

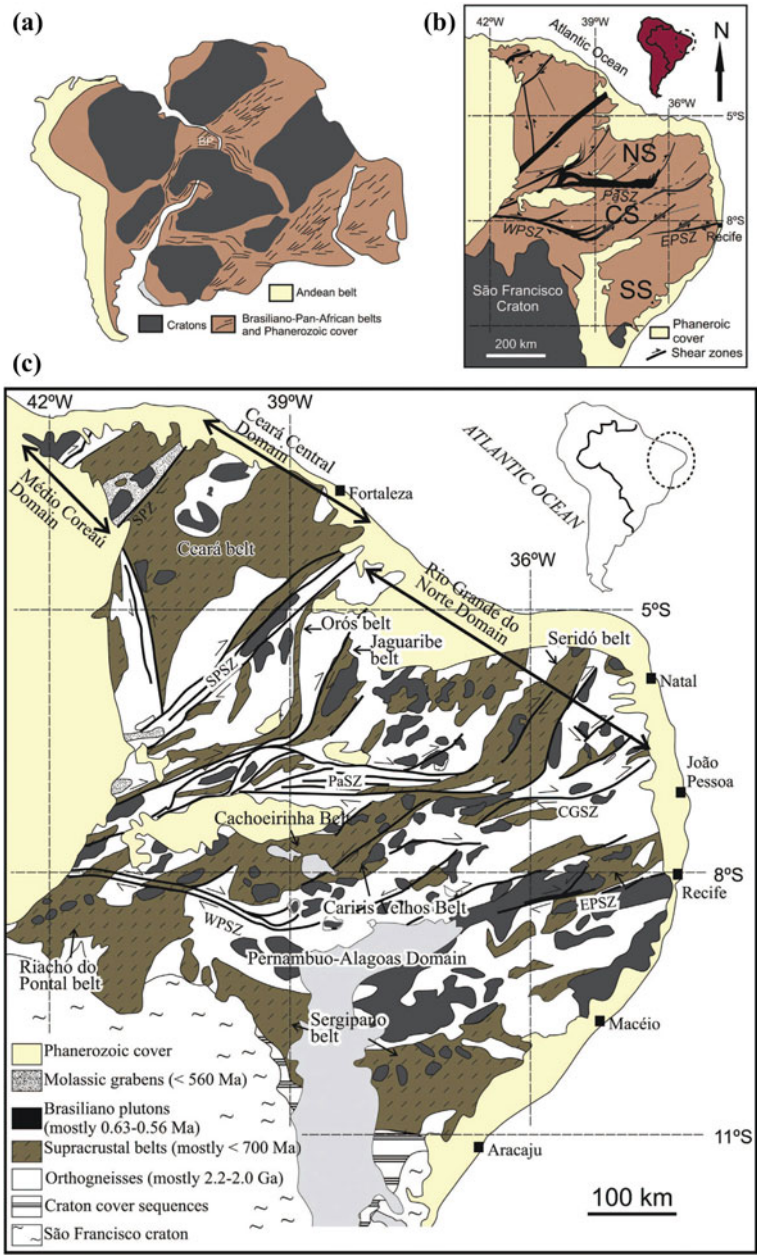
Chapter 2

Geological Setting: The Borborema Province

Abstract The study area is part of the Brazilian Equatorial continental margin, formed after the Equatorial Atlantic opening in Aptian times. Onshore, a Precambrian basement—the Borborema structural province—is subdivided into several geological domains by a wide system of Late Proterozoic shear zones partly reactivated in the Cretaceous. The present structural pattern is organized around a discontinuous NE–SW set of basins and half grabens—the intracratonic Cariri-Potiguar rift zone. Representing failed rift structures of Early Cretaceous age with remnants of their post-rift sedimentary cover, it is intersected by the transform margin in the Potiguar Basin area. Remains of the pre-rift cover of the basement are preserved outside these structures (the Parnaíba Basin, to the west) and inside the rift zone in southern Ceará (Araripe Basin). Along the coast, a thin dissected layer of Cenozoic continental sediments (the Barreiras Group) underlies the low-lying “tabuleiros” between the marginal escarpment and the shallow continental shelf.

Keywords Precambrian basement • Rifting • Oceanic opening • Transform margin • Clastic sedimentation • Volcanism • Northeast Brazil

The area described in this book is part of the Brazilian Equatorial continental margin, formed after the Equatorial Atlantic opening in Aptian times (Matos 2000). Onshore, a Precambrian basement—the Borborema structural province (Almeida et al. 1981; Caby et al. 1995; Arthaud et al. 2008)—is subdivided into several geological domains by a wide system of Late Proterozoic shear zones partly reactivated in the Cretaceous (Fig. 2.1). The present structural pattern is organized around a discontinuous NE–SW set of basins and half grabens—the 500-km long intracratonic Cariri-Potiguar rift zone. Representing failed rift structures of Early Cretaceous age with remnants of their post-rift sedimentary cover (Araripe and Potiguar basins, at both extremities), it is intersected by the transform margin in the Potiguar Basin area (Matos 1992). Remains of the pre-rift cover of the basement are preserved outside these structures (the Parnaíba Basin, to the west) and inside the rift zone in southern Ceará (Araripe Basin). Along the coast, a thin dissected layer of Cenozoic continental sediments (the Barreiras Group) underlies the low-lying “tabuleiros” between the marginal escarpment and the shallow continental shelf.



◀ **Fig. 2.1** **a** Pre-drift reconstruction of South America–Africa showing the Andean belt, Archean/Proterozoic cratons, and Brasiliano/Pan-African provinces of western Gondwana. *BP* Borborema Province. **b** Sketch showing the division of the Borborema Province in Northern (NS), Central (CS), and Southern (SS) subprovinces. Shear zone systems: PaSZ, Patos; EPSZ, East Pernambuco; WPSZ, West Pernambuco. **c** Schematic map of the Borborema Province showing the subdivision of the Northern and Southern subprovinces in the Medio Coreau, Ceará Central and Rio Grande do Norte domains, and in the Pernambuco-Alagoas Domain and Sergipano and Riacho do Pontal belts, respectively. Main shear zones and supracrustal belts are named. Abbreviations for transcurrent shear zones: CGSZ, Campina Grande; EPSZ, East Pernambuco; PaSZ, Patos; SPSZ, Senador Pompeu; SPZ, Sobral; WPSZ, West Pernambuco. From Neves (2015)

Only a few elements of the morphology—fault scarps, structural surfaces—directly reflect this structural pattern. Most other morphostructural features, including the marginal escarpment, the amphitheater pattern, and many medium- and small-scale landforms reflect more complex controls by the interplay of erosion, bedrock resistance, and tectonics (Peulvast et al. 2008).

2.1 The Basement

2.1.1 Structural Framework

The Borborema structural province is composed of “large tracts of Paleoproterozoic gneisses and migmatites surrounding several smaller nuclei of Archean crust” (Santos et al. 2008). These high-grade metamorphic rocks, formed at infrastructural levels and often affected by partial melting, are overlain by remnants of Paleoproterozoic to Neoproterozoic supracrustal rocks, and all of them are intruded by ubiquitous Neoproterozoic granitoids. The province is subdivided into tectonic blocks by branched, anastomosed EW- and NE-trending shear zones which form a mechanical coherent system over more than 200,000 km², one of the largest lithospheric transcurrent shear zone systems in the world (Vauchez et al. 1995; Fig. 2.1). This system, “a gigantic, dextral strike-slip duplex” (Alkmim et al. 2001), belongs to the Brasiliano/Pan-African orogen, the last of the Proterozoic collages which began with the closure of the large Pharusian-Goiás ocean between the Parnaíba and Borborema blocks at 620–600 Myear and progressively consolidated the West Gondwana (Almeida et al. 2000). This phase of generalized crust thickening marked by the development of eclogites and high-temperature thrusting foliation was followed by the dextral northward extrusion of the Borborema province along the set of shear zones during the final closure of the Sergipano ocean between the West Africa and São Francisco-Congo cratons (590–580 Myear: Araujo et al. 2013).

The EW-trending Patos shear zone, in Paraíba and southern Ceará, divides the basement of the study area into two domains: the Northern Domain, to the north, and the Transverse Zone domain, to the south (Ferreira et al. 1998a). According to these authors and to Vauchez et al. (1995), at least six crustal blocks are recognized in the Northern Domain, five of which are represented here, from NW to SE: the

Médio Coreau, Central Ceará, Schist Belt, Rio Piranhas, and Seridó tectonostratigraphic units (Fig. 2.1). The last three units correspond to the Rio Grande do Norte block of Santos et al. (2008). In most of these, Proterozoic cover sequences represented by former cratonic to pericratonic sediments, locally of rift type, rest upon a Paleoproterozoic continental basement (Caby et al. 1995; Monié et al. 1997).

Between the Sobral-Pedro II (or Transbrasiliano) and Senador Pompeu shear zones, in the 200-km wide *Central Ceará domain*, the basement is formed by monotonous orthogneisses of tonalitic to granodioritic composition, migmatitic granites, and migmatites, and remnants of amphibolites and metasediments from former greenstone belts (southern Ceará), of Paleoproterozoic age, but reworked from a mostly Archean reactivated basement (Caby and Arthaud 1986; Monié et al. 1997; Fetter et al. 1999). Better preserved Archean terranes are identified within this domain. In its southern part, between the Farias Brito Shear Zone and the Patos Lineament, the Granjeiro Unit (2.55 Ga; Arthaud et al. 2008) is made of strongly deformed plutonic rocks (tonalities, granodiorite) cross-cutting mafic metavolcanic rocks and associated metasediments. In central Ceará, the Troia-Pedra Branca massif (Santos et al. 2008), corresponding to the Mombaça and Cruzeta complexes of Arthaud et al. (2.8 and 2.7 Ga) is mostly made of migmatitic gneiss with compositional layering (granodiorite bands alternating with tonalite and granite bands). The overlying cover rocks of the Ceará Group are pelitic to semipelitic schists and paragneisses of high-grade amphibolite facies and Mesoproterozoic age, more or less mobilized and migmatitized, and interlayered with quartzites, marbles, and calc-silicates, with gneisses derived from former sills and laccoliths, and with thick sheets of leucocratic granitoids. They are interpreted as a passive margin-type sedimentary unit, the sedimentation of which began around 750 Myear, following rifting of the Archean/proterozoic basement (Arthaud et al. 2008, 2014).

All these structures have been affected by later development of Himalayan-type plurikilometric nappes (Independência nappes) with westward to southwestward vergence accompanied by reverse metamorphism (presence of migmatites in the upper part of the nappes) and involving both the Archean basement and the Proterozoic units. These nappes are well-identified west and southwest of Fortaleza (Maranguape and Uruburetama klippes) and in central Ceará, where the supra-crustal rocks (amphibolites, meta-arkose, quartzite, calc-silicate rocks) of the Algodões Unit (Arthaud et al. 2008) lie with a flat retrogressive sole thrust upon the less deformed and non-migmatitic foreland (the Troia-Pedra Branca inlier of Archean crust; Santos et al. 2008). To the west, the gneisses of granodioritic and granitic origin of the Tamboril-Santa Quiteria Complex may represent a vast batholith (40,000 km²) intruded in late- to post-tectonic continental magmatic arc of Neoproterozoic age and its fore-arc and back-arc sediments, volcanic and volcanoclastic rocks (665–622 Myear; Fetter et al. 2003; Arthaud et al. 2008). This structure requires the subduction of oceanic crust and implies that an oceanic domain existed in the NW of the Borborema Province prior to the amalgamation of West Gondwana (Santos et al. 2008; Amaral et al. 2011).

