and is here assumed to have taken place between the Campanian and the Eocene uplift events (cf. Cobbold et al. 2008a,b). Post-rift sediments preserved within the in the inshore part of the Camamu Basin today, may have been down-faulted during the Eocene event.

77 Ma, Campanian maximum burial of the rift sediments and a Cretaceous cover that most likely extended over the interior highlands and into the Sanfranciscana basin in the western Bahia.

7. Implications for source rock maturation and hydrocarbon prospectivity

7.1 Introduction

In this section, we briefly review conclusions reached in Geotrack Reports GC990 and GC1013 regarding maturity levels and maturation histories of the sedimentary sections in onshore basins and in the offshore wells analysed in this report, and then proceed to discuss the implications of these observations regarding the prospectivity of the Camamu Basin, in the light of other information presented in this report.

7.2 Observations in onshore Mesozoic rift basins

Results from three wells in the centre of the Tucano Basin analysed in this study show very similar thermal histories, resulting in very similar maturity levels and maturation histories for these wells. Similarly, results from four Recôncavo Basin wells also show very similar histories, although detailed data coverage is only available in the 6-MGP-34 well. Results in this study in all wells analysed from these basins, as well as outcrop samples across the region, suggest a very similar history applies across the region (as summarised in Figures 5-10 and 5-11). Therefore we base the discussion here on results from the 1-FVM-1 well as typical of this region of the Tucano Basin while the 6-MGP-34 well is used to typify the Recôncavo Basin.

Maturity-depth profiles

Figure 7-1 shows the maturity-depth profile for the 1-FVM-1 well predicted from the thermal history reconstruction for this well developed in Section 14 of Geotrack Report GC990, together with measured maturity data in the well (also presented in Geotrack Report GC990). Based on this reconstruction, the Early Cretaceous units intersected in these well span the Early to Late Mature (Oil) windows, while deeper units below TD are likely to lie within the Main Gas Generation window. Similar results were found in the 1-BRN-1 and 1-FPO-1 wells in Geotrack Report GC990. Note that because of the very low thermal gradient of 15°C/km in these wells, the base of the oil window lies at a depth greater than 6 km, a large thickness of section lies within the oil generation window, suggesting that hydrocarbon generation may be more prolific in this basin compared to others where thermal gradients are higher (assuming that suitable source horizons are present). Note also that for the purposes of comparison with Figure 5-18, the top of the oil window of 0.6% as defined by Magnavita et al. (1994) lies at a depth of ~2 km, which is rather shallower than suggested by Magnavita et al. (1994). The source of this difference is not known, but could reflect differences in data sources or data quality.

Figure 7-2 shows a similar maturity-depth plot for the 6-MGP-34 well. Early Cretaceous units intersected in this well again span the Early to Late Mature (Oil) windows, while the deepest section is likely to lie just within the Main Gas Generation window. Although the thermal gradient of 20°C/km used in this reconstruction is higher than in the Tucano Basin (above), the base of the oil window still lies at a depth of ~3.5 km, and a considerable thickness of section lies within the oil generation window. The top of the oil window (as defined by Magnavita et al., 1994) lies at a depth of around 1 km, which is rather shallower than suggested by Magnavita et al. (1994), but clearly shallower than in the Tucano Basin wells analysed in this study, supporting the basic difference between the two basins highlighted by Magnavita et al. (1994).

Evolution of maturity with time

Figure 7-3 shows the evolution of maturity with time for the 1-FVM-1 well (using the maturation algorithm of Burnham and Sweeney, 1989) derived from the thermal history reconstruction for this well developed in Section 14.2 of Geotrack Report GC990. Figure 7-4 shows a similar plot for the 6-MGP-34 well from the Recôncavo Basin. In both cases, maximum maturity levels in Early Cretaceous units in this well were reached as a result of deeper burial in the Campanian, and active hydrocarbon generation from any potential source rocks within the section ceased at the onset of exhumation, shown at 77 Ma although any time between 80 and 75 Ma is allowed by the AFTA data from this well. The regional nature of the palaeo-thermal effects identified in this study suggests that similar patterns are expected to apply over much of the Mesozoic rift basin system of NE Brazil.

7.3 Observations in offshore wells

In each of the four offshore wells analysed for this report, AFTA and VR data show a different style of thermal history, controlled by a variety different processes. This is illustrated in Figures 5-14 and 5-15, which shows the reconstructed thermal histories and the corresponding reconstructed burial/uplift histories in three of the four wells, while the reconstructions in well 1-BAS-113 are shown in Figure 5-10 and 5-11.

1-BAS-88 well

In this well, burial appears to have been more or less continuous (Figure 5-15), with no episodes of deeper burial and subsequent uplift and erosion detected. The only palaeo-thermal effects identified in this well appear to be due to contact heating associated with thin intrusives within the Valanginian section. All post-Valanginian units are currently at their maximum post-depositional palaeotemperatures.

Figure 7-5 shows the maturity-depth profile for this well predicted from the thermal history reconstruction presented in Geotrack Report GC1013, together with measured maturity data from the well. The maturity profile at depths greater than 3.2 km has been hand drawn to schematically illustrate the preferred interpretation of palaeo-thermal processes at these depths. Deeper parts of the Aptian section lie in the Early Mature (oil) Window while shallower units remain immature. Localised parts of the Valanginian and older section span the Main Gas Generation window or beyond, while unaffected parts lie within the Middle to Late Mature (oil) windows.

The corresponding evolution of maturity with time for this well (calculated using the maturation algorithm of Burnham and Sweeney, 1989) is shown in Figure 7-6. In this reconstruction the effects of local heating within Valanginian and older units are shown schematically. Neither the full extent of these local heating effects or their timing is known with confidence. Maturation within post-Valanginian units as well as that part of the Valanginian and older section that was not affected by local heating effects has continued to the present day and is likely to be currently active. Active generation from source horizons within the Early Cretaceous section which escaped the effects of contact alteration would explain the presence of oil droplets observed during the VR analyses as reported in Geotrack Report GC1013.

1-BAS-102 well

In this well burial also appears to have been more or less continuous, with no episodes of deeper burial and subsequent uplift and erosion detected. Palaeo-thermal effects in this well are restricted to highly localised heating within the Albian section.

Figure 7-7 shows the maturity-depth profile for this well predicted from the thermal history reconstruction presented in Geotrack Report GC1013, together with measured VR values that are considered to provide reliable estimates of maturity levels in the well. Early Cretaceous units intersected in this well span the Early to Mid Mature (oil) windows.

The corresponding evolution of maturity with time for this well (calculated using the maturation algorithm of Burnham and Sweeney, 1989) is shown in Figure 7-8, where the effects of local heating within Valanginian and older units are shown schematically. As in the 1-BAS-88 well, neither the full extent of these local heating effects or their timing is known with confidence. Maturation in all units has continued to the present day and is currently active, with most of the Early Cretaceous section within the oil window.

1-BAS-113 well

In contrast to the two wells discussed above, all units in this well (except for a thin veneer of Late Cenozoic sediments) were heated to maximum palaeotemperatures around 50 to 60°C above present-day temperatures as a result of burial by around 2 km of additional section of Aptian to Campanian age, removed in two major episodes of exhumation which began in the intervals 90 to 70 Ma and 25 to 10 Ma. Palaeogeothermal gradients throughout the history have remained at levels similar to the present-day value of 24.9°C/km, and the results from this well preclude significantly elevated basal heat flow associated with Early Cretaceous rifting on this margin. As noted in Section 5, this history is similar to those that apply in onshore wells from the onshore basins.

Figure 7-9 shows the maturity-depth profile for this well predicted from the thermal history reconstructions presented in Geotrack Report GC1013, together with measured maturity data from the well. Early Cretaceous units intersected in this well span the Early to Late Mature (Oil) windows while deeper units are likely to lie within the Main Gas Generation window. This profile is similar to that in the Recôncavo Basin well 6-MGP-34 well, discussed earlier.

The corresponding evolution of maturity with time for this well (calculated using the maturation algorithm of Burnham and Sweeney, 1989) is shown in Figure 7-10. Maximum maturity levels in all pre-Cenozoic units were reached as a result of deeper burial in the Late Cretaceous, and active hydrocarbon generation from any potential source rocks within the section ceased at the onset of exhumation, shown at 80 Ma although any time between 90 and 75 Ma is allowed by the AFTA data from this well. This pattern is similar to those in Figures 7-3 and 7-4 for the onshore Tucano and Recôncavo basins, and is likely to apply over most of the inshore shelf where Early Cretaceous sediments are present at or close to the sea bed.

1-BAS-129 well

In this well, burial appears to have been more or less continuous, with no episodes of deeper burial and subsequent uplift and erosion detected (Figure 5-11). Extreme palaeothermal effects in the Aptian-Albian section in this well, involving palaeotemperatures in excess of 250°C, are interpreted as due to early (pre-110 Ma) hydrothermal circulation. This circulation is probably due to upward circulation of hot fluids along a fault and may indirectly be related to igneous intrusions, of which a few are visible on seismic sections, although most of them are far away from the well.

probably related to the presence of numerous intrusives identified on seismic sections. Palaeogene units in this well were affected by an unrelated episode of hot fluid flow during the Middle Eocene, the effects of which have produced local heating in the shallower section.

Figure 7-11 shows the maturity-depth profile for this well predicted from the thermal history reconstruction presented in Geotrack Report GC1013, together with measured maturity data from the well. Most of the Early Cretaceous section in this well is post-Mature, while Eocene to Palaeocene (and Late Cretaceous?) span the oil generation windows over a very narrow depth range.

The corresponding evolution of maturity with time for this well (calculated using the maturation algorithm of Burnham and Sweeney, 1989) is shown in Figure 7-12. Active maturation within the Early Cretaceous section ceased following the hydrothermal circulation episode which AFTA suggests terminated earlier than 110 Ma. Similarly maturation in Middle Eocene to Late Cretaceous units ceased following the Middle Miocene fluid-related heating episode, in the interval 49 to 45 Ma. Late Eocene and younger units remain immature.

7.4 Absence of evidence for elevated basal heat flow associated with rifting

One clear outcome of this study is that paleogeothermal gradients during the key paleothermal episodes were very similar to present-day gradients. In none of the wells analysed in this study do the AFTA and VR data show any evidence of higher paleogeothermal gradients that might be diagnostic of elevated basal heat flow during Early Cretaceous rifting of the Atlantic margin of Brazil. This might be considered surprising in the light of results from other continental margins, such as SE Australia (Green et al. 2004), West Greenland (Japsen et al. 2007) and West Africa (Turner et al. (2008), where AFTA and VR data show very clear evidence of basal heat flow up to twice present-day values at the time that the respective continental margin was developing. Indeed, such a model was adopted by Gonçalves et al. (2000) as the basis of their modelling of the petroleum system of the Camamu-Almada basins, and exerts a critical control on the timing of hydrocarbon generation in their models.

Nevertheless, the results of this study are very clear in this respect. While the results of this study would allow a basal heat flow during Aptian times up to ~65% higher than the present-day value (explained in Geotrack report 990), the results of this study clearly show that the main phase of hydrocarbon generation must have taken place under a regime in which the heat flow was very similar to the present-day value (i.e. any elevated heat flow must have returned to present-day levels by ~80 Ma). From the point of view of hydrocarbon prospectivity, this has the advantage of preventing the early exhaustion of all generation potential, as is common in provinces characterised by elevated heat flow.

7.5 General implications for the hydrocarbon prospectivity of the Camamu Basin

The results of this study suggest that most of the inshore region has undergone deeper burial during the earlier part of the Late Cretaceous, and has subsequently undergone exhumation beginning between 80 and 75 Ma, with up to 2 km of post-Aptian section deposited and removed (Figure 5-9). Across this region, maturation patterns will be similar to those shown in Figures 7-9 and 7-10 for the 1-BAS-113 well. The major implication of the maturation history in this area is that generation of hydrocarbons from any source rocks within the Early Cretaceous section would have ceased with the onset or exhumation in the Campanian. Therefore throughout this inshore region, structures formed during (or after) this phase of uplift are unlikely to be prospective unless they have been charged from local source rocks in close contact with reservoir horizons, or perhaps by long-distance migration from the more basinal settings offshore, following the main phase of exhumation. However, structures that were already formed during rifting will have been available for charging during burial by the post-rift section which caused the main phase of oil generation prior to Campanian exhumation, and may be particularly prospective.