Northwest of the Transbrasiliano Lineament or Sobral-Pedro II shear zone, a strike-slip belt reactivating previous sutures (Araujo et al. 2013), the *Médio Coreau*

domain is correlated with the more external part of the Pan-African belt exposed east of the Pan-African suture in Ghana, Togo, and Benin (Monié et al. 1997). To the north, it comprises deformed rocks of Paleoproterozoic origin, mainly represented by the Granja granulite belt (orthogneisses, metapelitic rocks, mafic granulites affected by retrogressive metamorphism during the Brasiliano orogeny). Locally bearing the marks of a Late Paleoproterozoic extensional event (felsic to intermediate volcanic rocks of the Saquinho Volcanic Sequence), this basement complex is unconformably covered by two main supracrustal sequences: the Neoproterozoic Martinópolis and Ubajara groups. The oldest (Martinópolis Group, 775 Myear) is formed of fine-grained sedimentary rocks (schists, quartzites) deposited in an intracontinental rift evolving to marine conditions and then metamorphosed to greenschist or amphibolites facies during the Brasiliano orogenesis (Santos et al. 2008). South of Coreau and of the Arapa fault, the Ubajara Group, mainly made of metamorphosed slate, siltstone, sandstone, and carbonates, represents a proximal, stable-shelf sedimentary sequence. To the south, this metamorphic sequence is adjacent to a Late-Brasiliano (Early Paleozoic) molassic or rift basin (the narrow Jaibaras trough, between the Café-Ipueiras fault and the Transbrasiliano Lineament: Oliveira and Mohriak 2003). These last units are described further (Chap. 3), together with the Brasiliano and Late-Brasiliano structures to which they are related, as well as the latest of the granitic intrusions that intrude the basement rocks and the sedimentary sequences. One of these granites (the porphyritic granite of Chaval, in the NW of the domain) is slightly older (591 ± 10 Myear: Fetter et al. 2000), and was affected by the Brasiliano deformation.

To the southeast of the Senador Pompeu shear zone, along which the Quixadá-Quixeramobim synkinematic batholith and the Mombaça granulites are exposed, the *Schist Belt domain* (part of the Rio Grande do Norte block) displays a linear trend on hundreds of kilometers, with spectacular bends. It is made of an association of antiformal gneiss cores representing the pre-Brasiliano basement rocks, and of synformal schist belts of the Proterozoic cover, that have only undergone low-pressure metamorphic conditions (Monié et al. 1997). Between the Óros and Jaguaribe shear zones, the *Óros-Jaguaribe* belt is made of two subparallel, sinuous, and narrow (40 km in the south, 4 km in the north) synformal quartzitic, calcareous and metapelitic zones derived from the former sedimentary and volcanic rocks formed in an intracontinental rift 1.79 Ga ago (Fetter et al. 1999). This belt is preserved in a Brasiliano structure which does not correspond to a deep lithospheric discontinuity (De Castro and Costa 1999), but has played an important role in the subsequent evolution. It separates through a steep tectonic contact, the westerly migmatitic domain from a wide easterly *Rio Piranhas domain*, composed of polycyclic pre-Brasiliano basement gneisses (Vaucher et al. 1995), and severely intruded by Brasiliano granitoids. To the east, in the *Seridó belt*, the lower pre-Brasiliano granitic-gneissic basement (Caicó complex) crops out as elongated NNE–SSW domes and synformal metasedimentary units (carbonates, metapelites, and quartzites) between belts of the younger Neoproterozoic cover (Jucurutu, Equador, and Seridó Formations, <650 Myear; Caby et al. 1995; Neves 2002; Arthaud et al. 2008).

South of the 20–30-km wide mylonitic and migmatitic Patos dextral shear zone, a probable suture of Neoproterozoic age running EW for 300 km (Costa et al. 2002), the *Transverse Zone domain* is represented in the study area by several terranes in which late Mesoproterozoic supracrustal belts alternate with blocks of Archean to Paleoproterozoic high-grade gneisses and migmatites. They are widely intruded by numerous Brasiliano plutons of varied compositions (Ferreira et al. 1998b).

2.1.2 *Brasiliano and Late-Brasiliano Structural Heritage*

The structural pattern of the basement is mainly inherited from the Brasiliano orogeny. In the study area, this orogenic cycle is the result of an end-Proterozoic, probably oblique, convergence between the West African-São Luis Craton, in the west, and the Congo-São Francisco Craton, in the southeast, following a rifting stage recognized in western Ceará around 800 Myear (Martinópole and Independência Groups: Fetter et al. 1999). This phase of crustal stretching would have been controlled by slab pull forces generated by outwardly dipping subduction zones, with formation of oceanic crust after ca 700 Myear, only to be subducted shortly afterward (Neves 2015). Therefore, the Borborema Province is mainly the result of a dominantly intracratonic evolution. Trench retreat and slab rolling back of the plate would have led to collision of the different terranes of the Transbrasiliano Belt with the passive margin of the paleocontinent, giving rise to the beginning of contractional deformation. 880–800 Myear old rocks with juvenile characteristics recently discovery in the Tamboril-Santa Quitéria Complex of the Ceara Domain (Araújo et al. 2014) could be slices of arc rocks transported southwards.

The main tectono-metamorphic events (620–580 Myear) generally culminated in the amphibolite facies (Monié et al. 1997). They were followed by the intrusion of a large volume of syn- to late-kinematic granitoids, by late-orogenic transcurrent movements under decreasing temperature conditions until 500 Myear, and by opening of molassic grabens in Ceará (Trompette 1994; Almeida et al. 2000). Earlier cooling occurred in the outer part of the belt, especially in the northern Medio Coreau domain by 575–560 Myear, whereas to the south of the Senador Pompeu shear zone, the inner part experienced cooling later, in the range 550–500 Myear (Monié et al. 1997).

Many important morphological features are controlled by the huge ductile lithospheric faults which cross-cut the region. These faults belong to a vast system where, in the pre-drift situation, “EW-trending lineaments, more than 1000 km long from NE Brazil to Cameroon, merge into NE-trending lineaments that run about 3000 km from central Brazil to Hoggar” (Vauchez et al. 1995). Steeply dipping, they are typically 1–10-km wide (up to 30 km for the Patos shear zone) and comprise mylonites, migmatites, granulites (e.g., the Mombaça granulite belt) and syn- to late-kinematic granitic plutons and dykes. To the west (Ceará), this system comprises NE–SW shear zones which postdate nappe emplacement (the Granja,

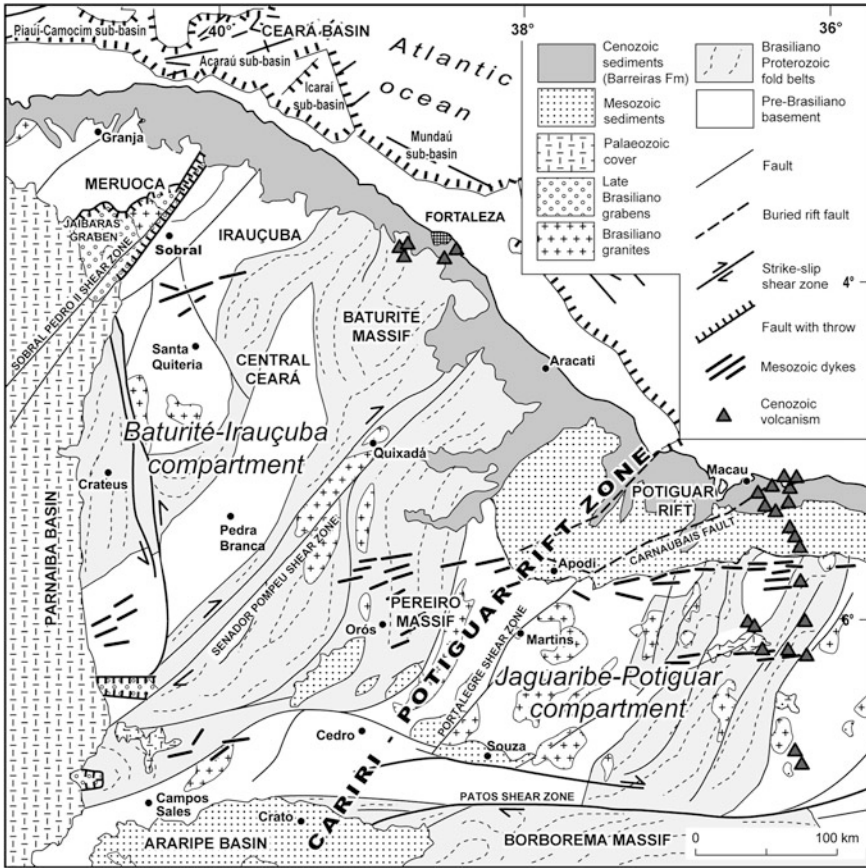


Fig. 2.2 Geological map of the study area, compiled after Brito Neves et al. (2000), Carneiro et al. (1989), and Caby et al. (1995)

Sobral-Pedro II or Transbrasiliano, Senador Pompeu-Quixeramobim, Tatajuba, and Potengi shear zones; Fig. 2.2), and along some of which megafolds and sigmoidal structures locally affect the Mesoproterozoic cover (Tatajuba shear zone near Pio IX: Oliveira and Maas 2002). In the east (mainly Paraíba and Rio Grande do Norte states), sinuous NE–SW shear zones (Jaguaribe, Portalegre) and transpressional belts—the Seridó and Cachoeirinha belts—branch on the EW Patos system. Tectonic activity along these shear zones took place at shallow depths until the Cambrian–Ordovician, and perhaps until the Devonian or later along the Transbrasiliano lineament (tilted and sheared Devonian sandstones near Santana do Acaraú; Arthaud et al. 2008).

The mylonitisation began around 600–570 Myear, in continuity with the previous deformation, forming crystalline nappes and a thickened crust in northern and central Ceará, and upright folding in a dextral transpressional regime without

significant crustal thickening, SE of the Senador Pompeu shear zone (Caby et al. 1995; Monié et al. 1997). This was coeval with the abundant (>50 %) calc-alkaline to alkaline (in the latest stages) magmatism that has formed the syn- and late-orogenic granites (up to 500 Myear). The «younger granites», generally considered as mostly resistant rocks (Godard et al. 2001) are well represented in the Rio Piranhas and Seridó domains, and along the Patos shear zone, but are also present in central and northwestern Ceará, in scattered stocks (Palmacia, in the Baturité massif) and along major shear zones: the Senador Pompeu shear zone (Quixeramobim-Quixadá intrusive complex, ca 600 Myear: Torquato 1989; Almeida et al. 1999; De Castro et al. 2002), and the Transbrasiliano Lineament (Meruoca-Mucambo post-tectonic plutons, ca 540 and 500 Myear: Ferreira et al. 1998b; Nogueira et al. 1997; Oliveira and Mohriak 2003).

Several basins are associated with shear zones, especially in northern and western Ceará (Trompette 1994), where they are partially preserved in pull-apart structures controlled by reactivation of the shear zones in the interval 0.58–0.50 Ga (Arthaud et al. 2008). Reflecting a widespread continental breakup which separated Laurentia and Baltica from West Gondwana without evolving to oceanic opening (De Castro et al. 2014), they generally contain two continental sedimentary sequences separated by an erosional unconformity. The most important, the Ubajara-Jaibaras basin (Fig. 2.2), is linked to the Sobral shear zone. The 3–4 km thick deposits of the Ubajara Group are composed of clastic rocks (red slates, sandstones, arkoses) and carbonates (Freicheirinha Formation, 0.98 Ga: Sial et al. 2002), metamorphosed to upper greenschist facies, and intruded by the Mucambo and Meruoca plutons. Slightly folded, these Late Proterozoic deposits may represent a pre-rift sequence in the development of the continental rifting that would have preceded the formation of the Parnaíba basin (Oliveira and Mohriak 2003). Between two parallel faults of the Sobral or Transbrasiliano shear zone (Sobral-Pedro II and Café-Ipueiras faults), they are covered by the anchimetamorphic, 3-km thick, clastic fluvial deposits of the Jaibaras Group, which are also intruded by the Meruoca granite, probably emplaced in a pull-apart structure (Teixeira et al. 2004), and by other magmatic rocks (sills and dikes of the Parapuí suite). Considered by Destro et al. (1994) as late-orogenic molassic deposits of fluvial origin formed in a narrow graben (5–10 km), they include conglomerates and sandstones (the Massapê basal unit, Vendian-Cambrian), fine sandstones, siltstone, and shales (the Pacujá Formation, of fluvial to lacustrine origin), and finally conglomerates with clasts of plutonic/volcanic rocks (Mucambo/Meruoca plutons, Parapuí suite). This structure is interpreted by Oliveira and Mohriak (2003) as an aborted rift branch developed in a previously thickened lithospheric-crustal system after the Brasiliano orogeny, between the West African and Brazilian cratonic nuclei, and slightly inverted, before the sag subsidence of the intracratonic Parnaíba basin in the Silurian.

Other occurrences of coarse continental clastic and volcanic-sedimentary rocks are known in grabens of northern Ceará (Sairi-Jaguarapi), eastern Ceará (Sitiá) and southern Ceará (Cococi, Catolé-São Julião, Barro; Teixeira et al. 2004; Fig. 2.2).

Large parts of the orogen were already deeply eroded and even planated at the onset of the Silurian-Devonian post-orogenic sedimentation. The influence of their

structures on the present morphological pattern is only indirect. Later faulting was strongly controlled by zones of weakness (Maia and Bezerra 2014a), whereas the complex tectonic and lithological patterns of this orogen allowed a generalized contribution of differential erosion to landform shaping.

2.2 Post-orogenic Rocks and Structures: Pre-rift Deposition and Magmatism

2.2.1 The Post-orogenic Sedimentary Cover

The basement sedimentary cover is geographically and stratigraphically discontinuous. The distribution of its elements reflects strong tectonic and geomorphic controls. The main sequences are Paleozoic deposits of a large sedimentary basin—the Parnaíba Basin—the syn- and post-rift deposits of the Mesozoic Cariri-Potiguar rift zone and of the transform margin, and a thin coastal fringe of Cenozoic sediments.

The study area comprises the eastern edge of the Parnaíba Basin (Serra da Ibiapaba), a large sedimentary basin centered on a set of Cambrian-Ordovician grabens formed during the last stages of the Brasiliano orogeny (Almeida et al. 2000; Oliveira and Mohriak 2003; De Castro et al. 2014). Its basal layers—fluvial to coastal or neritic conglomerates and sandstones of the Ordovician-Devonian Serra Grande Formation, a few hundreds of meters thick—, grade upwards to finer sandstones. They are flat-lying or slightly tilted westwards, and lie unconformably on the eroded faulted structures and intrusions related to the Sobral shear zone. The metamorphic or igneous substrate is often deeply weathered, as shown by thick kaolinized horizons outcropping below the Ibiapaba escarpment (e.g., Ubajara, Ipu; Fig. 2.3a). The abrupt erosive edge of the basin and the presence of remote outliers, mainly in NW Ceará (graben of Santana do Acarau, on the Sobral shear zone: Destro et al. 1994; Galvão and Da Silva 2002) and southern Ceará, suggest that the initial size of the Parnaíba Basin was much larger and was reduced by erosion at later times. In southern Ceará, the Cariri Formation is considered by some authors as a counterpart of the Serra Grande Formation outside the Parnaíba basin (Hegarty et al. 2002; Assine 2007). Its quartz conglomerate and coarse sandstone layers (former alluvial fans and braided streams), as well as the overlying deposits of the Late Jurassic (Callovian-Tithonian) pre-rift sequence of the Araripe basin (Brejo Santo and Missão Velha Formations), fill an irregular basement topography. They are preserved in small faulted basins located in the Patos shear zone (Lavras da Mangabeira, Barro) and also outcrop at the periphery of the Araripe Basin (Matos 1992), below the Cretaceous deposits (Nova Olinda, Juazeiro do Norte, Milagres...). On the contrary, such sediments are not found below the Cretaceous deposits of the other basins of the Cariri-Potiguar rift

Fig. 2.3 **a** Ipu (between Sobral and Crateus, south Ceará); the Serra da Ibiapaba, a sandstone glint (Serra do Grande Formation) overlooking the strongly weathered and excavated metamorphic basement, as seen to the south. Slightly dissected pediments below the high sandstone ledge. **b** The north spur of the Serra de Portalegre. The top of this dissected mesa corresponds to a thin layer of lateritized fluvial sandstone (Serra do Martins Formation).
Photographs J.P. Peulvast



zone and of the margin (Matos 1992, 2000), and more elevated regions might have existed to the north of the Patos shear zone.

Many deposits considered as pre-Cretaceous in age rest on a deeply weathered and kaolinized basement with a typical etch morphology. The same was observed for similar flat-lying sediments (coarse quartz conglomerate, sandstone and siltstone layers with oblique stratifications of fluvial origin, coming from distant regions of the basement in the south: Menezes and Lima Filho 1997; Menezes et al. 2002) which cap the small Portalegre, Martins and Santana mesas, south of the Potiguar rift (e.g., north of Portalegre: Fig. 2.3b).

Classically dated as Cenozoic on the basis of lithostratigraphical analogies with mid-Tertiary sediments of the margin (Tibau and Guamaré Formations of the Potiguar Basin; Mabesoone et al. 1972; Saadi and Torquato 1992; Jardim de Sá et al. 1999), and considered by many authors as a key deposit to understanding the morphotectonic history of the Borborema massif (Ab'Sáber 2000; Morais Neto and Alkmim 2001), this so-called Serra do Martins Formation presently occurs as narrow erosive remnants in a culminating position, without any identified source area. Its deposits, a few meters to 50-m thick, are locally intruded by a Late Oligocene (25 ± 1 Myear) basaltic plug (Serrote Preto, Serra De Santana: Morais Neto et al. 2002) and are, therefore, older than Late Oligocene. Deeply weathered and capped by thick laterites, lacking fossils, they could be considered as older than

is generally accepted, corresponding to Eocene (Jardim de Sá et al. 1999), Paleocene (up to 64 Myear: Morais Neto et al. 2008) or even older deposits (Peulvast et al. 2008). A diachronous post-Ordovician, pre-Cretaceous sedimentary cover exists or has probably existed in several parts of the area, belonging to the Parnaíba Basin or to smaller basins whose nearby source areas might have been paleo-fault scarps and local uplifts related to late-orogenic or pre-rift movements (Martill 1993). It had already been eroded before the Cretaceous, or had never been deposited, in the areas presently occupied by the continental margin (Matos 2000) and by most continental rifts north of the Patos shear zone.

2.2.2 Early Magmatism and Rifting

Whereas the final rifting and continental separation occurred during the Aptian, Albanian, and Cenomanian (Matos 2000), deformation associated with the South Atlantic opening began earlier, during Jurassic-Triassic time (225–160 Myear), accompanied by early extension and magmatic activity within the Gondwana supercontinent (Maurin and Guiraud 1993; Guiraud and Bellion 1995). The widespread fluvial and shallow sedimentation of Late Jurassic age known in the Recôncavo-Tucano-Jatobá, Sergipe-Alagoas, and Araripe basins is interpreted by some authors as recording the early phase of crustal stretching (Matos 1992; Martill 1993).

Pre-rift magmatic activity is only known north of the Patos shear zone, with a roughly EW array of mafic dykes (olivine-free diabases)—the Rio Ceará Mirim Dyke Swarm—which may be related to this early phase of crustal stretching. This swarm was intruded in the basement of the Borborema Province during two main pulses around 145 and 130 Myear (Tithonian-Hauterivian; Sial et al. 1981; Almeida et al. 1988; Oliveira and Gomes 1996; Mizusaki et al. 2002) or 134–110 Myear (Hauterivian-Aptian; Hollanda et al. 2006). This 400-km long tholeiitic dyke swarm is mainly identified from the southern border of the Potiguar basin to the Jaguaribe valley between the Iguatu and Icó basins, widening from 30 to 100 km. Probably associated with the initial stages of the formation of the Potiguar basin (Françolin and Sztamari 1987), it forms an arcuate array trending from N90°E (northeastern Borborema Province) to N55°–70°E in the southwest, where the dykes become nearly parallel to the NE-trending Eocretaceous rift system (Matos 1992; Fig. 2.4).

2.3 The Continental Rift

The occurrence of well-dated Mesozoic and younger sedimentary basins in the northern Nordeste is restricted to the rift structures and the transform margin formed during the Cretaceous as a result of the separation between Africa and South America. Therefore, they are found in the intracratonic Cariri-Potiguar rift zone or depression (Matos 1992; Valença et al. 2003), an aulacogen of Early Cretaceous age,

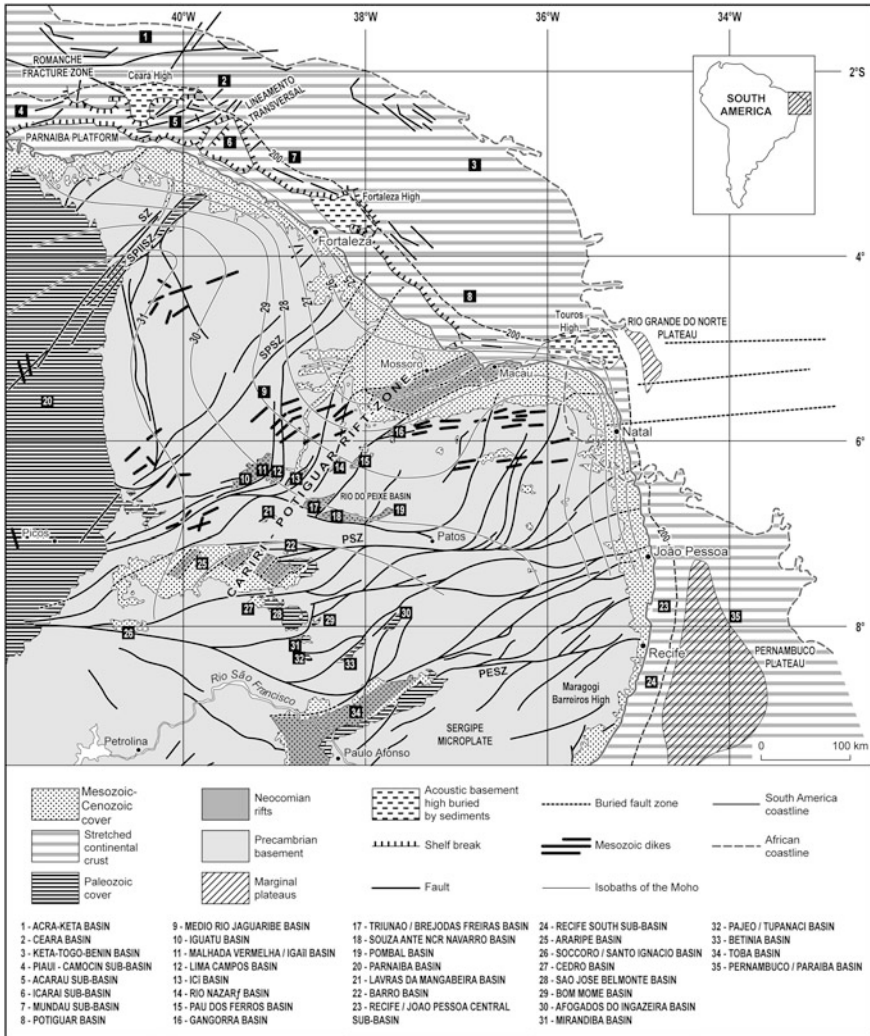


Fig. 2.4 Structural map of the Borborema province, showing the pre-, syn-, and post-rift structures along the Cariri-Potiguar rift zone. Compiled from Matos (1992, 2000) and Valença et al. (2003)

and along the Equatorial Atlantic margin, whose formation was initiated by almost instantaneous oblique extension during the Aptian stage (Matos 2000). According to this author, the intracontinental and offshore basins of the study area can be grouped into two ages: Neocomian-Barremian and Aptian. The location and architecture of the first group are strongly controlled by upper crustal heterogeneities—the shear zone systems of the Borborema province—, whereas the second group was not significantly influenced by this heritage, indicating different processes of lithospheric thinning.