Further offshore where a more complete sedimentary section is preserved, and the effects of the Campanian exhumation episode diminish, palaeo-thermal effects appear to be limited to those associated with hydrothermal effects. Minor effects associated with localised hot fluid flow involving relatively low degrees of heating appear to be ubiquitous, being recognised in the 1-BAS-88, 1-BAS-102 and 1-BAS-129 (Eocene section) wells. The impact of these events on maturation histories is likely to be minor, although local diagenetic effects as recognised in the Eocene section of the 1-BAS-129 well (Geotrack Report GC1013A) may affect reservoir quality.

The most important factor affecting maturation patterns in the offshore is undoubtedly the hydrothermal circulation identified in the 1-BAS-129 well, which we interpret as associated with early Cretaceous intrusive activity nearby. Circulation of hot fluids, instigated by intrusive activity, has created a variety of diagenetic effects within sandstones and has also caused excessive levels of maturation way beyond the gas window. Palaeo-thermal effects due to these intrusive bodies are likely to be widespread wherever the intrusions are present, although the nature of the effects will vary, as shown by the contact heating effects identified in the **1-BAS-88** well compared to the more pervasive heating in the **1-BAS-129** well.

Situations where source rocks have escaped the effects of these hydrothermal events would appear to provide the most attractive targets for exploration in the Camamu Basin. In this context, it is worth noting that despite the extensive fluid-related heating effects identified in the West of Shetland region of the UK offshore shelf (Section 7.5, below), this region is host to a number of major hydrocarbon accumulations. Thus, the identification of the hydrothermal effects need not have a negative impact on prospectivity overall.

7.6 Hydrothermal events in offshore wells: comparison with other areas

Hydrothermal effects similar to those identified in the **1-BAS-88, 1-BAS-102** and **1-BAS-129** wells have been identified in numerous studies of the West of Shetland region of the UK Atlantic margin (Duddy et al. 1994, 1998; Green et al., 1999; Parnell et al. 1999, 2005; Mark et al. 2008). Heating related to hydrothermal circulation is characterised by highly non-linear palaeotemperature profiles, as illustrated in Figure 7-13. Figure 7-14 shows some examples of real data from the West of Shetland region. Different wells show a variety of different types of profile, depending on the timescale of fluid circulation, the depth at which fluids enter the system and the nature of the flow (pervasive or localised).

In many of these studies, thermal history information from AFTA and VR has been integrated with evidence from fluid inclusion measurements, providing highly consistent results. In the West of Shetland region, Palaeogene intrusions related to the opening of the Atlantic Ocean are a common source of hot fluids. However, in some cases basinal fluids released from faulting and rising up-dip on a major structural arch also provide a Late Cenozoic phase. Similar effects have been identified in wells on the North West Shelf of Australia (O'Brien et al 1996), while further evidence of hydrothermal heating related to intrusive activity comes from the Canning Basin of NW Australia, where emplacement of intrusions into unconsolidated sediments produced regional heating due to hot fluid circulation (Duddy et al. 1994, 1998). Such effects are commonly (though not exclusively) most strongly pronounced where thin quartzose sandstones forming regional aquifer horizons occur within thick muds, which serve to seal and constrain fluid movement.

We suggest that the range of effects identified in the West of Shetland region provide a good analogue to those identified in this study.

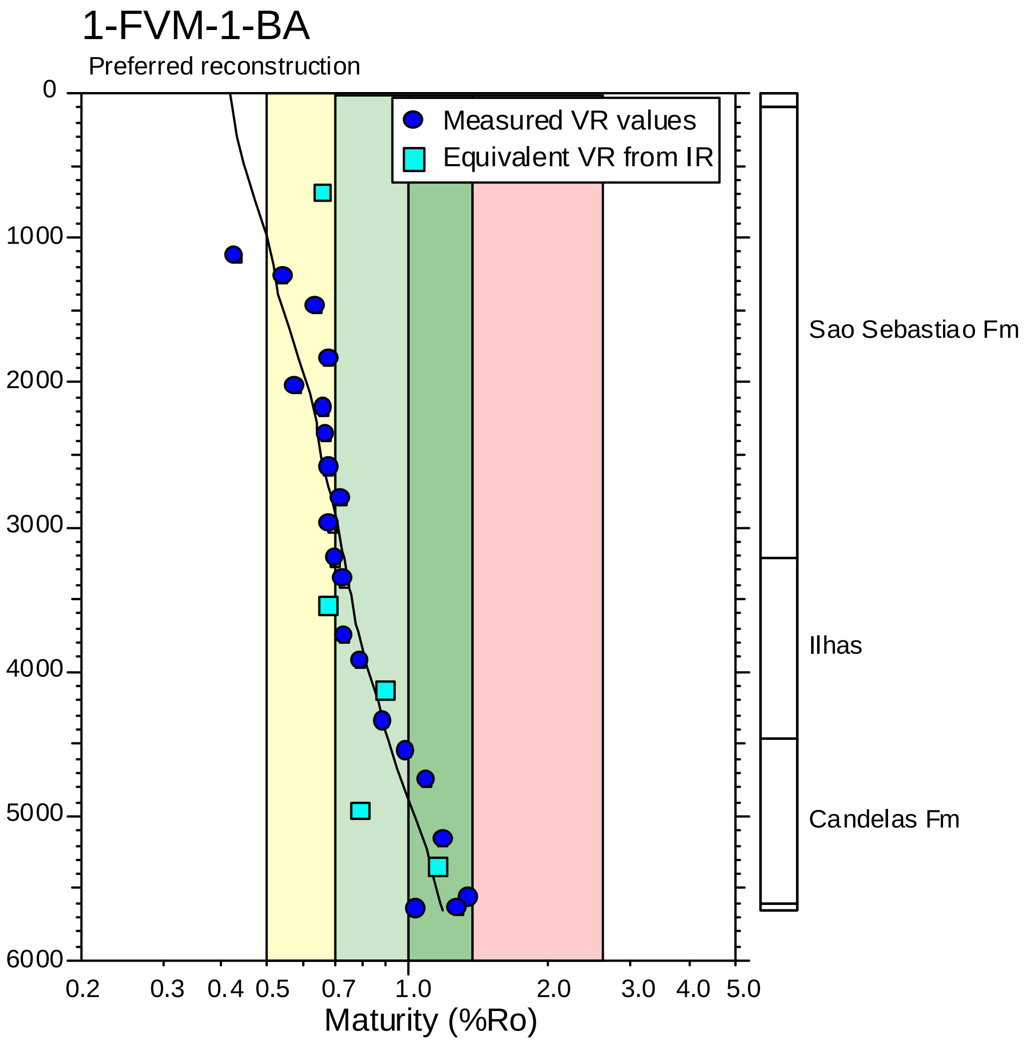


Figure 7-1. *Vitrinite reflectance data and equivalent VR values derived from Inertinite Reflectance data in the* ***1-FVM-1 well, Tucano Basin, Onshore Brazil****, plotted against depth, together with the maturity profile predicted by the preferred Thermal History Reconstructions derived from AFTA and VR data in this well. Maturity windows corresponding to different stages of source rock maturation are also shown (Yellow - Early Mature (oil), 0.5 – 0.7%Ro: Light Green – Mid Mature (oil), 0.7 – 1.0%Ro: Dark Green – Late Mature (oil), 1.0 – 1.3% Ro: Light Red - Main Gas Generation, 1.3 – 2.6%Ro). The Early Cretaceous units intersected in this well span the Early Mature to Late Mature (oil) windows, due to the effects of deeper burial during the Late Cretaceous.*

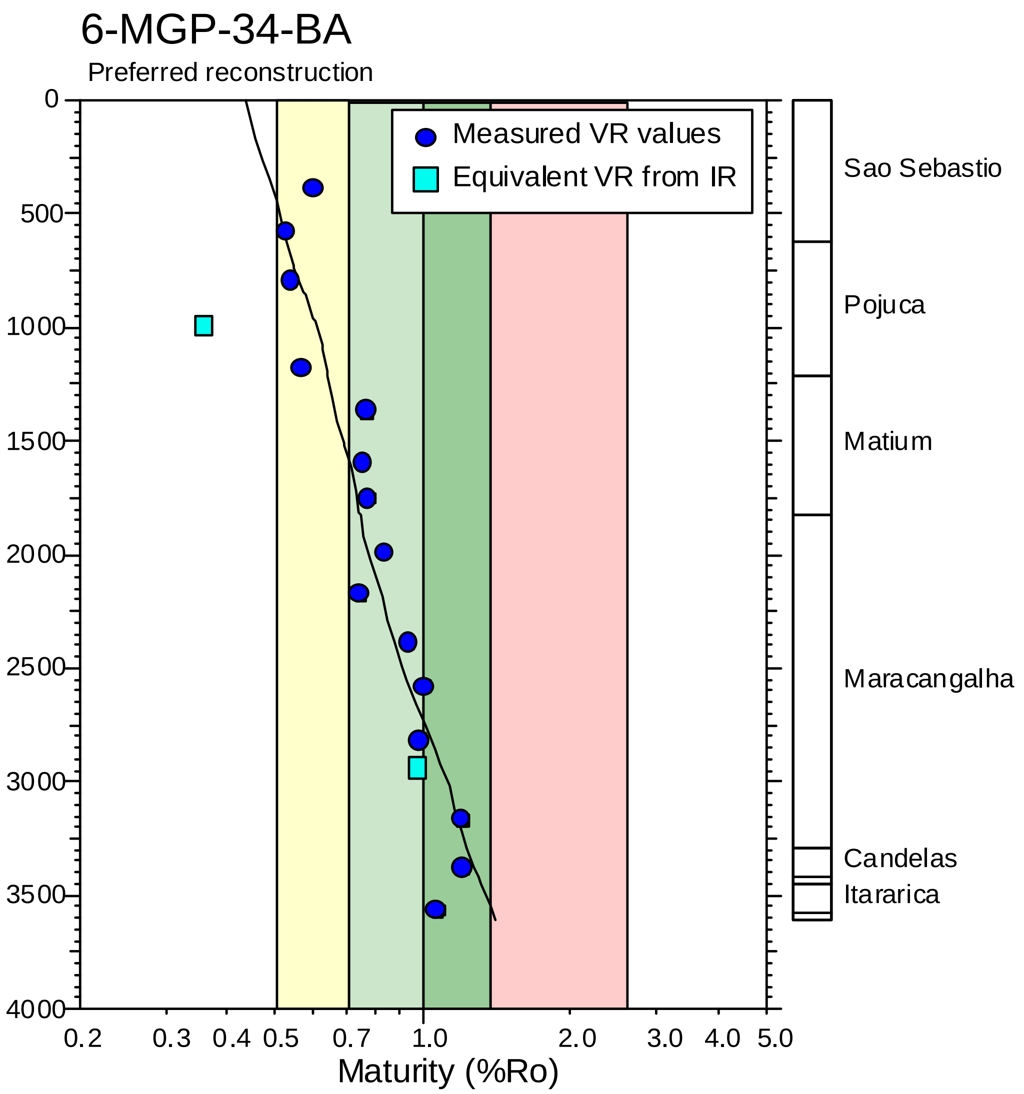


Figure 7-2. *Vitrinite reflectance data and equivalent VR values derived from Inertinite Reflectance data in the* ***6-MGP-34 well, Recôncavo Basin, Onshore Brazil****, plotted against depth, together with the maturity profile predicted by the preferred Thermal History Reconstructions derived from AFTA and VR data in this well. Maturity windows corresponding to different stages of source rock maturation are also shown (Yellow - Early Mature (oil), 0.5 – 0.7%Ro: Light Green – Mid Mature (oil), 0.7 – 1.0%Ro: Dark Green – Late Mature (oil), 1.0 – 1.3% Ro: Light Red - Main Gas Generation, 1.3 – 2.6%Ro). The Early Cretaceous units intersected in this well span the Early Mature to Late Mature (oil) windows, due to the effects of deeper burial during the Late Cretaceous*.

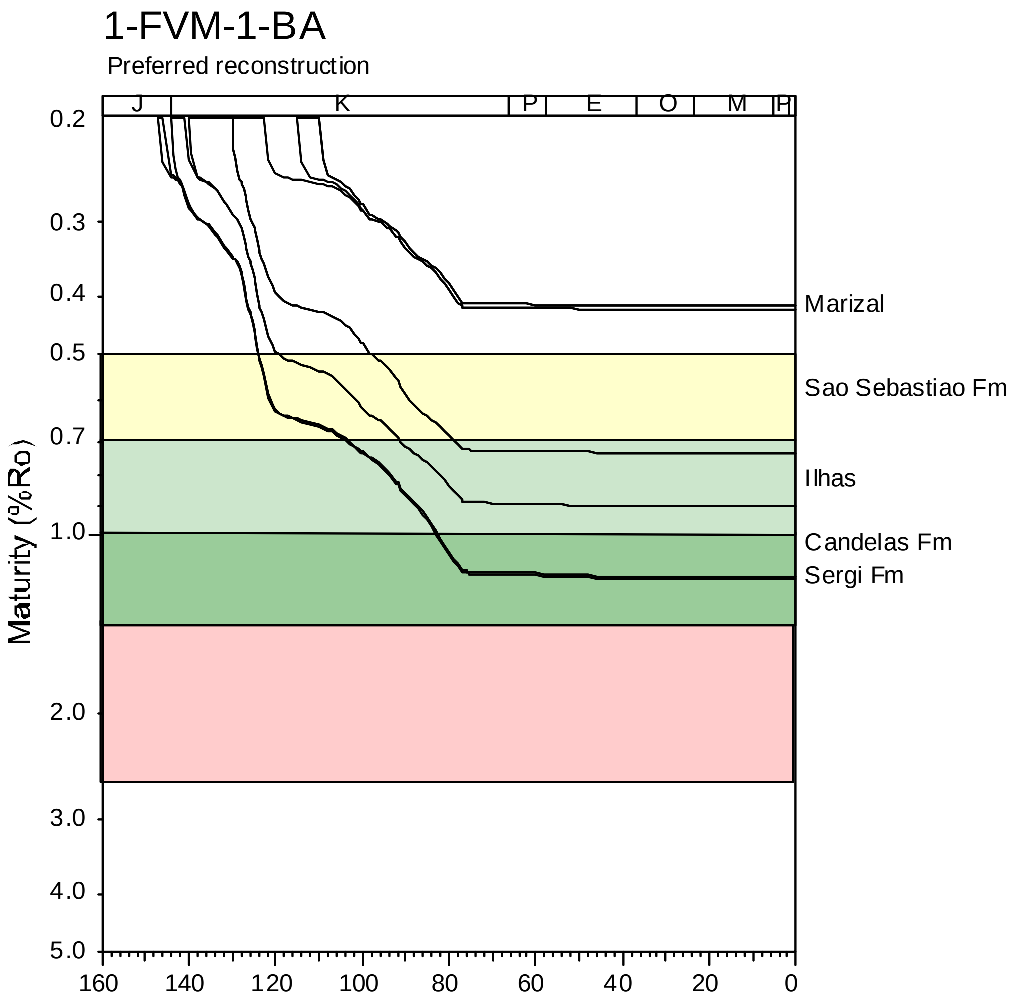


Figure 7-3. *Pattern of maturation vs time for the preserved sedimentary section in the* ***1-FVM-1 well, Tucano Basin, Onshore Brazil****, predicted by the preferred thermal history reconstruction for this well. Maturity windows as in Figure 7-1. In this reconstruction, active maturation within the entire section ceased with the onset of cooling at 77 Ma (any time between 80 and 75 Ma is allowed by the AFTA data from this well).*

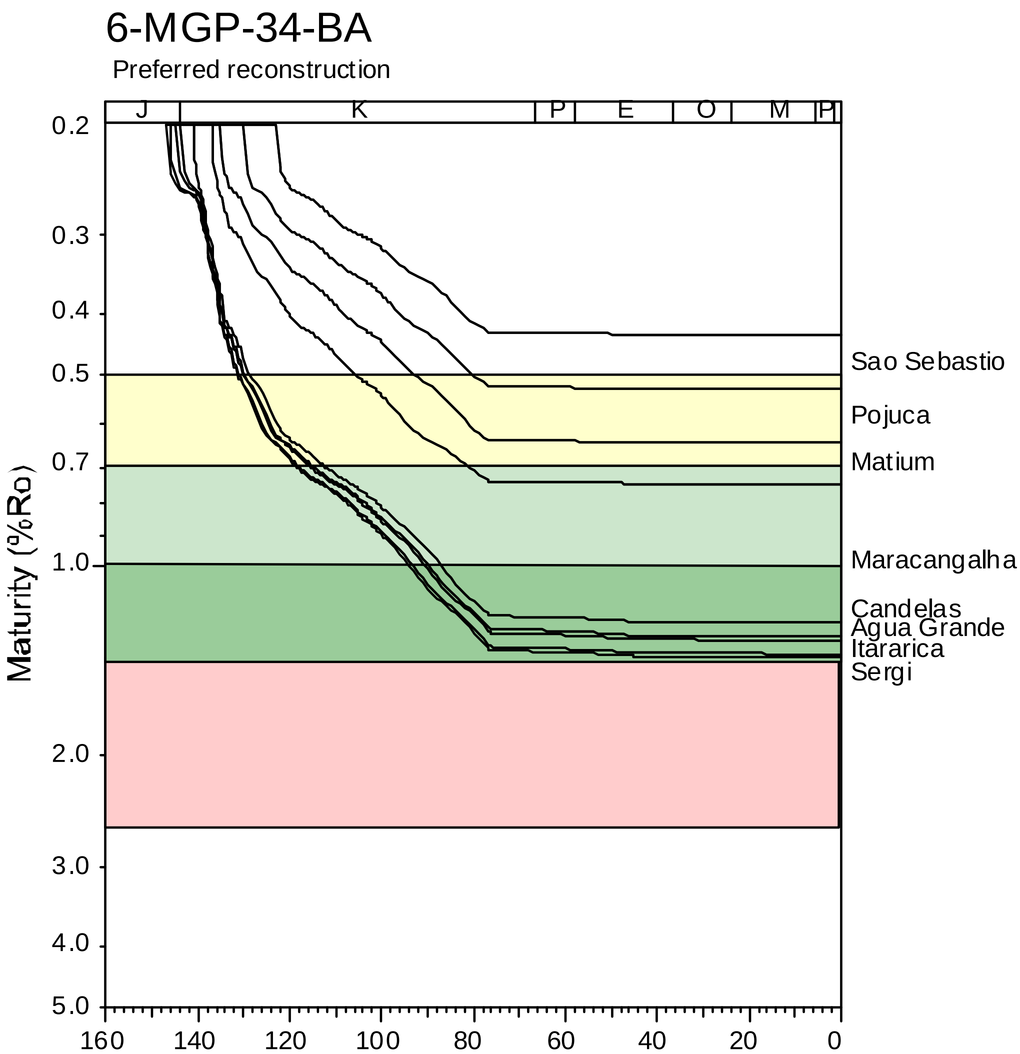


Figure 7-4. *Pattern of maturation vs time for the preserved sedimentary section in the* ***6-MGP-34 well, Recôncavo Basin, Onshore Brazil****, predicted by the preferred thermal history reconstruction for this well. Maturity windows as in Figure 7-1. In this reconstruction, active maturation within the entire section ceased with the onset of cooling at 77 Ma (any time between 80 and 75 Ma is allowed by the AFTA data from this well).*

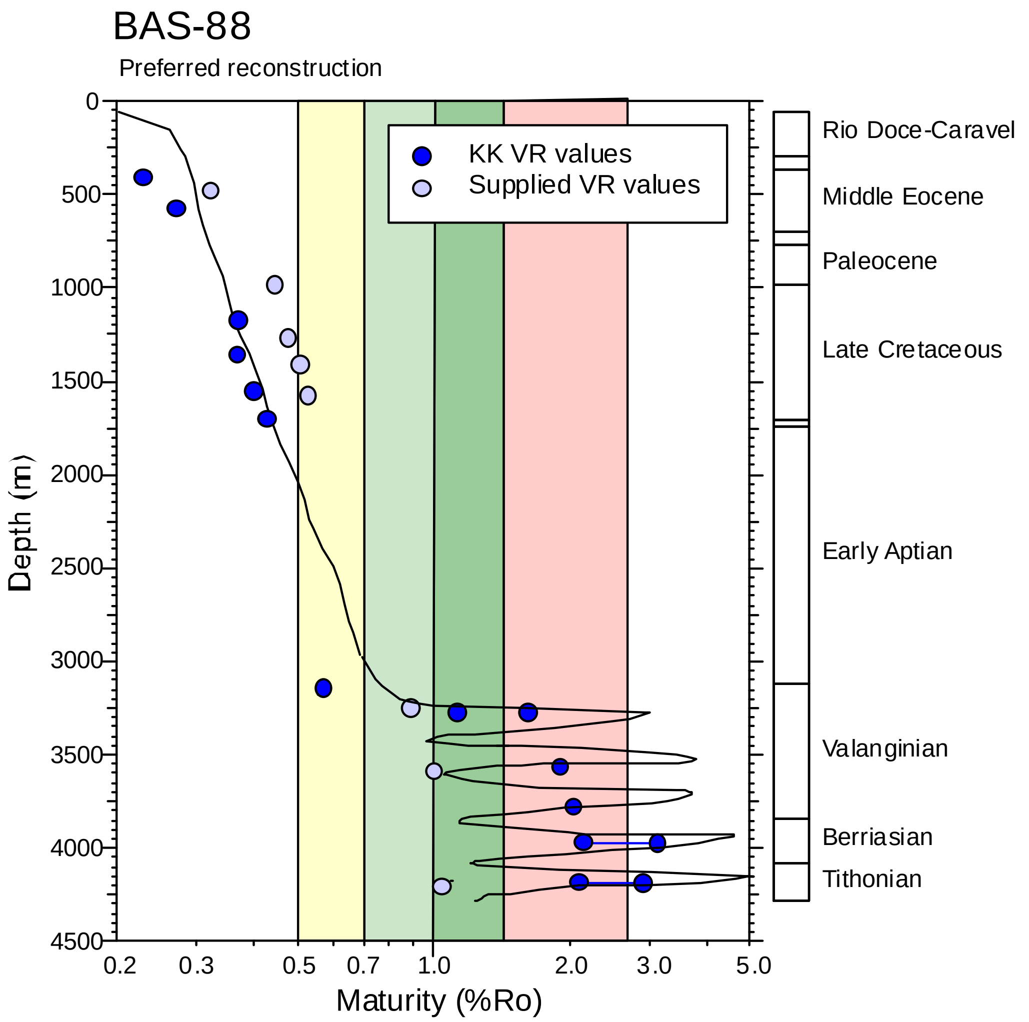


Figure 7-5. *Vitrinite reflectance data in **Offshore Brasil well 1-BAS-88** plotted against depth, together with the maturity profile predicted by the preferred Thermal History Reconstruction derived from AFTA and VR data in this well. Effects of local heating within the Early Cretaceous section are shown schematically. Maturity windows corresponding to different stages of source rock maturation are also shown (Yellow - Early Mature (oil), 0.5 – 0.7%Ro: Light Green – Mid Mature (oil), 0.7 – 1.0%Ro: Dark Green – Late Mature (oil), 1.0 – 1.3% Ro: Light Red - Main Gas Generation, 1.3 – 2.6%Ro). Deeper parts of the Aptian section line in the Early Mature (oil) Window and shallower units remain immature, while localised parts of the Valanginian and older section span the Main Gas Generation window or beyond, while unaffected parts lie within the Middle to Late Mature (oil) windows.*