2.3.1 Limits of the Rift Zone

According to Matos (1992), the Cariri-Potiguar basins typically consist of asymmetric half grabens separated by basement highs, transfer faults, and/or accommodation zones. Most of these are a few tens of kilometers wide with a NE–SW trend, perpendicular to the extension direction. Master normal faults are often controlled by Proterozoic shear zones (Orós, Jaguaribe, Portalegre; De Castro et al. 2012), but the Rio do Peixe Basin was also formed in left-lateral transtensional conditions along the EW Patos shear zone (Françolin et al. 1994). Together with minor isolated basins (Tarrafas, Pau dos Ferros, Nazaré, Gangorra), they are grouped in a 150 km wide, 500-km long NE–SW zone, from the offshore Potiguar basin to the Araripe basin (Fig. 2.4). Most of their asymmetric structures dip to the SE, like the wide basement blocks which form their shoulders, the Aracati Platform–Central Ceará highlands to the NW, and the Touros High–Borborema to the SE.

Since the presently observed basins mainly represent erosional remnants, the timing of the last stages of sedimentation and rifting processes as well as the initial limits of the rift zone are not precisely known, but the shallow topography of the basement on both sides precludes the former existence of other deep basins outside the present limits. However, the structural control of the southern edge of the Parnaíba basin by the SW continuation of the Senador Pompeu shear zone (Carneiro et al. 1988) suggests some post-Paleozoic reactivation of this fault zone, which could have belonged to *en échelons* systems of antithetic border faults reinforcing the rotation of the hanging wall block on the NW margin of the Cariri-Potiguar rift zone (Fig. 2.5).

Faulting and tilting of basement blocks related to passive preopening stretching may have occurred in a wider region, outside the Cariri-Potiguar rift, as suggested by the width (300–400 km and more) of the rifting zone south of the study area. In spite of the lack of Mesozoic sediments, faulting related to Cretaceous rifting may be inferred along a few Proterozoic shear zones. The most probable case of reactivation is recorded on the Sobral-Pedro II shear zone (NW Ceará) by the intense, transpressional deformation of an early Devonian sandstone body preserved at low altitude as an outlier of the Parnaíba basin in the Santana do Acaraú graben, about 30-km long and 4-km wide (Destro et al. 1994; Galvão and Da Silva 2002). The age of the reactivation is poorly constrained. According to Arthaud et al. (2008), it might correspond to the continuation of tectonic activity along the Transbrasiliano lineament during the Devonian. However, the identification of similar structures along the same fault zone in the Parnaíba Basin (Serra da Ibiapaba north of Ipu: Fig. 2.4), and in Aptian to early Cenomanian sediments of the offshore Ceará basin (Costa et al. 1990; Matos 2000) suggests that dextral transpressional reactivation might have occurred in the mid-Cretaceous, possibly related to transform faulting and opening of the Equatorial Atlantic. Downfaulting of the sandstone body along normal faults of a probable pull-apart basin (Galvão and Da Silva 2002), which allowed its preservation from erosion, has occurred earlier, in the Late-Devonian, or during the Early Cretaceous intracontinental stretching phase.

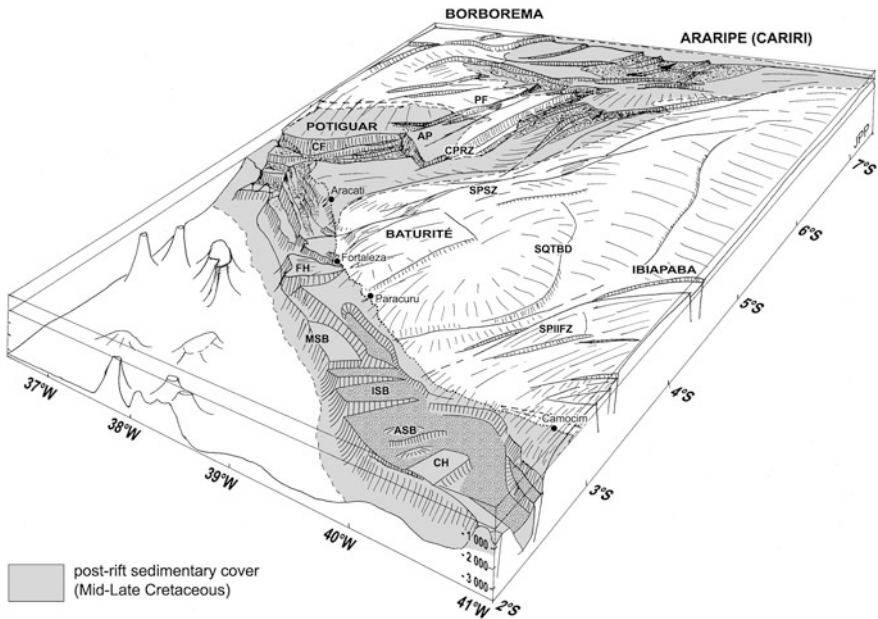


Fig. 2.5 Sketch block diagram of the study area showing the Mesozoic tectonic pattern such as it would hypothetically look like without erosion and post-rift deposition. *Dotted areas* syn-rift deposits. *AP* Apodi transfer fault; *ASB* Acaraú sub-basin; *CF* Carnaubais fault; *CH* Ceará High; *CPRZ* Cariri-Potiguar rift zone; *FH* Fortaleza High; *ISB* Icarai sub-basin; *MSB* Mundaú sub-basin; *PF* Portalegre fault; *SPIIFZ*: Sobral-Pedro II fault zone; *SPSZ* Senador Pompeu shear zone; *SQTBD* Santa Quiteria-Tamboril-Baturité Domain

The limits of the onshore area of crustal thinning related to NW–SE extension in the Cariri-Potiguar rift zone (from 32- to 26-km in thickness: De Castro and Medeiros 1997; De Castro et al. 1997, 2012) do not include the narrow Araripe basins, to the southwest. Therefore, maximum crustal stretching occurred north of the Patos shear zone, in a wide and short area around the Potiguar basin, between the Touros High and the Borborema in the southeast, and the Senador Pompeu shear zone, which forms the limit of the crustal thickening zone of the Central Ceará highlands in the northwest (Fig. 2.4).

2.3.2 The Cariri-Potiguar Rift Zone

In southern Ceará, the Araripe Basin is presently uplifted to 700–900 m above sea level and, due to Late- to Post-Cretaceous regional uplift and topographic inversion, overlooks the surrounding basement areas (Peulvast and Bétard 2015). Below the post-rift cover, the Araripe rift basin is divided into two sub-basins (W: Feitoria or Feira Nova sub-basin; E: Eastern or Cariri sub-basin; Ponte and Ponte-Filho 1996;

De Castro and Castelo Branco 1999; Martill et al. 2007; Assine 2007) separated by the Dom Leme crystalline horst. Inside, numerous NE–SW grabens filled by rift sediments are separated by minor horsts, transfer faults, and/or accommodation zones formed along preexistent sigmoid shear zones connected to the north and the south with the major E–W-trending Patos and Pernambuco shear zones (Corsini et al. 1991; Matos 1992). They contain up to 1800 m of Late Jurassic and Early Cretaceous fluvio-lacustrine sediments lying on the pre-rift series.

Before and during the rifting, fluvial and lacustrine deposits of Jurassic and Early Cretaceous age (Vale do Cariri Group) were deposited upon the sandstone cover of the basement (Mauriti or Cariri Formation, Paleozoic; Martill et al. 2007; Assine 2007; Fig. 2.6). Following a Late Jurassic–Early Cretaceous phase of regional subsidence and continental sedimentation (Brejo Santo and Missão Velha Formations: clay, siltites, sandstones, up to 600-m thick; Coimbra et al. 2002; Valença et al. 2003), the main rifting stage (Berriasian–Early Barremian) was that of graben infilling by thick fluvial, deltaic, and lacustrine sediments transported to the SSW (Abaíara Formation: siltites, sandstones, and conglomerates). In the same time, the intervening basement areas and the overlying sediments were eroded, and then partially beveled during the transitional post-rift stage (Early Aptian), except for some residuals ultimately buried below post-rift series and then exhumed (Horto, Serra do Juá). Along the faults limiting the Crato–Juazeiro do Norte graben, throws and sediment thicknesses reach up to 1000 m (Assine 2007).

Beyond the small isolated grabens of Barro and Lavra da Mangabeira, filled with pre-rift sandstones, and the narrow Tarrafas basin, aligned on the Tatajuba shear zone and filled with Neocomian sediments, two groups of basins are found 80 km to the N and NE. Along the Jaguaribe valley, the Iguatu–Malhada Vermelha–Icó–Lima Campos group consists of NE-trending shallow half grabens, 5–20-km wide, with listric normal faults on their SE sides. Controlled, as the Potiguar basin, by reactivated basement shear zones (De Castro et al. 2008), they are filled with Neocomian continental conglomerates, sandstones, siltstones, shales, and rhythmites (Matos 1992). To the east, the Pereiro horst zone, including a narrow NE-trending graben (Icózinho), separates them from the Rio do Peixe basin. From W to E, this basin is made of four adjacent sub-basins (Triunfo, Brejo das Freiras, Sousa, Pombal: Sénant and Popoff 1991; Françolin et al. 1994), separated from each other by small basement highs and aligned on the EW Patos shear zone which forms the southern limit of the system (De Castro et al. 2007; Nogueira et al. 2015). They correspond to SW–NE or EW (Sousa) trending half grabens, 5–15-km wide, and contain up to 1000–1500 m of syntectonic fluvial and lacustrine sediments of Berriasian to Aptian or Early Albian age. From the base to the top, these deposits comprise conglomerates, sandstones, siltstones, shales, and white calcareous lenses. They are downfaulted and tilted to the SE along the Malta, Portalegre, and Rio Piranhas faults. To the north, the small Nazaré, Pau dos Ferros, and Gangorra basins contain similar deposits, finding their source from nearby fault escarpments (Srivastava et al. 1989; Corsino and Tiriba 1985; Fig. 2.4).

The largest intracontinental basin in the study area is the Potiguar basin, which extends both onshore and offshore in Ceará and Rio Grande do Norte, from about

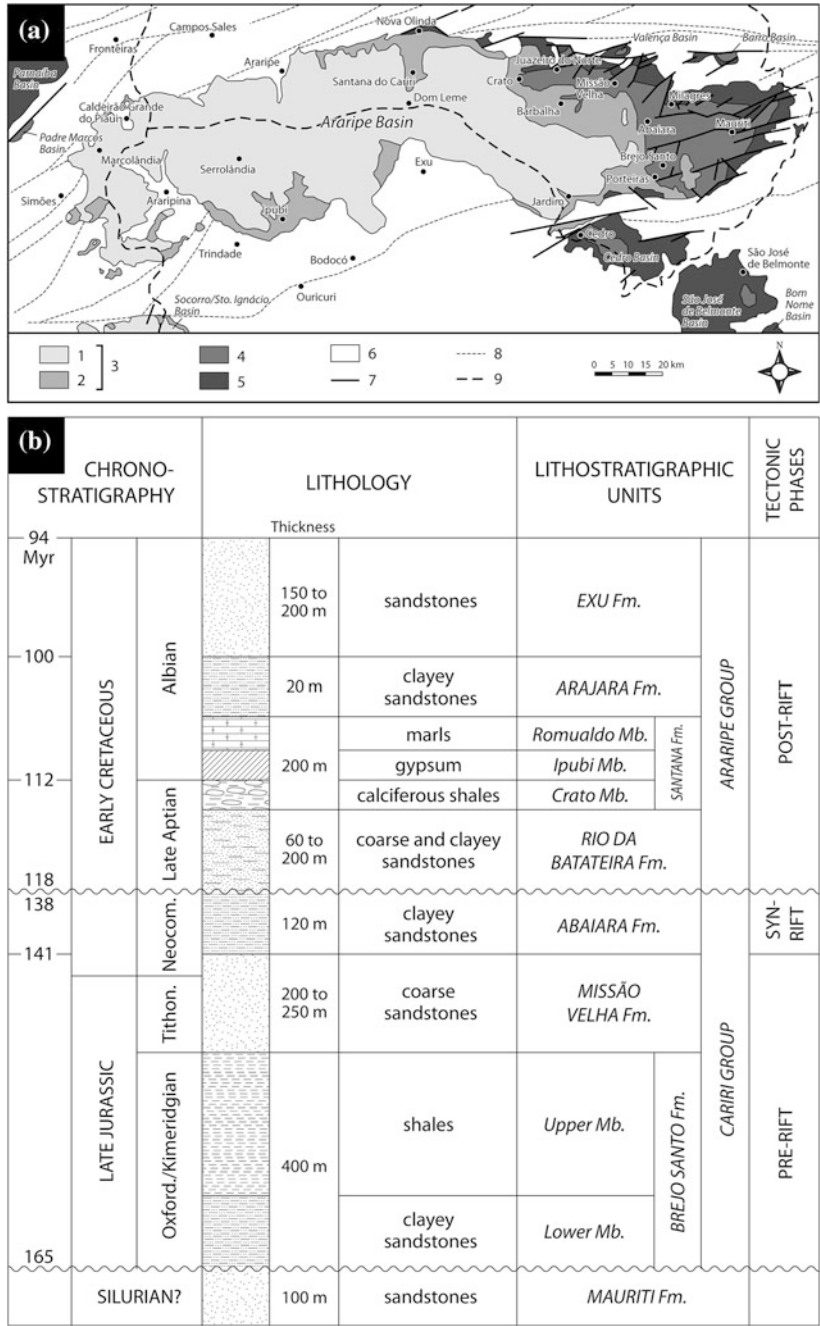


Fig. 2.6 Geological map and stratigraphic log of the Araripe-Cariri region. **a** Map modified from Ponte and Ponte-Filho (1996), Assine (1994). 1 Exu Formation; 2 Arajara, Santana, Rio da Batateira Formations; 3 Araripe Group; 4 Cariri Group; 5 Mauriti Formation; 6 basement complex; 7 fault; 8 lineament; 9 state border. **b** Log compiled from Ponte and Ponte-Filho (1996), Neumann (oral comm. 2008)

200-km inland to the present continental shelf and slope, at least to water depths of 2000 m (Bertani et al. 1990). Reaching 6000 m in thickness, it covers 48,000 km² (including 21,000 km² onshore). The Early Cretaceous rift is entirely covered by the post-rift series of Late Cretaceous age which form the Chapada do Apodi (Fig. 2.7). Below a thin transitional sequence of Aptian-Eo-Albian age, it contains up to 4 km of syn-rift fluvial, deltaic, and lacustrine sediments of Early Neocomian to Early Barremian age. These deposits—mainly sandstones and siltites—are found in two main NE–SW trending half grabens (Umbuzeiro, Boa Vista), separated by horsts or half-horsts which were locally beveled by erosion before the deposition of the transitional series (Quixaba, Serra do Carmo highs) (Neves 1989). To the NE, the Macau basement high separates these grabens from the offshore Macau low. The basins are limited to the SE by major listric faults, the Carnaubais (in the NE continuation of the Portalegre fault: De Castro et al. 2012), and Quixaba-Serra do Carmo fault zones, and to the SW by the NW–SE Apodi transfer fault, which corresponds to the southern limit of the extended crust (Fig. 2.7). The main depocenters are concentrated along the Carnaubais fault.

2.3.3 From Continental Rifting to Transtensional Opening of the Equatorial Atlantic

To the NW of the Potiguar basin, the triangular Aracati platform (Fig. 2.5) is a southward tilted portion of the basement, limited on its northeast side by the offshore continuation of the Potiguar basin. Its northern part includes small *en échelon* offshore transtensional grabens, NW–SE trending, bounded by EW transfer faults, and filled with Late Barremian sediments (Jacaúna and Messejana grabens; Fig. 2.4). Whereas, onshore rifting failed in the whole Cariri-Potiguar rift system by the end of Barremian (Matos 2000), the formation of these basins, contemporaneous with the early rifting stages in the Benue trough in Africa, suggests that the major deformation became from that time onwards located on the Equatorial branch of the rift system. The onset of EW extension generated transtensional conditions in the Potiguar basin, and rift-controlled sedimentation in its offshore parts up to the Fortaleza high, accompanied by southward tilting of the Aracati platform and of the onshore rift system (Matos 1992).

Along the future Equatorial margin, this new early Aptian tectonic phase first induced the formation of NW–SE trending *en échelon* sag-type basins or synclines truncated by a diffuse fault pattern, without typical rift structures and associated sedimentary facies (offshore Potiguar Basin, Ceará Basin: Matos 2000; Fig. 2.8). The transition between continental and marine conditions occurred during the lower Albian in most of these basins (Potiguar, Piauí-Camocim, Barreirinhas). A deep oceanic circulation was already organized between the Equatorial and eastern margins of Brazil during the middle Albian (Benkhelil 1988; Koutsoukos 1992), but the definitive open ocean connection seems to have been established during the Cenomanian-Turonian transition, when the last link of continental crust between Brazil and Africa had subsided (Valença et al. 2003).

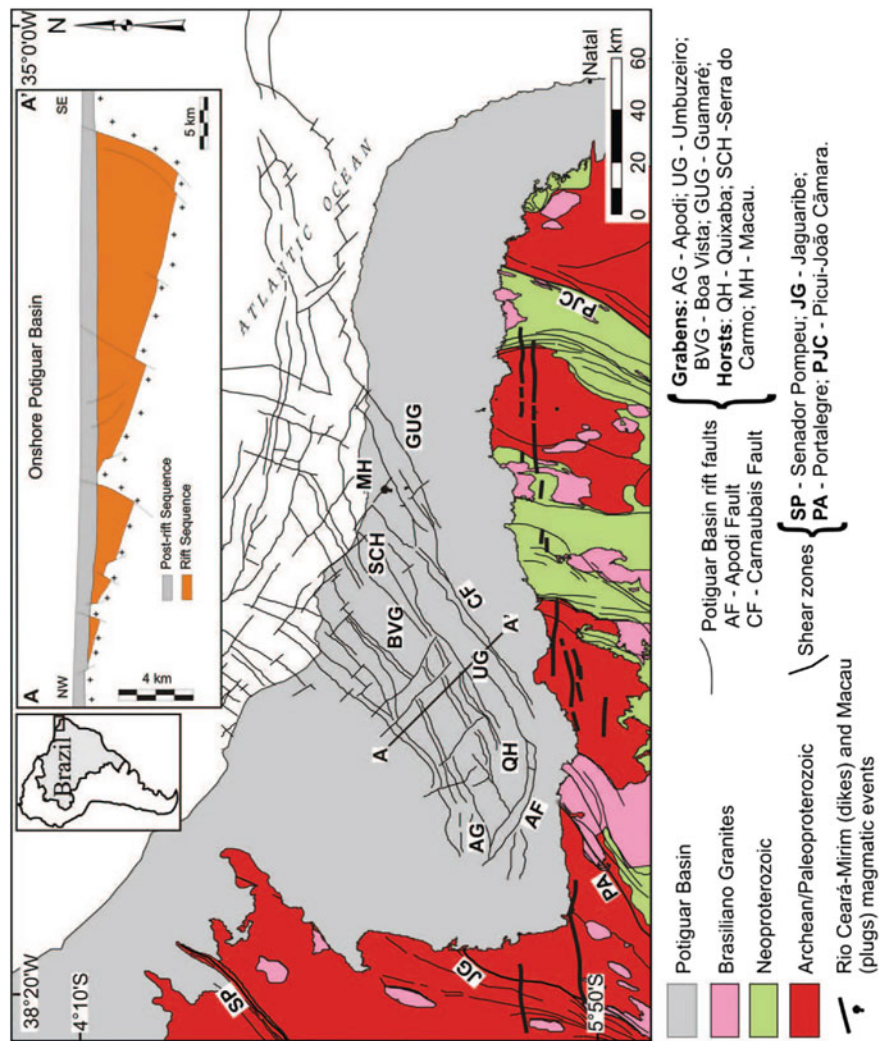


Fig. 2.7 Simplified geologic map of the Potiguar Basin area. From De Castro et al. (2012)

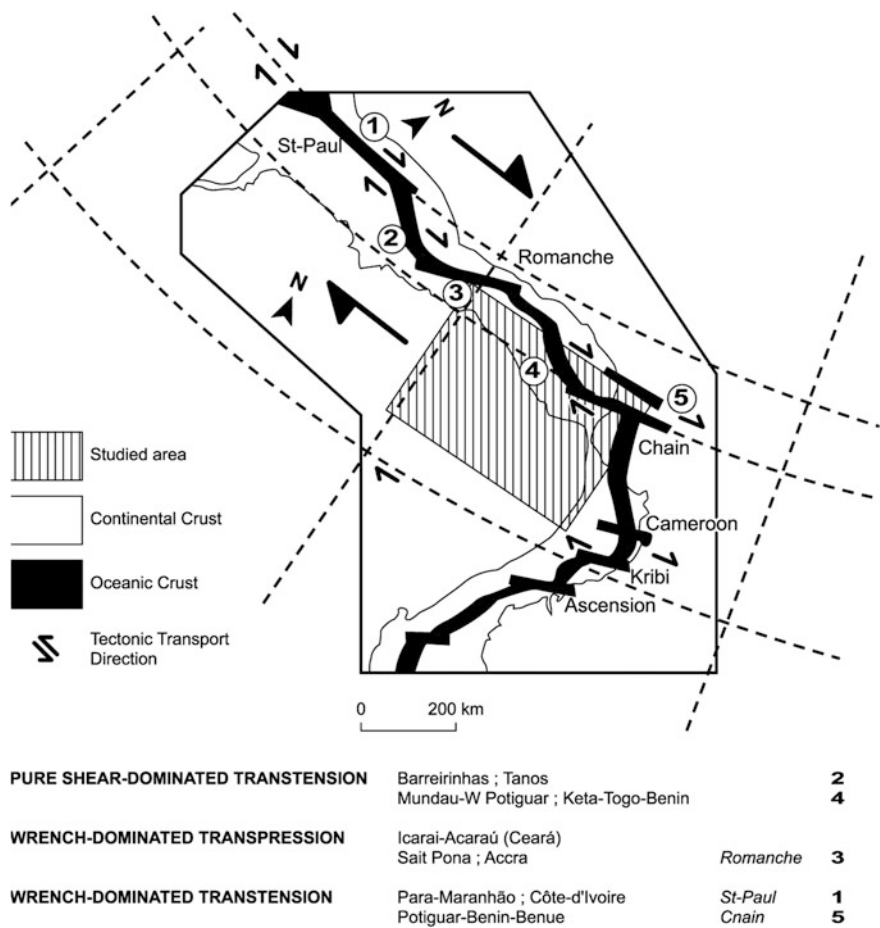


Fig. 2.8 Opening of the Equatorial Atlantic (Albian) and major releasing and restraining bends in the Equatorial shear corridor. Redrawn from Matos (2000)

2.4 The Post-rift Evolution and the Transform Margin

2.4.1 Onshore Post-rift Covers

By the time when transtensional conditions had become prevailing in the Equatorial Atlantic domain, the aborted intracontinental rifts of the Cariri-Potiguar trend had already begun to evolve in post-rift conditions, through thermally induced subsidence (Mello 1989). Until the Cenomanian or Campanian stages, and after a 20 Myear interval of erosion/nondeposition, these rifts and the topographically depressed adjoining areas became locations of widespread sedimentation: first lacustrine or transitional continental/marine, finally continental in the Araripe basin,

or continental and then marine in the Potiguar basin. Transitional syn-rift/post-rift series of Aptian age and post-rift deposits are only known in the Araripe (Rio da Batateira Formation: Neumann 1999; Neumann et al. 2003) and Potiguar basins, where they lie unconformably on syn-rift series and structures. In the Potiguar basin, the sandstones and marls of the thin Alagamar Formation, with fluvial-deltaic or lacustrine deposits, are surmounted by marine-deltaic deposits (Alagamar Formation, Apodi Group: Araripe and Feijó 1994). As observed in the Recôncavo-Tucano-Jatoba basin (Magnavita et al. 1994), a regional unconformity (ca 20 Myear) shows that widespread erosion of rift shoulders and syn-rift sediments had taken place soon after rifting or during its last stages, before ~ 114 Myear, followed by thermal subsidence which allowed deposition of sediments in vast lake systems beyond the limits of the syn-rift deposition, especially to the south of the Araripe basin (Socorro, Cedro, and São José de Belmonte outliers; Assine 1994; Hegarty et al. 2002; Valença et al. 2003). However, in the Potiguar basin, a few basement residual ridges locally controlled the post-rift sedimentation and still participate in the formation of oil traps in these clastic sediments (Açu sandstones: Sousa et al. 2008a).