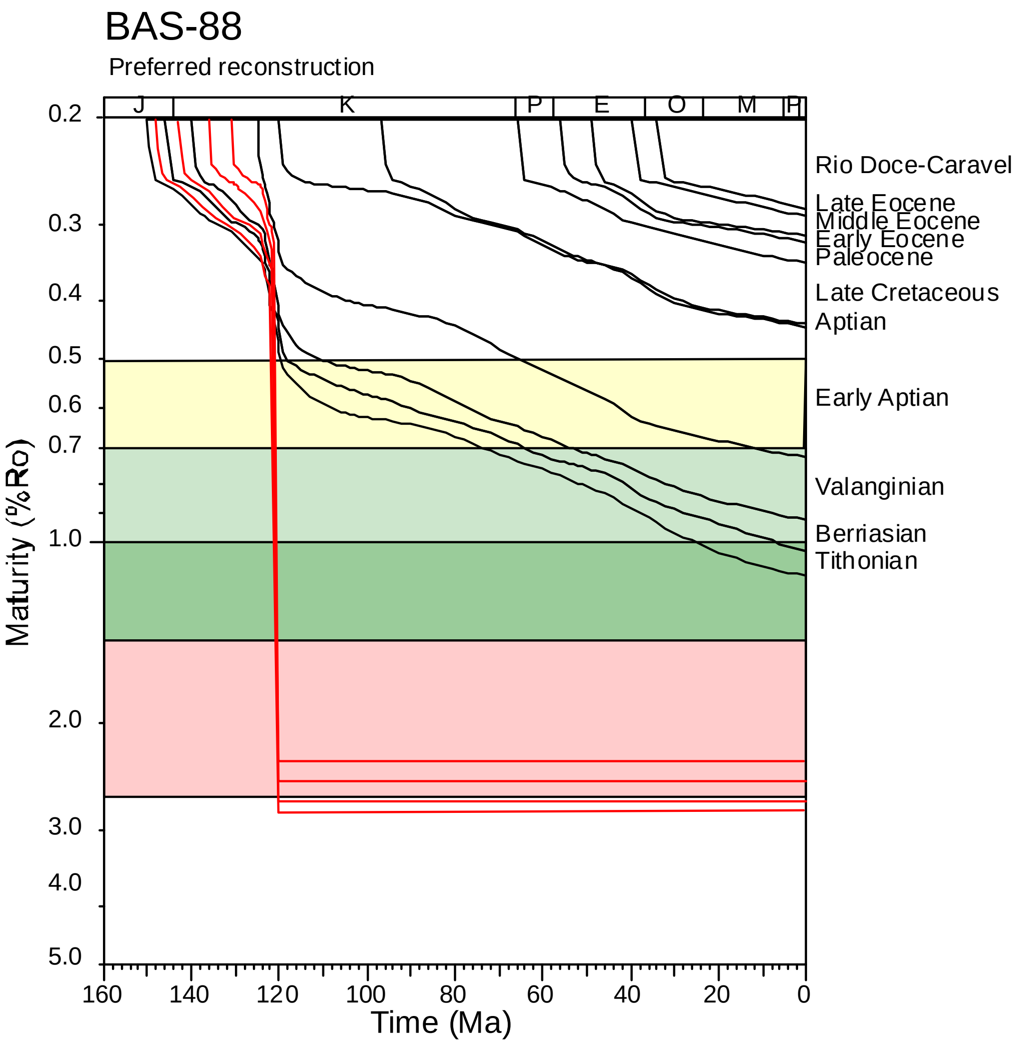


Figure 7-6. *Pattern of maturation vs time for the preserved sedimentary section in the* ***Offshore Brasil well 1-BAS-88,*** *predicted by the preferred thermal history reconstruction for this well. Effects of local heating within Valanginian and older units are shown schematically by the red lines. Maturity windows as in Figure 7-5. In this reconstruction, maturation within post-Valanginian units as well as that part of the Valanginian and older section that was not affected by local heating effects has continued to the present day and is currently active.*

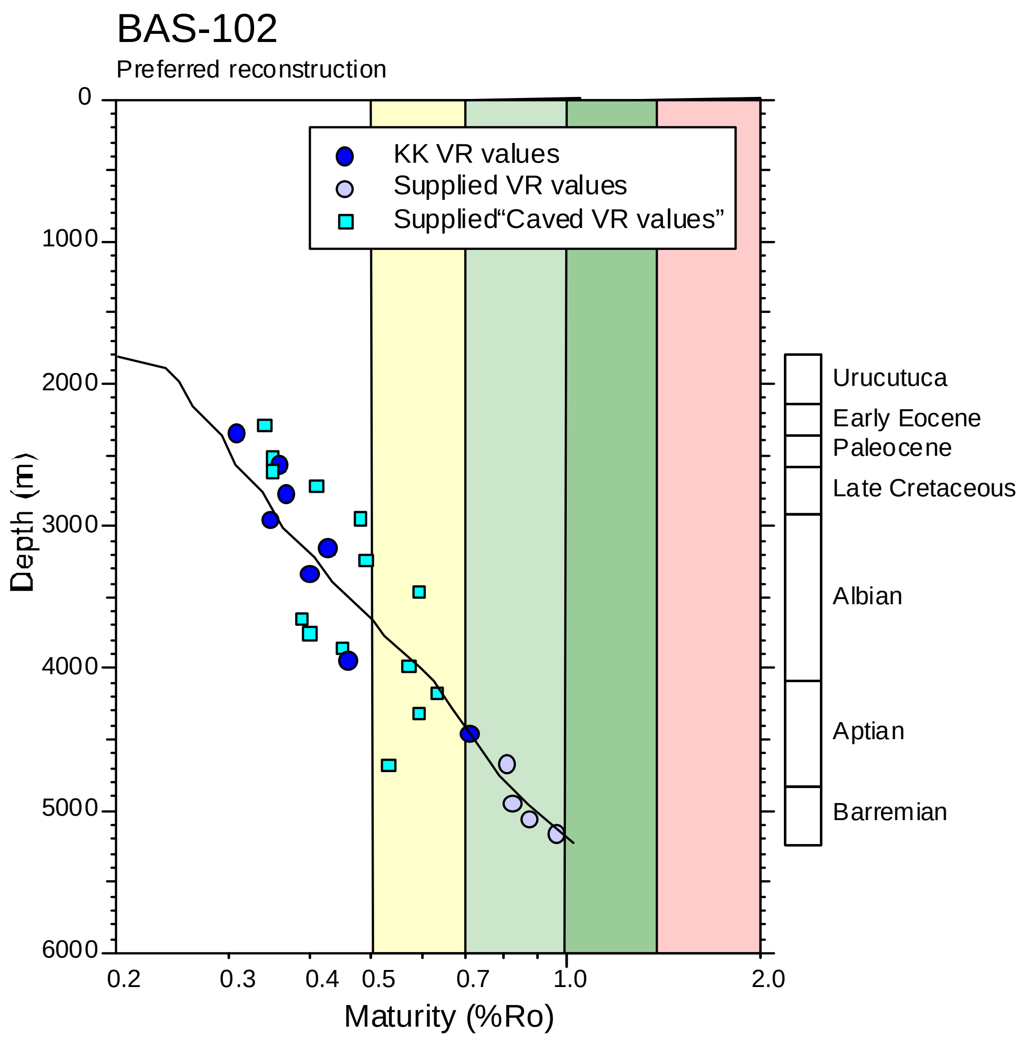


Figure 7-7. *Vitrinite reflectance data regarded as providing reliable indications of maturity levels in* ***Offshore Brasil well 1-BAS-102,*** *plotted against depth, together with the maturity profile predicted by the preferred Thermal History Reconstruction derived from AFTA and VR data in this well. Maturity windows corresponding to different stages of source rock maturation are also shown (Yellow - Early Mature (oil), 0.5 – 0.7%Ro: Light Green – Mid Mature (oil), 0.7 – 1.0%Ro: Dark Green – Late Mature (oil), 1.0 – 1.3% Ro: Light Red - Main Gas Generation, 1.3 – 2.6%Ro). Early Cretaceous units intersected in this well span the Early to Mid Mature (oil) windows. Effects of local heating as seen in AFTA data from sample GC1013-25 are not shown.*

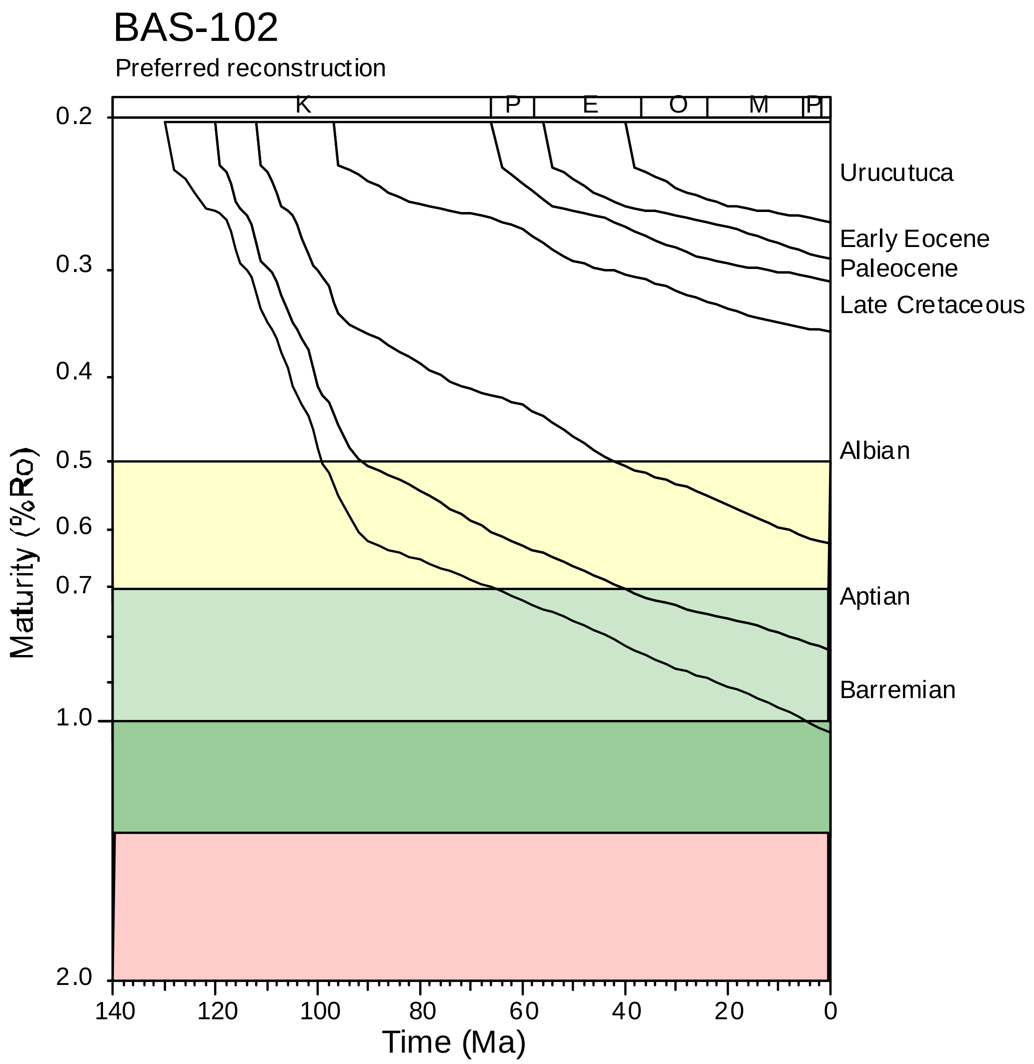


Figure 7-8. *Pattern of maturation vs time for the preserved sedimentary section in the* ***Offshore Brasil well 1-BAS-102,*** *predicted by the preferred thermal history reconstruction for this well. Maturity windows as in Figure 7-7. Effects of local heating as seen in AFTA data from sample GC1013-25 are not shown. In this reconstruction, maturation in all units has continued to the present day and is currently active, with most of the Early Cretaceous section within the oil window.*

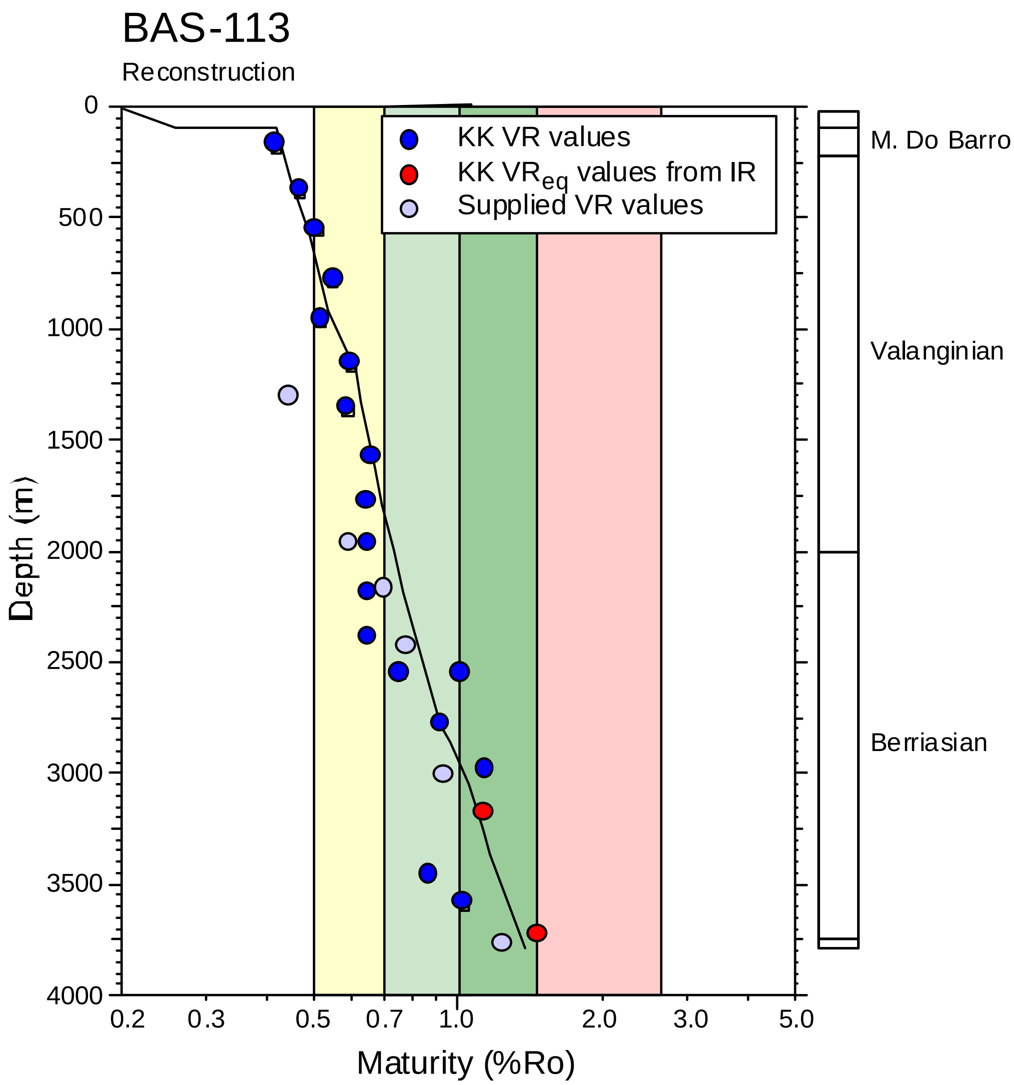


Figure 7-9. *Vitrinite reflectance data and equivalent VR values derived from Inertinite reflectance data in* ***Offshore Brasil well 1-BAS-113,*** *plotted against depth, together with the maturity profile predicted by the preferred Thermal History Reconstructions derived from AFTA and VR data in this well. Maturity windows corresponding to different stages of source rock maturation are also shown (Yellow - Early Mature (oil), 0.5 – 0.7%Ro: Light Green – Mid Mature (oil), 0.7 – 1.0%Ro: Dark Green – Late Mature (oil), 1.0 – 1.3% Ro: Light Red - Main Gas Generation, 1.3 – 2.6%Ro). The Early Cretaceous units intersected in this well span the Early Mature to Late Mature (oil) windows, due to the effects of deeper burial during the Late Cretaceous.*

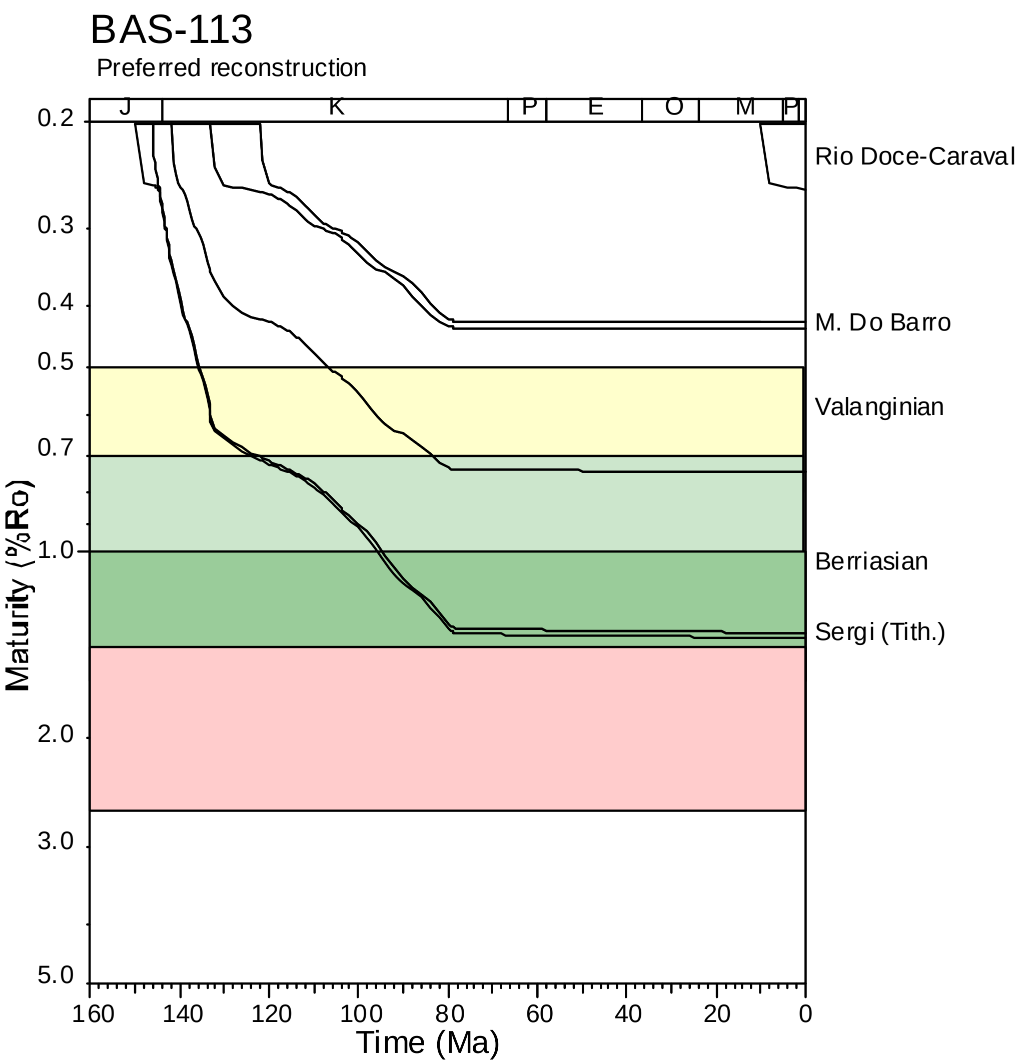


Figure 7-10*. Pattern of maturation vs time for the preserved sedimentary section in the* ***Offshore Brasil well 1-BAS-88,*** *predicted by the preferred thermal history reconstruction for this well. Maturity windows as in Figure 7-9. In this reconstruction, active maturation within the entire section ceased with the onset of cooling at 80 Ma (any time between 90 and 75 Ma is allowed by the AFTA data from this well).*

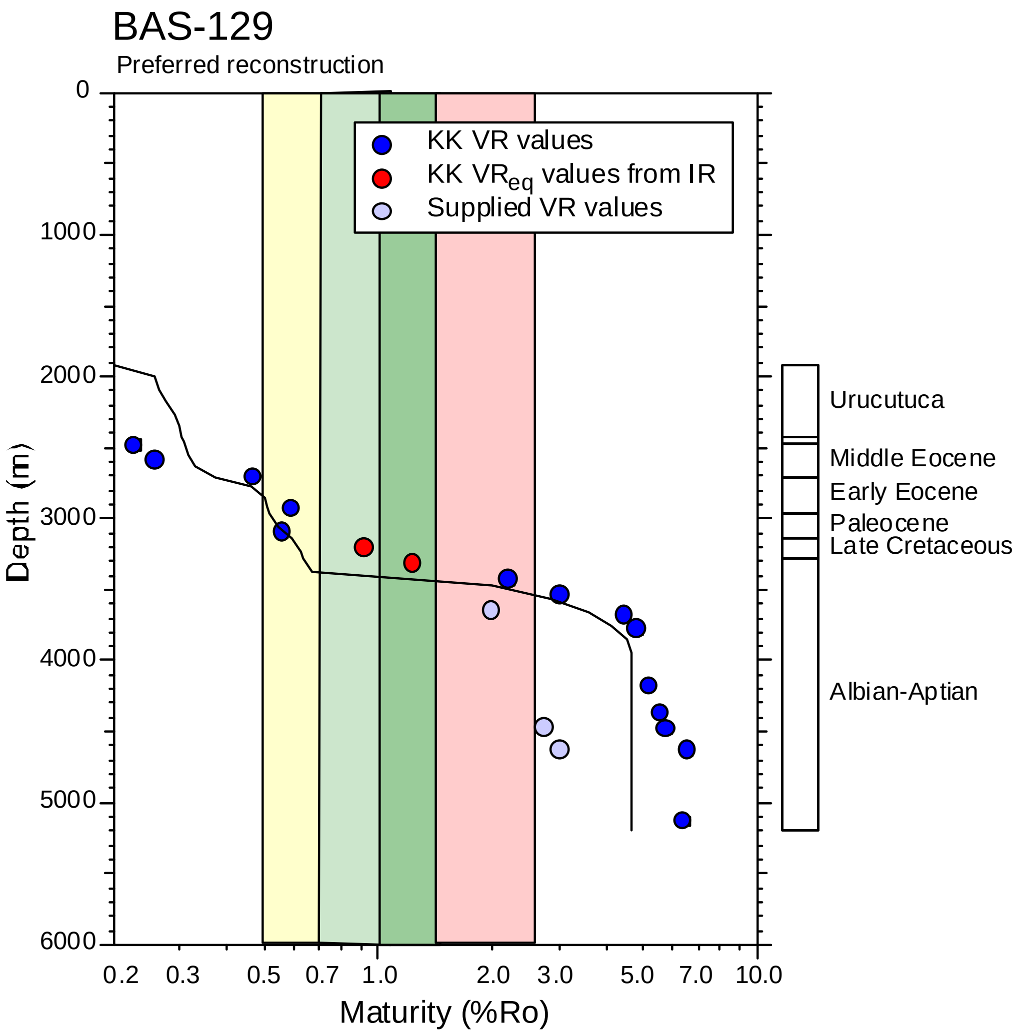


Figure 7-11. *Vitrinite reflectance data and equivalent VR values derived from Inertinite reflectance data in* ***Offshore Brasil well 1-BAS-129,*** *plotted against depth, together with the maturity profile predicted by the preferred Thermal History Reconstruction derived from AFTA and VR data in this well. Note that the fit to the measured VR data is only approximate because of the difficulties in modelling non-linear heating scenarios. In addition, the VR kinetics do not predict values greater than 5% so the mismatch near TD is particularly accentuated. Maturity windows corresponding to different stages of source rock maturation are also shown (Yellow - Early Mature (oil), 0.5 – 0.7%Ro: Light Green – Mid Mature (oil), 0.7 – 1.0%Ro: Dark Green – Late Mature (oil), 1.0 – 1.3% Ro: Light Red - Main Gas Generation, 1.3 – 2.6%Ro). Most of the Early Cretaceous section in this well is post-Mature, while Eocene to Palaeocene (and Late Cretaceous?) span the oil generation windows over a very narrow depth range.*