In the Araripe basin, the sedimentation resumed after a 10–12 Myear gap following the deposition of the last rift layers. Owing to a combination of thermal subsidence and global eustatic events, the post-rift series were deposited in the whole Araripe basin and beyond its present limits. The post-rift basin first formed in the northeast, where the Albian-Cenomanian series are more complete, and then extended to the south and the west, progressively lapping onto the basement (Fig. 2.6). This stratigraphic transgressive–regressive sequence, known as Araripe Group (Ponte and Ponte-Filho 1996) is made of fluvial, lacustrine, lagoonal, and marine sediments of Aptian to Cenomanian age, divided into several formations: Rio da Bateira (or Barbalha: Assine 2007), Santana (Crato, Ipubi, Romualdo Members), Arajara, and Exu.

In the east (Cariri depression), the post-rift series comprises 250–280 m of mainly soft rocks overlain by thick massive sandstones (Exu Formation, 150–250 m). In this area, they offer the best potential to differential erosion. The coarse to fine and clayey sandstones of the basal post-rift layers (Rio da Batateira or Barbalha Formation) correspond to two fluvial cycles with upward decrease of grain size and lacustrine pelitico-carbonated intervals (“Batateira layers”: Assine 2007). Reaching 60–200 m in thickness (Baudin and Berthou 1996), these layers are overlain by the 80–180 m thick Santana Formation. Showing interdigitation with the second cycle of the Batateira sandstones or foliated clays, the Crato member of this formation corresponds to 20–70 m of discontinuous laminated limestones interlayered with mudstones, siltstones, or shales (Martill et al. 2007; Fig. 2.9a). The overlying Ipubi Member, of Late Aptian age, is mainly composed of discontinuous and thick layers of gypsum (up to 20 m) alternating with black to brown or green foliated clays passing upwards to marls, clays, and sandstones (Romualdo Member, Early Albian) deposited after an unconformity indicating a short period of erosion (Assine 2007).

Abundant fossils in the Romualdo layers indicate a shallow marine ingression, coming from the SSE and having reached the west end of the basin. The overlying

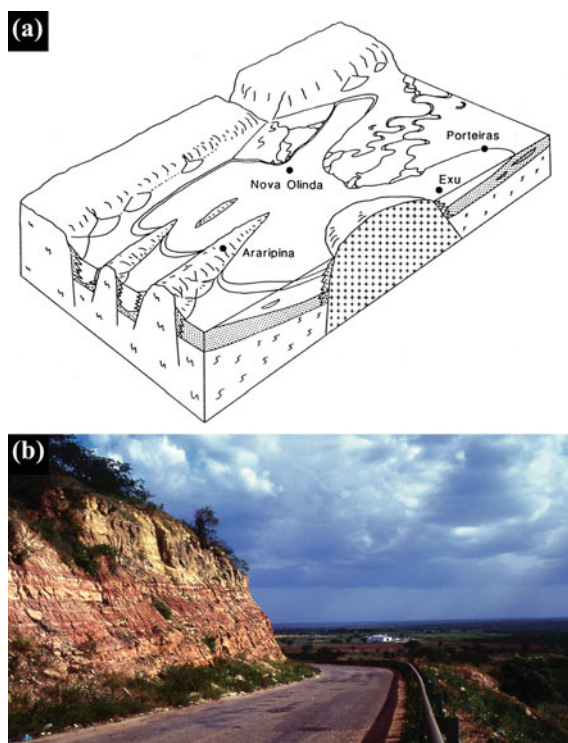


Fig. 2.9 Mesozoic post-rift sedimentary covers and their palaeogeographical implications. **a** Reconstruction of the lake/lagoon in which the Crato Member plattenkalks were deposited (Martill 1993); a large delta advances from the east and large fans of coarse clastic material are accumulating at the foot of the escarpment produced by the Aurora fault zone (Nova Olinda). Presence of residual scarps and uncompletely beveled horsts and granitic hills (Exu). **b** Cuesta forming the south edge of the Chapada do Apodi, north of Apodi. Gradation between estuarine or deltaic sandstones of the upper part of the Açú Formation and the marine Jandaira limestone (Turonien-Campanien; top, left). Exhumed pre-Cenomanian surface truncating the basement at right and at the back. Photograph J.P. Peulvast

clayey sandstones are the last deposits of the lacustrine to marine phases of sedimentation. Reaching 20–80 m in thickness, they form the Arajara Formation of Ponte and Appi (1990), or the final part of the Santana Formation according to Assine (2007). Outliers of lacustrine limestones, similar to those of the Crato Member, exist in the Tucano basin, indicating a continuation of the lake systems to the south of the Pernambuco lineament. Other outliers containing the whole sequence are located in the Socorro basin (Serra Vermelha, Pernambuco-Piauí border) and the Serra Negra (Jatobá basin), at similar altitudes.

Whereas, the other basins of the eastern margin of northeast Brazil were still submitted to transgressive marine conditions until the Late Cretaceous, the end of the sedimentary sequence in the Araripe basin was continental. The alluvial sediments of the so-called Exu Formation (150–250 m in thickness) unconformably

cover the older layers and, to the south, west, and northwest, the basement (Fig. 2.6). According to Assine (2007), they consist in two distinct lithological units separated by an erosive unconformity. Only the upper one should receive the name of Exu Formation. The lower unit, of Meso-Albian age, is called Araripina Formation. Restricted to the western part of the basin, it is made of rhythmites where reddish fine-grained, laminated sandstones contain plurimetric lenses of coarse sandstones with overweigh structures and cross-bedding, indicating sedimentation in alluvial plains. Where present, this basal layer induces a strong contrast in mechanical resistance to erosion between the sedimentary cover and the crystalline rocks of the basement.

An erosive unconformity separates the Araripina sediments from the Exu sandstones, with a slight angle suggesting ongoing synsedimentary deformation. Sedimentary cycles with graded bedding and upward decrease of grain size (conglomerates to fine-grained sandstones) are identified in the western (distal) part of the basin, where flood plain pelitic facies are intercalated. In the eastern (proximal) part of the basin, the sandstones are coarser and more immature, with abundant conglomeratic beds and cross beddings, reflecting sedimentation in braided channels. The age is considered as Albian-Cenomanian, and the paleoflows indicate a transport to the west (Assine 2007). The source area is the Borborema region whose uplift, more intense to the east, has begun as soon as the middle Albian (Assine 1994).

Whereas the Araripe post-rift cover presently culminates above 900 m, the post-rift sediments of the Potiguar basin form the low-lying Chapada do Apodi (80–150 m in altitude). The onshore basin corresponds to a broad (100 km wide or more) and shallow synform with a NE–SW axis which is also that of secondary compressive undulations deforming the post-rift cover (Maia and Bezerra 2014b). It is filled with a thick transgressive sequence whose lower layers, the 400–800-m thick Açu sandstones (Albian-Cenomanian) rest unconformably on syn-rift or transitional deposits and incompletely beveled basement highs (Sousa et al. 2008a), extending up to 30–40 km beyond the border fault of the buried rifts, on the planated Aracati Platform and Touros High (Castro et al. 1981; Araripe and Feijó 1994; see Fig. 3.3). Grading upwards to 100 m of fine estuarine or deltaic sediments (Souza 1982), these coarse fluvial sandstones are conformably covered by thick (up to 400 m) bioclastic calcarenites and calcilutites deposited together with minor siliciclastic sediments in estuaries, intertidal plains, beaches, lagoons, and shallow open sea of increasing depth from Turonian to Early Campanian (Jandaira Formation, 90–80 Myear; Córdoba and Castro 2002; Fig. 2.9b).

2.4.2 Offshore Basins and Formation of the Transform Margin

Marine conditions of sedimentation prevailed during the same period in the offshore Potiguar basin, which became part of the Equatorial continental margin after the Albian. The sandstones of the Açu Formation interdigitate with the more calcareous

rocks of the Ponta do Mel Formation, and the limestones of the Jandaira Formation grade seaward and upward to the foliated clays, siltites, and sandstones of the regressive Ubarana Formation, deposited on the continental slope. After a transgressive phase (Albian-Early Campanian), the post-Campanian deposits make up a mixed platform where a large regressive cycle is recognized until the Holocene, forming a seaward thickening coastal-shelf-slope-basin system (Pessoa Neto 2003). These deposits are composed of three lithostratigraphic units known as the Tibau Formation (sandstones and conglomerates), the Guamaré Formation (limestones), and the Ubarana Formation (marine shales). These units respectively represent the siliciclastic sedimentation of the inner shelf, the carbonate deposits of the outer shelf, and the pelitic sedimentation on the continental slope. Several unconformities, stages of canyon incision and infilling (Neogene), and variations in the position of the limits between the clastic and carbonate deposition reflect eustatic fluctuations and variations in the clastic supply from the continent.

Deformations and unconformities have been identified in this series. After a long tectonically quiet period of subsidence, from Albian to Middle Campanian, the Potiguar basin underwent tectonic activity with the formation of the Ubarana transcurrent zone, 20-km north of the present coast line (Cremonini 1995, 1996; Cremonini et al. 1996). This event was followed by erosion—the Pre-Ubarana Unconformity—after which the offshore basin was covered by the Ubarana Formation. This unconformity is related to a major reorganization of the Potiguar Basin, with transient regional uplift, after which no sedimentation is known in the onshore part of the basin, until the deposition of Cenozoic clastic sediments in a narrow coastal zone (Bigarella 1975). This may have resulted from thermal uplift related to proximity of the mid-oceanic spreading zone, characterized by the presence of recently formed oceanic crust in front of the basin (Cremonini and Karner 1995), before this zone moved away along the recently created transform margin, resulting in later lithospheric cooling and subsidence (mechanism described by Boillot and Coulon 1998).

To the west of the Potiguar Basin and of the Caponga High, the Equatorial margin comprises several buried basins (the Mundaú, Icarai, Acaraú, and Piauí-Camocim sub-basins), separated by basement “highs” (Fortaleza and Ceará highs; Fig. 2.4). Forming the greater Ceará basin (34,000 km²), these sub-basins lack the typical rift structures of most passive margins (half grabens, tilted blocks resulting from brittle extension and stretching of the crust: Boillot and Coulon 1998). According to Matos (2000, 2002), transform faulting linking the wide and shallow precursory basins began in the Albian, defining a lithospheric boundary between Africa and South America from the mouth of the Amazon to the Niger delta, without control by the basement structural fabric, and leading to the formation of oceanic crust. Wrench tectonics induced the formation of conjugate strike-slip fault systems linked to the newly formed oceanic transform fault zones (Chain, Romanche), with associated secondary normal faults, reverse faults and folded structures, respectively, in the releasing and restraining transform segments (Fig. 2.8).

The migration process of active transform faults resulted in diachronous relationships and significant differences between basins in terms of subsidence

histories, geometries, and facies distribution. Whereas the East Potiguar (Benue) basin and Touroso high evolved through transtension along a narrow zone, the Potiguar-Mundaú-Icarai (Keta-Togo-Benin) segment formed a broad region dominated by extension, limited by discrete shear zones, which evolved under pure shear-dominated transtension. To the west, a large transpressive belt developed in the Piauí-Camocim-Acaraú (Accra) basin, comprised of major oblique/strike-slip faults and *en échelon* folds. A typical passive margin environment was only reached later, with progressive oceanward migration of active transform zones, and after the thermal effect of nearby spreading centers was finished (Matos 2000, 2002).

2.5 Post-campanian Sedimentation and Volcanism: The “Drift Phase”

The increasing proportion of terrigenous facies among the deposits of the offshore Potiguar basin reflects an increase of onshore erosion since the Late Cretaceous. The total thickness of Cenozoic sediments on this part of the margin is locally important (up to 3200 m below the shelf break: Morais Neto 1999). A sharp increase in the clastic discharge recorded in the Miocene (especially Late Miocene) and younger series (Pessoa Neto 1999, 2003) was interpreted by this author and by Morais Neto et al. (2000) as a result of significant erosion processes—also reflected by the deposition of the Barreiras sediments—that would have affected the east Borborema Province in relation with uplift during Late Tertiary time, since 20 Myear.

In the Ceará basin, the continental input seems to have remained moderate and often discontinuous. Only Cretaceous deposits are found on the most salient areas. The diversity of the structural controls along the equatorial margin (Matos 2000), but also the strong asymmetry of the drainage patterns in the Jaguaribe-Piranhas hemicycle explain the heterogeneity of the sedimentation. Whereas, a long sedimentary hiatus of 50 Myear separates the Albion or Cenomanian and Late Eocene sequences in the Piauí-Camocim sub-basin (Beltrami et al. 1994), a less discontinuous sedimentation is recorded in the Acaraú and Icarai sub-basins (shorter interruptions in the Cenomanian and Paleocene periods), and at least six erosive/non depositional events are recognized in the Mundaú sub-basin from Early Paleocene to Early Oligocene. The Oligocene period seems to have undergone higher rates of sedimentation, at least in the Mundaú sub-basin (Cunha 1991).

An important volcanism known offshore in the Tibau and Ubarana Formations (Araripe and Feijó 1994; Beltrami et al. 1994) of the Potiguar basin and of the Mundaú sub-basin (Macaú Formation: 31.1–22.6 Myear and 19.9–12.4 Myear: Vieira et al. 2002), and on the Fortaleza High (Mundaú Volcanism: 32 ± 1 Myear; Almeida et al. 1988; Fig. 2.2) has occurred at the continental termination of the volcanic ridge associated with the Chain Fracture Zone (Mizusaki et al. 2002). It is chronologically related to the onshore Oligocene Messejana Volcanism (30–34 Myear), mainly recognized around Fortaleza, with several necks and dykes of

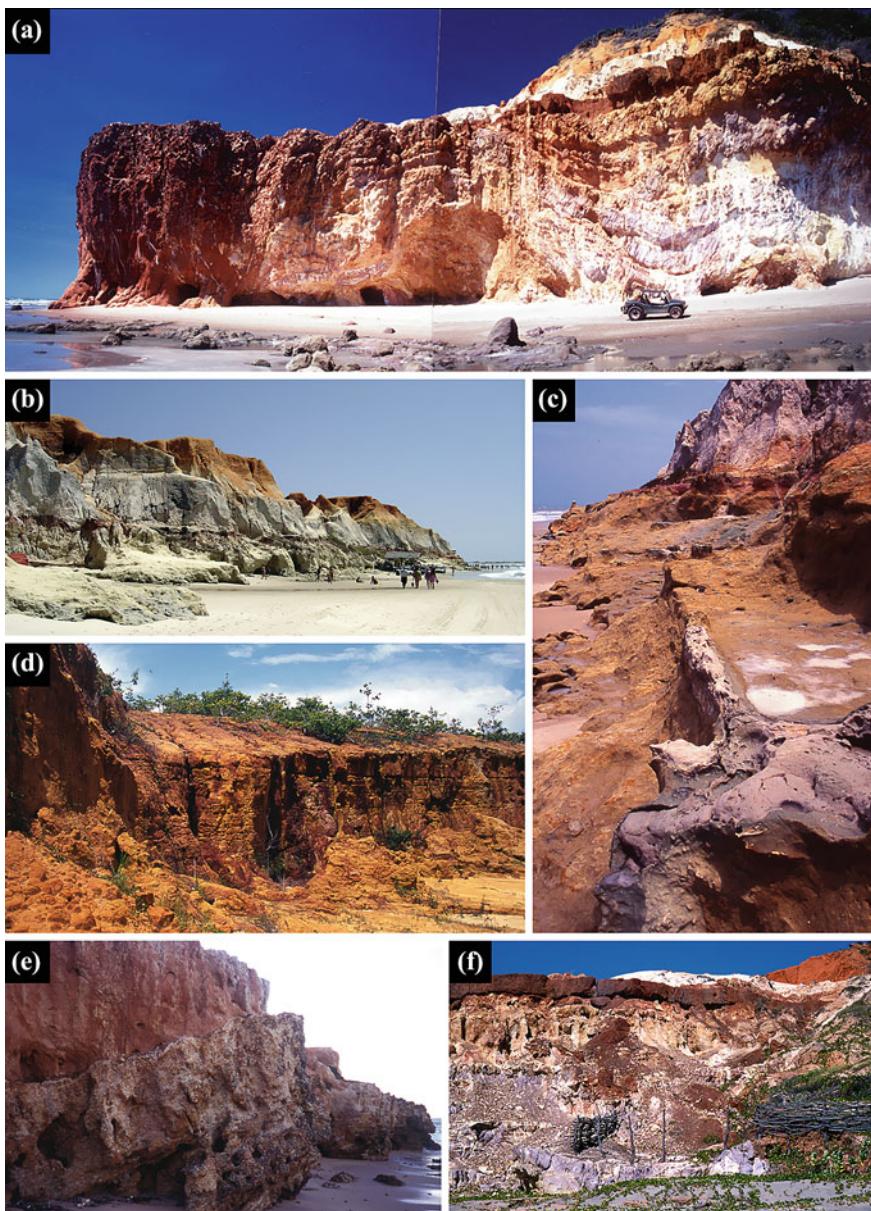


Fig. 2.10 The «Serrote de Jericoacoara» (northwest Ceará), quartzitic residual hill protruding from the beveled basement through the Barreiras sediments and abruptly cut by the highest sea-cliff of the study area. The mega-barchans of Jericoacoara at the back. *Photograph J.P. Peulvast*

phonolite, trachyte, and basalt up to 35 km inland (Almeida et al. 1988; Carneiro et al. 1989). The Macaú volcanism is also found onshore, in the eastern Rio Grande do Norte and Paraíba states, forming scattered dykes and flows of olivine basalts, and plugs or necks of basanites and ankaratrites, in the basement (Pico de Cabugi) as well as in the Mesozoic cover of the Potiguar basin, within a 400-km long and 60 km wide strip trending NNW (Dantas et al. 2002). Most of them were intruded in the crust between 30 and 20 Myear (Silveira 2006), although ages from 57.0 to 6.4 Myear are reported (Oliveira and Medeiros 2012).

The onshore deposits differ from their offshore counterparts—the upper part of the Tibau Formation (Saadi and Torquato 1992; Araripe and Feijó 1994; Pessoa Neto 2003)—by several features such as limited thicknesses (less than 80 m and often less than 15 m) and relatively uniform distribution along the coast. Presenting many similarities with the “Continental Terminal” of West Africa (Lappartient 1985; Conrad and Lappartient 1987; Lang et al. 1990) or with the Cuddalore and Warkali beds of peninsular India (Gunnell 1996, 1998), these clastic sediments are known as part of the “Barreiras Group” (Mabesoone et al. 1972) identified along major parts of the northern and eastern Brazilian coasts (Bigarella 1975) and considered as mainly Miocene in age (Arai 2006; Lima 2008; Sousa et al. 2008a, b; Rossetti et al. 2011, 2013).

In the study area, the Barreiras Group sediments directly overlie the weathered basement (Cunha and Castelo Branco 2002), but also lie unconformably on Late Cretaceous sediments (Jandaira limestones) in the Potiguar Basin. They underlie the 5–50-km wide “tabuleiros”, but narrow outcrops of the basement locally separate them from the continental shelf, forming weakly prominent points on the shoulder of the Messejana graben (Iguape) and on the Fortaleza High (Mucuripe, Pecém), and a well-marked salient at Jericoacoara (western Ceará), where high sea-cliffs cut the base of a residual quartzitic hill on the southern margin of the Acaraú sub-basin (Fig. 2.10). Covering the distal parts of the planated pedestal of the marginal



◀ **Fig. 2.11** The Barreiras Group sediments. **a** Deformed post-Turonian sediments and unconformable deposits (allochthonous laterite, paleodunes) at Ponta Peroba (Icapui). **b** Sea-cliffs at Morro Branco, exposing the upper facies of the Barreiras sediments, represented by yellowish, fine-grained sandstones of probable fluvio-marine origin, and covered at the top by oxidized, nonconsolidated palaeodune deposits. **c** Seismites in the Barreiras Group sediments: a sand dyke at Praia das Fontes (Beberibe). The Barreiras sediments are overlain by palaeodune material (at the back). **d** Quarry to the west of Beberibe, showing *red to yellow* layered argillaceous sands, containing minor amounts of quartz gravel and partly consolidated. **e** Camocim conglomerate (northwest Ceará): mature fluvial quartz conglomerate, with well-rounded pebbles cemented by a red silica-ferruginous matrix. **f** Laterite cap developed from iron-rich Barreiras sediments and fossilized by palaeodune material at Ponta Peroba (Icapui). *Photographs* J.P. Peulvast and F. Bétard

escarpment, they are reduced to erosive remnants disconnected from source areas and dissected by rivers flowing to the ocean (Bétard 2007). Therefore the “tabuleiros” form a succession of triangular units separated by outcrops of the substratum along the floors of the main valleys or by mountain ridges approaching the coast (Fortaleza High). They mostly overlook the sea by low active or abandoned sea-cliffs, 2–20-m high, resulting from marine erosion (Fig. 1.3).

The Barreiras sediments slightly dip seaward from a few tens of meters inland to sea level or lower at the coast. They present multiple vertical and lateral facies variations which have been studied in detail along the coast of the Potiguar basin, in eastern Ceará (Sousa et al. 2008a, b). Between Lagoa do Mato and Icapui, on a 40-km long sea-cliff tract (Fig. 2.11a), these sediments are found in horizontal layers, or highly deformed beds, mainly from Icapui to Retirinho. In the nondeformed sectors (e.g., between Redonda and Ponta Grossa), the cliffs expose the upper facies of the Barreiras sediments, represented by reddish medium- to coarse-grained sandstones with conglomerate intercalations and massive structure.