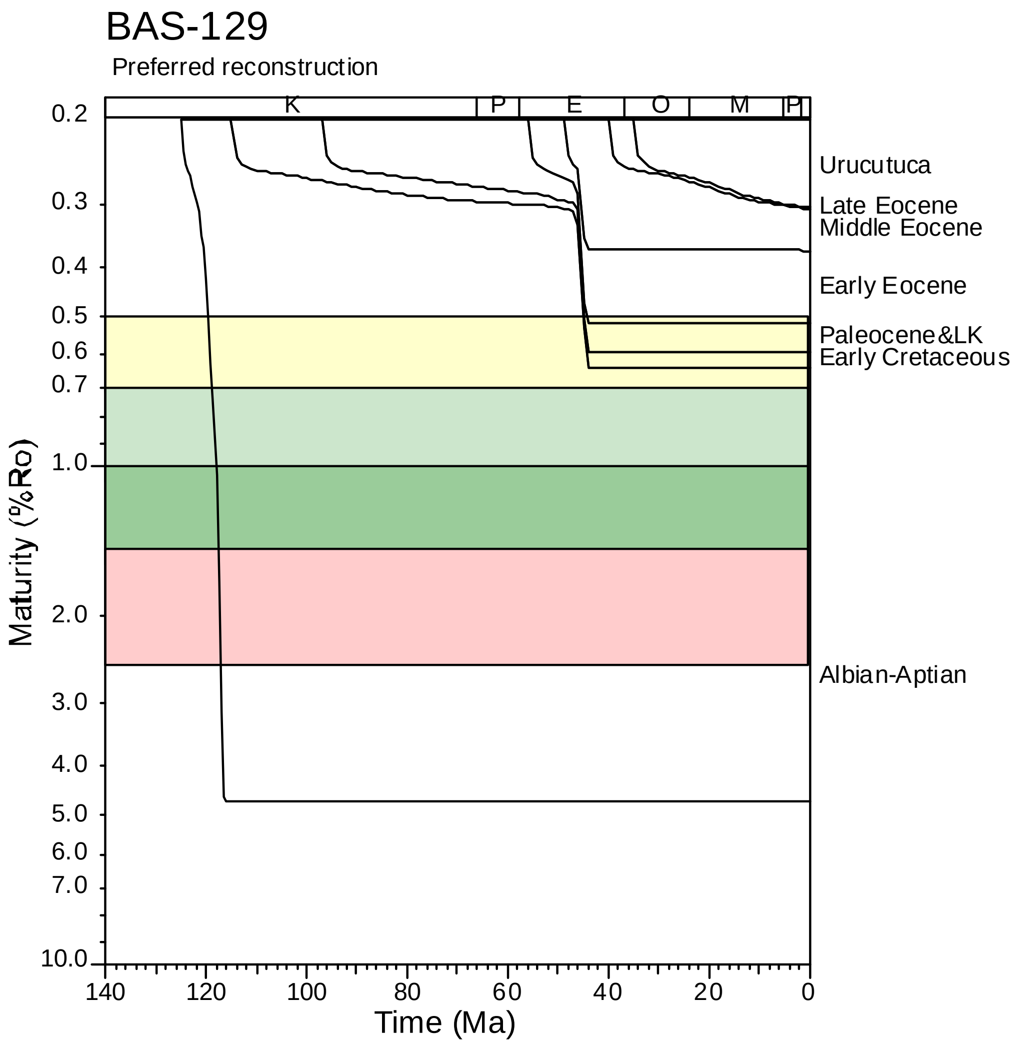


Figure 7-12. *Pattern of maturation vs time for the preserved sedimentary section in the* ***Offshore Brasil well 1-BAS-129,*** *predicted by the preferred thermal history reconstruction for this well. Maturity windows as in Figure 7-11. In this reconstruction, active maturation within the Early Cretaceous section ceased following the hydrothermal circulation episode which AFTA suggests terminated earlier than 110 Ma. Similarly, maturation in Middle Eocene to Late Cretaceous units ceased following the Middle Miocene fluid-related heating episode, in the interval 49 to 45 Ma. Late Eocene and younger units remain immature.*

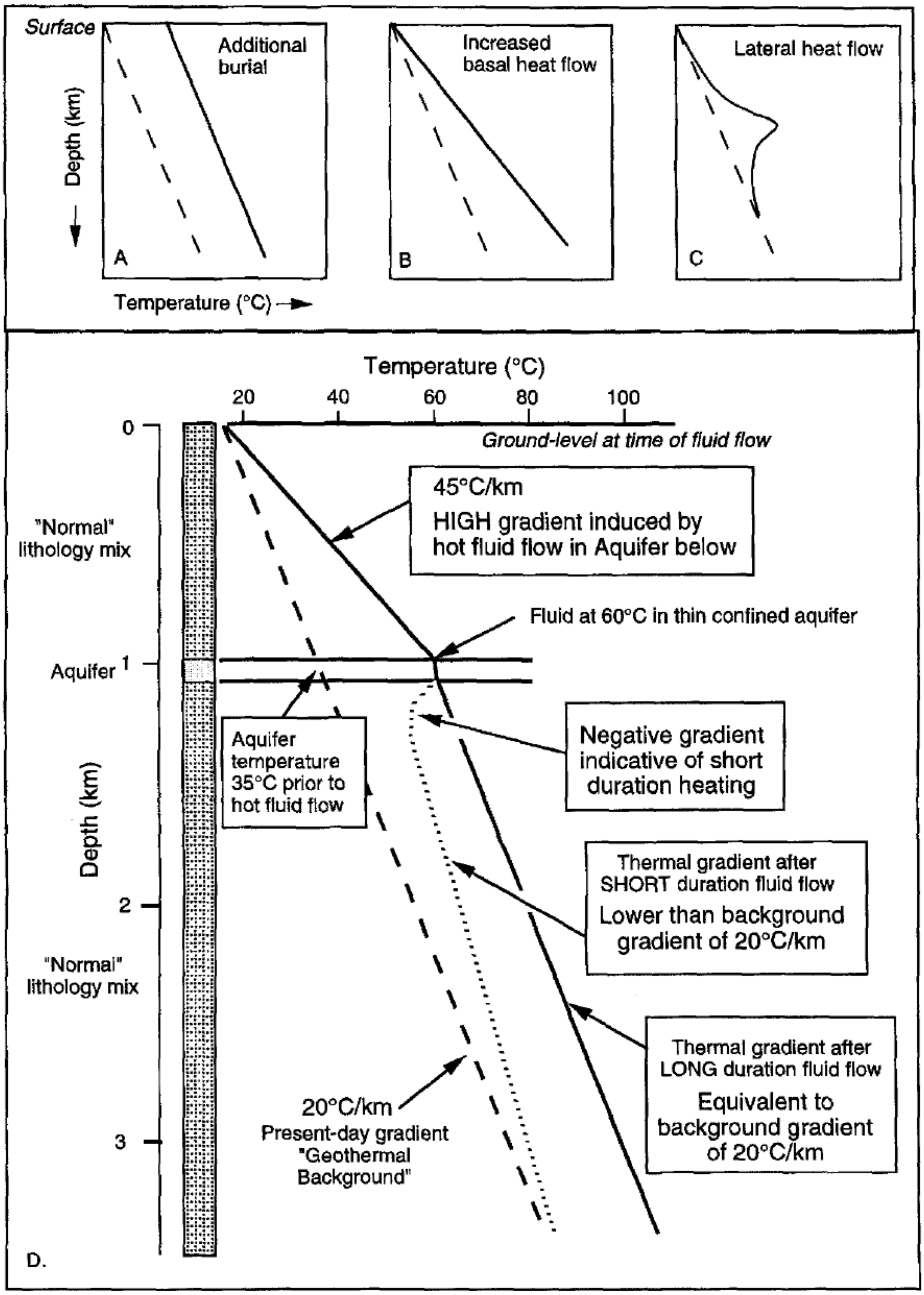


Figure 7-13. *Palaeotemperature profile resulting from different processes: (A) deeper burial with constant basal heat flow. (B) increased heat flow and decline without deeper burial. (C) Bell-shaped profile resulting from a transient increase lateral heat flow in a constant basal heat flow regime. (D) hot fluid circulation. Dashed line represents the present-day temperature profile in each case.*

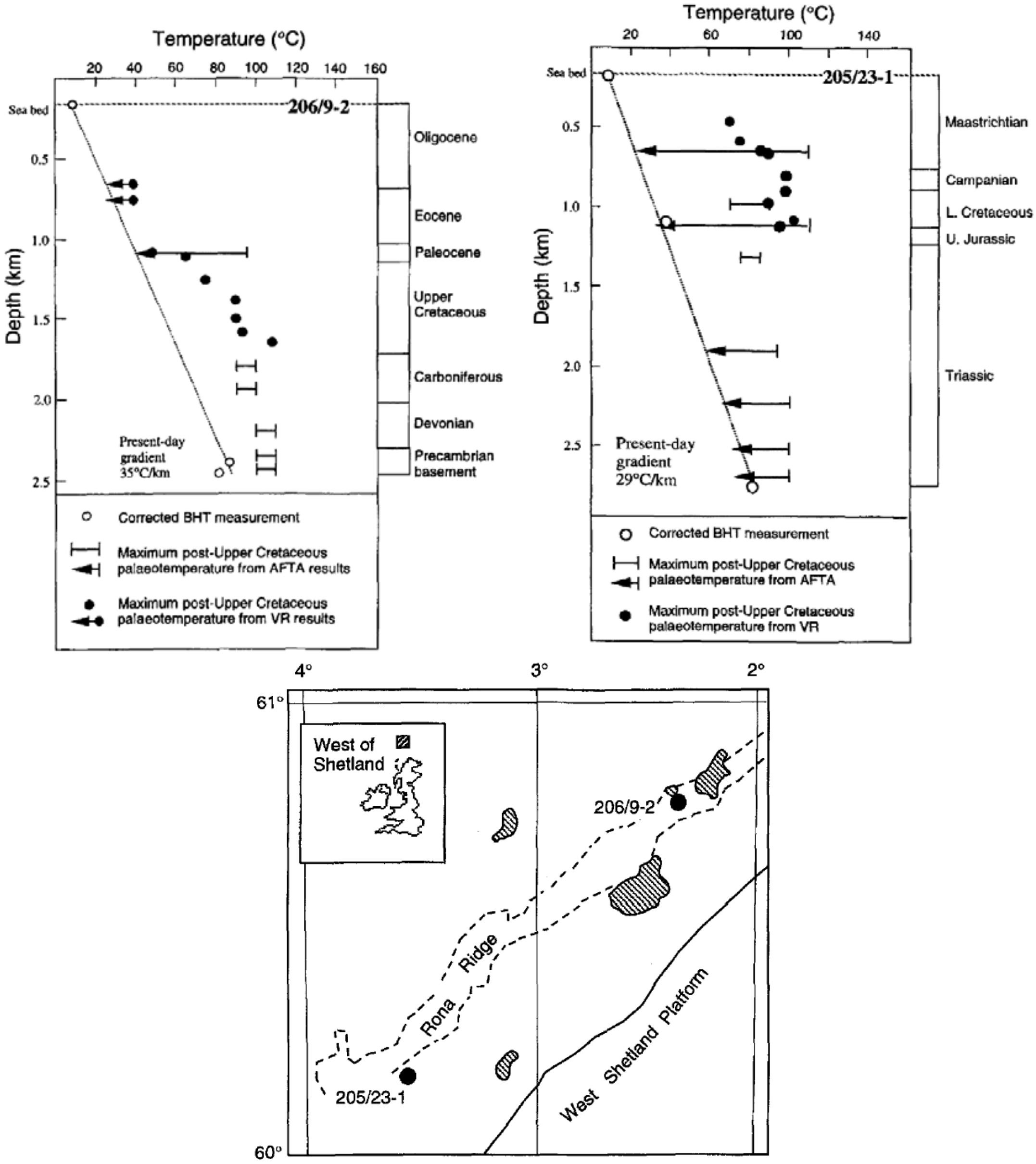


Figure 7-14. *Palaeotemperature profiles defined by AFTA and VR data in two wells from the UK West of Shetland region, illustrating non-linear nature due to introduction of hot fluids at a shallow level in the section.*

8. Comparison of burial and exhumation history in north-east Brazil with results from West Greenland

8.1 Do rift margins reflect rifting?

Many passive continental margins around the world are similar to the Brazilian Atlantic margin; they are characterized by elevated plateaus (i.e. large-scale, low-relief, high-level landscapes) at 1 to 2 km or more a.s.l. cut by deeply incised valleys (Fig. 8-1). As in Bahia and near Rio de Janeiro, plateaus and their adjacent coastal plains are commonly separated by one or more escarpments and Mesozoic-Cenozoic rift systems parallel to the coast are commonly present offshore with a transition from continental to oceanic crust further offshore.

McKenzie's (1978) theory of continental stretching predicts deposition of a thick post-rift sequence overlying the rift and its margins. Despite this, most geological and geomorphological studies of elevated passive continental margins are based on the assumption that the absence of post-rift sediments is evidence that none were ever deposited, that elevated margins have remained high since rifting or break-up and that the elevated plain along the margin is close to a pre-breakup surface (e.g. Weissel & Karner 1989; Gilchrist & Summerfield 1990; Ollier & Pain 1997). Low-temperature thermochronology studies are commonly interpreted in terms of denudational histories following this pattern (e.g. Gallagher et al. 1994; Brown et al. 1999), as are numerical modelling studies that attempt to show how erosional processes act on newly formed rifted margins to create the present-day topography (e.g. van der Beek et al. 2002).

8.2 Post-rift subsidence interrupted by uplift and exhumation

In this report we have presented observations to support a new model for the post-rift development of onshore and offshore areas of north-east Brazil by integrating a study of the burial and exhumation history with an analysis of the landscape development. The Brazilian Atlantic margin is classic example of rifting followed by sea-floor spreading, but our analysis has shown that its post-rift development in many aspects differs from that predicted by classic rift theory. The obvious deviation between classical rift theory and the geological facts of the Recôncavo–Tucano Basins is the limited post-rift sequence (the Marizal Fm, <400 m). Whereas Magnavita et al. (1994) found evidence to support that <2 km post-rift section had been deposited and then removed, others have based their analyses on the apparent limited post-rift subsidence in these basins to draw conclusions about e.g. the properties of the lithosphere (e.g. Karner et al. 1992). Our results have shown that a <3 km post-rift section was deposited in agreement with classical rift theory, but in contrast to the prediction of this theory it was removed after maximum burial in the Campanian after c. 35 Myr of burial and subsidence.

We have shown here that the landscape in the study areas in Bahia and around Rio de Janeiro developed during the Neogene, long after breakup in the Early Cretaceous. In Bahia the landscape is dominated by two main peneplains, a higher surface (HS) and a lower surface (LS) that were both formed as low-relief erosion surfaces. The higher surface developed during the Paleogene after removal of a 2-3 km thick cover that was present in the Campanian. Towards the end of the Paleogene this regional peneplain was reburied until Miocene uplift starting between 18 and 15 Ma led to the removal of most of this cover and to the formation of the lower surface during the Neogene by river incision below the higher surface that is now at an elevation around 1 km a.s.l. The thickness of the Oligocene–Miocene cover on the higher surface in the interior of the study area was several hundred metres thick whereas this cover may have been more than 1 km thick in the coastal region. The non-fossiliferous, continental deposits found today over many plateau remnants in Brazil, such as the Chapada de Canga and Serra do Martins Formations, are probably the remains of this cover. Deposits of the Sabiá, Barreiras Inferior and Rio Doce Formations may also have contributed to the burial along the coast.

West Greenland is another example of an elevated passive continental margin along the Atlantic, where one major difference relative to the Brazilian margin (apart from the present climate) is that rifting and sea-floor spreading happened much later, c. 65 Myr (Fig. 8-1). In West Greenland, where rifting occurred during mid-Cretaceous and earliest Paleocene times, km-thick Paleogene post-rift volcanic sequences with incursions of marine sediments at 1.2 km a.s.l. are exposed in mountains reaching above 2 km a.s.l. (Chalmers et al. 1999). Japsen et al. (2006) analyzed these landscapes by combining the cooling history from AFTA data with the denudation history from landscape analysis (Bonow et al. 2006a, b) and the stratigraphic record. These results demonstrate that post-rift subsidence and burial continued until the end of the Eocene when sea-floor spreading ceased between Canada and Greenland (Chalmers & Pulvertaft 2001). Maximum burial of the post-rift sequence (end-Eocene) was followed by uplift in which up to 1 km of the post-rift sequence was removed, forming a regional, low-relief planation surface (or peneplain) that was graded to sea level during the Oligocene-Miocene. This erosion surface (the upper planation surface, UPS) was offset by reactivated faults and uplifted to present-day altitudes of up to 2 km. Broad and uplifted paleo-valleys incised below the surface (the lower planation surface, LPS) demonstrate that the uplift took place in two phases and AFTA data date this uplift to the last 10 Ma. These results clearly show that the present-day elevated passive continental margin in West Greenland is not a remnant of the rifting process, but developed much later as we have shown here, also to be the case for the Brazilian margin.

8.3 Time available for the formation of peneplains

In Figure 8-2 we compare the post-rift development in NE Brazil (this study) and West Greenland (Japsen et al. 2006). It is seen that maximum burial (coloured circles) took place tens of millions of years after break-up, c. 35 and 30 Myr, respectively, and that maximum burial was followed by several phases of uplift and exhumation (vertical coloured bars) that are unexplained by the theory of rifting.

In Brazil, the plateau surfaces are defined by the HS while they are defined by UPS in Greenland.

- The HS was formed by denudation that occurred after maximum burial in the Campanian, but most likely after the Eocene uplift phase and prior to reburial of the HS after c. 30 Ma. This leaves a minimum of c. 17 Myr for the formation of the HS.
- The UPS was formed by denudation after maximum burial at the Eocene–Oligocene transition and the Late Miocene uplift (possibly before Miocene reburial of the surface). This leaves a minimum of c. 23 Myr for the formation of the UPS.

The time available for the formation of these regional peneplains is thus in both cases around 20 Myr (possibly more in the Brazilian case).

In Brazil, the LS forms an extensive surface below the plateaux, whereas the LPS in Greenland is a generation of paleo-valleys incised below the UPS.

- The LS was formed by incision below the HS between the Miocene and the Quaternary uplift events (before deposition of Barreiras Superior) and this leaves c 14 Ma for the formation of the LS. The magnitude of the Miocene uplift is >1 km (removal of several hundred metres of cover plus a vertical displacement of up to 700 m estimated from the vertical separation between the HS and LS in the interior of the study area. The vertical separation between two surfaces is reduced towards the coast and no significant offsets in the separation (indicating faulting) have been observed within the study area.
- The LPS was formed by incision below the UPS between the Late Miocene and the Latest Miocene–Pliocene uplift event and this leaves c. 6 Ma for the formation of the LPS. The magnitude of the Late Miocene uplift is up to 1000 m, but with significant variations on a lateral scale of 100 km.

There is thus about double as much time available for the formation of the LS in north-east Brazil than for the formation of the LPS in Greenland. This seems a reasonable result given that the LS is a more extensive surface than the LPS.

In Brazil, the coastal plain is incised below the LS and is rather restricted to the immediate coastal areas, but along some of the major valleys the plain reach far inland, but the extent here is narrow. In West Greenland the incision is also restricted to the present day valleys, however the incision patters have been totally rearranged due to glacial erosion.

- The coastal plain was formed after the Quaternary event for which the timing is low, maybe in the order of 100 to 200 m.
- The present-day valleys in Greenland were formed after uplift in the latest Miocene–Pliocene for which the timing is somewhat broadly defined. The magnitude of this event is up to 1 km, but with significant variations on a lateral scale of 100 km.

Despite the uncertainty, there is clearly much more time available for the latest phase of incision in the Greenland case where the magnitude of the uplift is much larger than in Brazil.

A time span of Myr appears to be needed to form regional peneplains, but in both cases the initial topography of the resistant basement is unknown and may have been regional surfaces of low relative relief; e.g. produced by pre- or syn-rift uplift movements such as the Jurassic and Aptian events in the study area or due to re-exposure of Paleozoic peneplains in Greenland. When time spans shorter than 20 Myr are available for the incision of the surfaces, there is clearly not time enough to produce regional peneplains, but the difference between two cases highlight that time with stable base-level conditions is a primary controlling factor.

Finally, it should be noted that there is a marked degree of synchronicity in the landscape development of the two areas. In Brazil, the HS is an Eocene–Oligocene peneplain whereas the UPS in Greenland was formed during the Oligocene–Miocene, after c. 47 and 33 Ma, respectively. It is thus tempting to speculate that this broad mid-Cenozoic time interval represents a period of relative tectonic quiescence (although earlier in Brazil than in Greenland). Furthermore, the present landscape was formed after Neogene uplift in both cases, but uplift was earlier in Brazil than in Greenland, c. 17 vs 10 Myr, respectively. The broad similarities between the landscapes – plateau remnants at elevations of 1 to 2 km a.s.l. – can thus be explained by broadly similar events that occurred around 10 Myr later in Greenland than in Brazil: Formation of mid-Cenozoic peneplains that are dissected after Miocene and varying degrees of Plio-Pleistocene uplift. It is beyond the scope of this report to determine whether this pattern is the result of common underlying forces or merely the result of random processes.

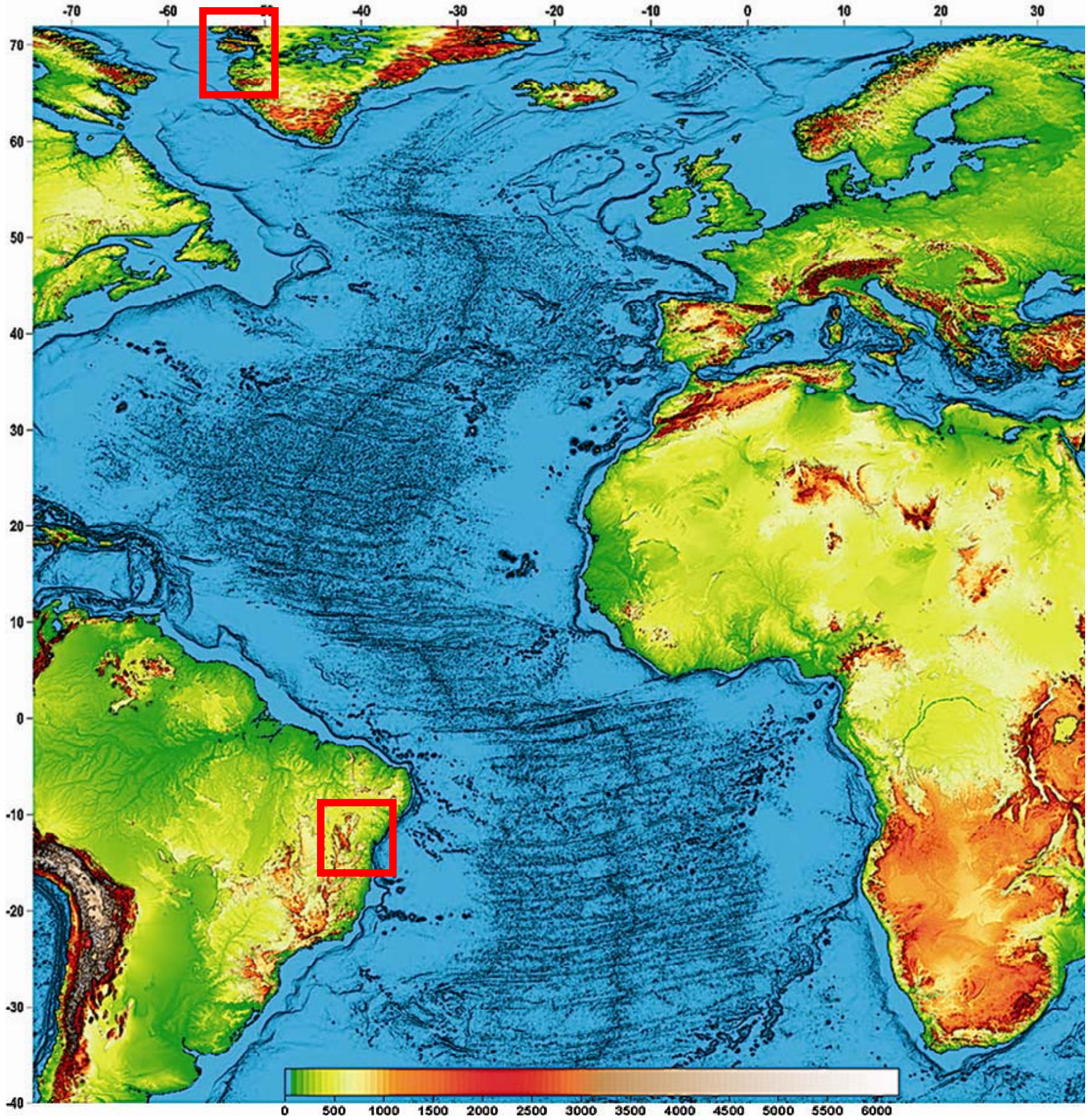


Figure 8-1. *Topography of the Atlantic region with indication of the study areas in Brazil and Greenland.*

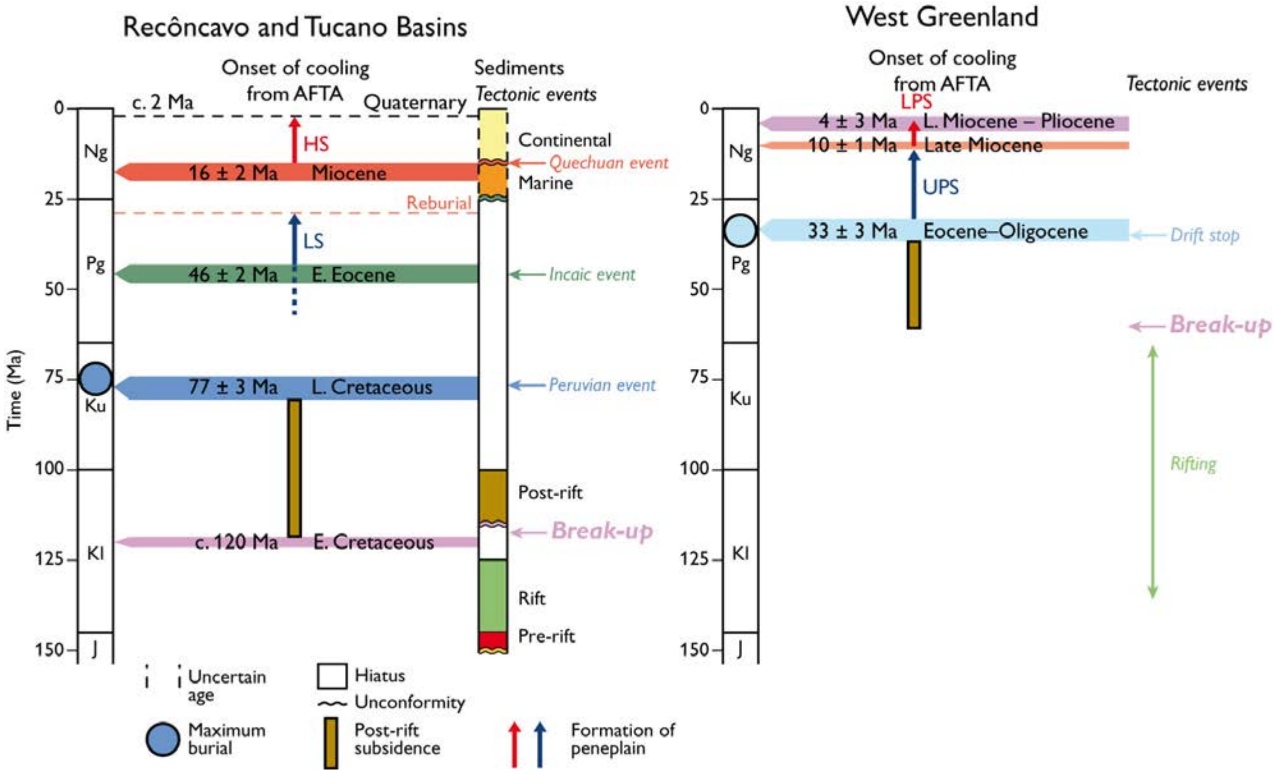


Figure 8-2. *Comparison between timing of post-rift uplift events and of maximum burial for the rift sequences in NE Brazil (this study) and West Greenland (Japsen et al. 2006). In both cases, maximum burial takes place tens of millions of years after break-up, c. 35 and 30 Myr in these two cases, but only a minor part of the post-rift sequence is preserved in the Recôncavo-Tucano rift. Furthermore, maximum burial is followed by several phases of uplift and exhumation that are unexplained by the theory of rifting (e.g. McKenzie 1978). The timing for the onset of cooling (uplift) is estimated from AFTA data, but the timing of the Quaternary event at c. 2 Ma is estimated from immature incision of rivers into soft sediments in the coastal region of NE Brazil. Red and blue arrows mark the time intervals available for formation of erosion surfaces. HS and LS: Higher and lower surface in NE Brazil; UPS and LPS: Upper and lower planation surface in West Greenland.*

9. Suggestions for further work

This study has successfully defined the major aspects of the tectonic development of northeast Brazil and the development of the landscape across the region, as well as the maturation histories of source rocks in Mesozoic rift basins and the offshore Camamu Basin. While the conclusions of the study are for the most part well defined, some remaining areas of uncertainty exist, and in the following we discuss various lines of investigation which may shed new light on these issues.

9.1 Further constraints on the burial and exhumation history of NE Brazil

Fieldwork combined with further AFTA and VR analyses at specific locations would establish further constraints on the post-rift evolution of north-east Brazil, as outlined below. These investigations are considered essential for trying to resolve the enigmas related to the origin of the Brazilian chapadas and planaltos.

Chapada do Araripe, Borborema

A study of AFTA and VR in outcrop samples along the slopes of Chapada (following up on the work of Morais Neto et al. 2008a), in combination with borehole material from deep wells in the area, and analysis of these with respect to the present plateau surface would provide improved constraints on both the timing and magnitude of exhumation of exhumation. This region is important because Upper Cretaceous sediments are preserved, and the geological evidence will provide a more complete framework for interpreting the AFTA and VR data than in areas where the post-rift section has been removed.

Chapada de Canga, Minas Gerais

A study of AFTA data in outcrop samples from the top of the plateau where the Eocene Fonseca Formation and the overlying Chapada de Canga Formation is found near Belo Horizonte and along the slopes of the Chapada will allow us to identify if there has been a significant post-Eocene cover on the plateau and possibly if the Chapadão Fm could be part of that cover (if samples for the two formations show evidence of having been heated equally). Without access to borehole samples (from mining companies?) the constraints on the possible amount of burial will be wide but still allow us to identify whether a considerable Cenozoic cover has been present. A further advantage of this study is that it will be possible to include samples from areas in Minas Gerais where weathering profiles have been dated (e.g. Spiers et al. 2006).

These programs would benefit from regional geomorphological mapping in the areas to the west and south of the present study area. Such overview mapping could be based on the experience from the detailed mapping carried out in this study and should include part of the Cretaceous cover in the Sanfranciscana Basin and part of Minas Gerais including Belo

Horizonte and the Eocene Fonseca outlier in order to use the geological constraints in the denudation chronology.

Recôncavo-Tucano-Jatobá basin system

While the AFTA and VR data in this study define extremely reliable definition of the Campanian as the onset of exhumation in these basins, and show very uniform thermal histories within each basin, published evidence suggesting major variation in the depth to the top of the oil window across the Tucano Basin suggests that further complexity exists in the regional tectonic framework. Analyses of wells at various locations around the basin would allow us to map out the magnitude of post-rift section that has been removed, as well as possibly identifying regions where a definite paleo-thermal disparity exists across the Aptian unconformity (perhaps close to the basin margins, as suggested by Magnavita et al, 1994). Extending these studies to the third element of the Mesozoic rift system of NE Brazil, the Jatobá Basin, would also allow mapping of the extent of exhumation, to test the suggestion from this study that the total amount of section removed since the Campanian increases from south to north.

9.2 A study of the burial and exhumation history of the Santos and Campos Basins

A study of AFTA, VR and sonic data from deep wells in the Santos and Campos Basins will throw new light on the burial and exhumation history of the basins in combination with the new results about the Cenozoic uplift history of the Serra do Mar obtained during this project. Such a study will in particular result in identifying areas in which the Lower Cretaceous rift sediments are no longer at maximum burial, estimating the timing and magnitude of exhumation, possibly defining episodes of exhumation subsequent to maximum burial. An outcome of this study will be to find out when hydrocarbon generation occurred in the exhumed areas and how migration routes may have changed after exhumation changed the basin geometry.

Such a study could be complemented by mapping denudation surfaces in order to gain insight into the Cenozoic tectonic processes in the area. The area west of Serra do Mar is well-suited for such a mapping because of its high topography and coherent surfaces. It seems possible to construct a relative denudation chronology here that may be constrained by the Cenozoic deposits in the region.

9.3 Further study of AFTA data from the Serra do Mar

In the present study, AFTA data have provided very clear and consistent evidence of a series of cooling episodes, which are highly consistent with independent geological evidence for repeated phases of tectonism. But the mechanisms behind these cooling episodes are not clear, and the disappearance of all evidence of the Eocene episode over a distance of 25 km remains enigmatic. Analyses of further samples across the region, with samples collected over a range of elevations as well as over a wide geographic area, would allow the individual episodes to be mapped in more detail. Such analyses would also provide clearer definition of faults responsible for producing offsets in paleo-thermal structure between different locations, allowing a more reliable reconstruction of the processes involved in the development of the modern-day mountain range.

9.4 Further study of AFTA, VR and sonic data from offshore wells

In the present study, AFTA and VR data have been investigated from four offshore wells, with each one showing a very different style of thermal history reconstruction. Analysis of sonic data from a larger number of wells have provided a wide areal coverage and have provided an evaluation – independent of the thermal history – of where the drilled sections are at maximum burial. Analyses from further wells across the offshore region would allow more refined mapping of the paleo-thermal episodes identified in this study, as well as the possible identification of additional episodes. The results of such studies would provide an improved knowledge of the thermal history framework for source rocks in the offshore region, helping to identify more prospective regions where hydrocarbon generation post-dates the formation of potential traps.

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