Although the lower level locally appears in this sector, directly overlying small outcrops of Jandaíra limestone (W of Ponta Grossa), it rather forms the bulk of the deformed sectors, with fine- to medium-grained sandstones of yellow to purple or red colors indicating strong oxidation. Intercalations of layers of massive ferruginous sandstones or conglomerates with well-rounded to subangular quartz and crystalline pebbles are observed, often poorly sorted. Westward, these units pass laterally to yellowish-greenish, medium- to coarse-grained sandstones deprived of clear bedding, containing clay beds. Forming the lower parts of the sea-cliffs to the west, from Lagoa do Mato to Retirinho and beyond, they are also identified west of the Jaguaribe river, along the lower estuary and in Fortim, well beyond the limits of the Potiguar basin, as far as Beberibe (Praia das Fontes, Morro Branco; Fig. 2.11b), and even west of Fortaleza (Caucaia: Icarai). Many sea-cliff outcrops also expose coarser sediments. Ferruginous gravels and clay balls (bentonite of possibly volcanic origin, smectite), and also carbonate concretions and bioturbations (ichnofossils) are found in the conglomerates which often form the lower parts of the outcrops. Bedding may be discontinuous or lacking, obliterated by synsedimentary plastic deformations (Morro Branco, Praia das Fontes; Fig. 2.11c). These sediments are considered by Sousa et al. (2008a) as belonging to the Tibau Formation. A more or less developed lateritic horizon locally tops the sediments of both deformed and

nondeformed units, below argillaceous sands which grade upwards to white, yellow to reddish sands with sparse subangular quartz gravels (Potengi Formation). Inland sections show layers of reddish to yellow or white argillaceous sands with minor amounts of quartz gravel (Fig. 2.11d), and more clay beds of variable thickness at depth (Cascavel: Cunha and Castelo Branco 2002).

Conglomeratic materials are best represented in the vicinity of present river mouths (Coreaú, Curu, Choró rivers) and of mountains approaching the coast (around the Baturité massif: Pecém-Taiba, Prainha). Around the Rio Coreaú mouth, the Camocim Formation forms a prominent sea-cliff where a mature fluvial quartz conglomerate, with well-rounded pebbles cemented by a red silica-ferruginous matrix, reaches a residual thickness of 20 m (Costa et al. 1979; Saadi and Torquato 1992; Fig. 2.11e). Thinner and often widespread conglomeratic formations are also identified around other river mouths (Jaguaribe).

The age of these non-fossiliferous sediments is now relatively well constrained on the basis of geochronological data obtained from K–Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of supergene minerals, and (U–Th)/He dating of supergene goethite grains taken in their weathering mantles (Lima 2008). According to these results, the maximum age of the Barreiras sediments in northeast Brazil would be 22 Myear (Aquitania), their deposition would have continued until 16–17 Myear (Burdigalian), before the middle Miocene highstand, and their weathering until 7 Myear, indicating mainly warm and humid climatic conditions in the coastal area during this period. According to Rossetti et al. (2013), the prolonged sea-level lowstand recorded since the Tortonian may explain the prevalence of subaerial conditions and the lateritic soil formation from mid-Miocene up to late Quaternary.

The relationship with the overlying sediments (Potengi Formation) is not clear in all publications since many of them deal either with the northern or the eastern coasts of Northeast Brazil, which are not entirely comparable. In the east of the study area, these Post-Barreiras deposits (Rossetti et al. 2011) cover unconformably both the Barreiras and Tibau Formations and their laterite cap (Fig. 2.11f). Commonly referred to as palaeodune material (Brandão 1995; Sousa et al. 1999, 2008a), these more or less consolidated sand deposits of white to yellow or red colors are probably more complex, representing weathered material formed in dune, interdune (creeks and ponds), lagoon, and shore environments, as suggested by the presence of scattered coarse quartz grains (up to 1 cm) in the fine-grained material at all levels (Menezes et al. 1998; Claudino Sales 2002). Outcropping in the upper part of the sea-cliffs of eastern Ceará, they form the main part of most cliffs and paleo-cliffs west of Caucaia, except in a few rocky shore segments which expose the underlying Barreiras sediments or basement rocks (e.g., Taiba, Camocim, and Jericoacoara). More than the less extensive Barreiras sediments *s.s.*, they form the substrate of the so-called tabuleiros on large widths (Bétard 2007), below a discontinuous veil of unconsolidated white sand corresponding to various generations of Holocene to Mid-Pleistocene paleodunes (Barretto et al. 2004) (Fig. 2.12).

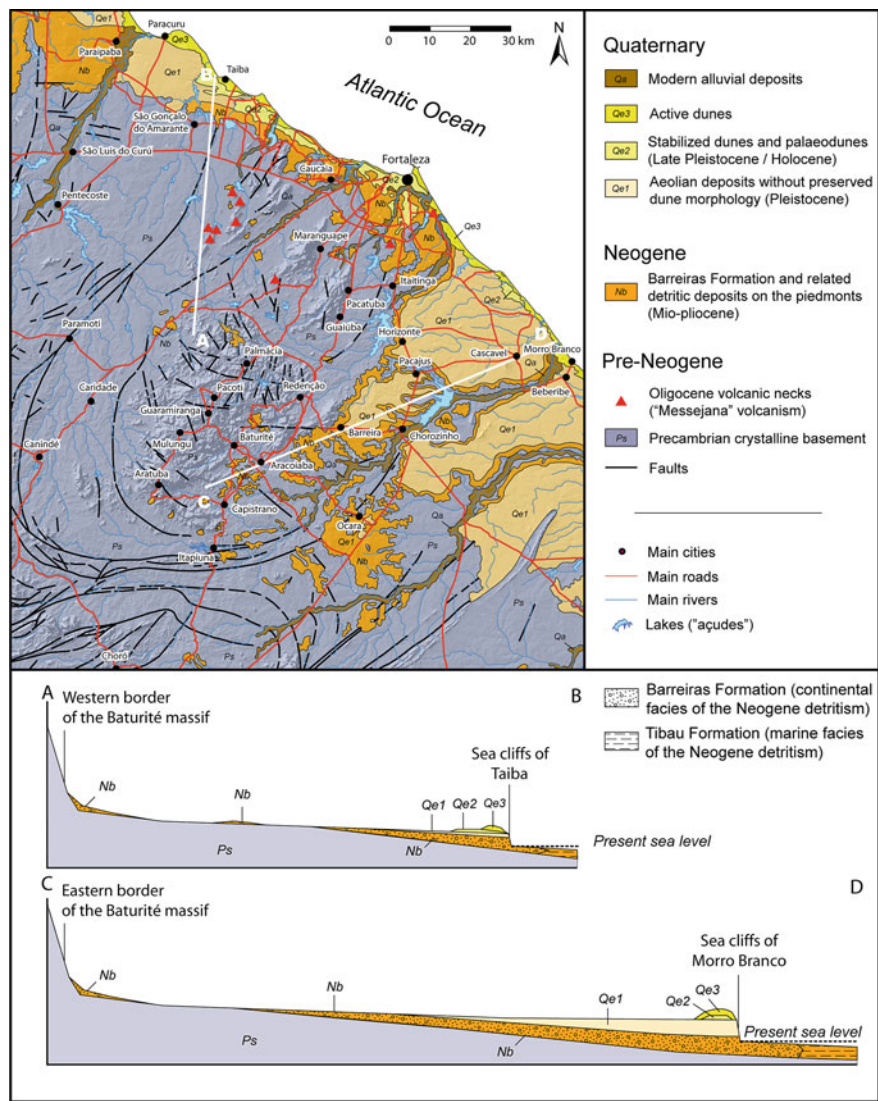


Fig. 2.12 Geological map of the Quaternary-Neogene deposits in the Baturité region, and synthetic profiles showing the geometric relationships between the different sets of deposits. From Bétard (2007)

References

- Ab'Saber AN (2000) Summit surfaces in Brazil. *Rev Bras Geociências* 30(3):515–516
- Alkmim FF, Marshak S, Fonseca MA (2001) Assembling West Gondwana in the Neoproterozoic: clues from the São Francisco craton region, Brazil. *Geology* 29:319–322
- Almeida FFM, Brito Neves BB, Carneiro CDR (2000) The origin and evolution of the South American platform. *Earth Sci Rev* 50:77–111
- Almeida FFM, Carneiro CDR, Machado DL, Dehira LK (1988) Magmatismo pós-paleozóico no Nordeste oriental do Brasil. *Rev Bras Geociências* 18(4):451–462
- Almeida FFM, Hasui Y, Brito Neves BB, Fuck RA (1981) Brazilian structural provinces: an introduction. *Earth Sci Rev* 17:1–21
- Almeida AR, Ulbrich HHG, McReath I (1999) O batólito Quixadá – petrologia e geoquímica. *Rev Geologia* 12:29–52
- Amaral WS, Santos TJS, Wernick E (2011) Occurrence and geochemistry of metamafic rocks from the Forquilha Eclogite zone, central Ceará (NE Brazil): geodynamic implications. *Geol J* 46:137–155
- Arai M (2006) A grande elevação eustática do Mioceno e sua influência na origem do Grupo Barreiras. *Revista do Instituto de Geociências, USP. Geol. USP Sér. Cient., São Paulo* 6(2):1–6
- Araripe PT, Feijo FJ (1994) Bacia Potiguar. *Bol Geoci Petrobras* 8(1):127–141
- Araújo CEG, Cordani UG, Weinberg RF, Basei MAS, Armstrong R, Sato K (2014) Tracing Neoproterozoic subduction in the Borborema Province (NE Brazil): clues from U–Pb geochronology and Sr–Nd–Hf–O isotopes on granitoids and migmatites. *Lithos* 202–203:167–189
- Araújo CEG, Weinberg RF, Cordani UG (2013) Extruding the Borborema Province (NE Brazil): a two-stage Neoproterozoic collision process. *Terra Nova* 0:1–12
- Arthaud MH, Caby R, Fuck RA, Dantas EL, Parente CV (2008) Geology of the northern Borborema Province, NE Brazil and its correlation with Nigeria, NW Africa. In: Pankhurst RJ, Trouw RAJ, Brito Neves BB, De Wit MJ (eds) *West Gondwana Pre-Cenozoic correlations across the South Atlantic region*. Geological Society, London (Special Publications 294), pp 49–67
- Arthaud MH, Fuck RA, Dantas EL, Santos TJS, Caby R, Armstrong R (2014) The Neoproterozoic Ceará Group, Ceará Central domain, NE Brazil: Depositional age and provenance of detrital material. New insights from UePb and SmeNd geochronology. *J South Am Earth Sci* 56:54–67. doi:[10.1016/j.jsames.2014.06.011](https://doi.org/10.1016/j.jsames.2014.06.011)
- Assine ML (1994) Paleocorrentes e paleogeografia na Bacia do Araripe, Nordeste do Brasil. *Rev Bras Geociências* 24(4):223–232
- Assine ML (2007) Bacia do Araripe. *Bol. Geociências Petrobrás* 15:371–389
- Barreto AMF, Suguio K, Bezerra FHR, Tatum SH, Yee M, Giannini PCF (2004) Geologia e geomorfologia do Quaternário Costeiro do Estado do Rio Grande do Norte. *Geol. USP Sér. Cient., São Paulo* 4(2):1–12
- Baudin F, Berthou PY (1996) Environnement de dépôt de la matière organique des sédiments aptiens-albiens du bassin d'Araripe (NE du Brésil). *Bull Centres Rech Explor Prod Elf-Aquitaine* 20(1):213–227
- Beltrami CV, Alves LEM, Feijo F (1994) Bacia do Ceará. *Bol Geoci Petrobras* 8(1):117–125
- Benkhelil J (1988) Structure et évolution géodynamique du bassin intracontinental de la Bénoué (Nigéria). *Bull Centres Rech Explor Prod Elf-Aquitaine* 12(1):29–128
- Bertani RT, Costa IG, Matos RMD (1990) Evolução tectono-sedimentar, estilo estrutural e habitat do petróleo na Bacia Potiguar. In: Raja Gabaglia GP, Milani EJ (eds) *Origem e evolução de bacias sedimentares*. Petrobras, pp 291–309
- Bétard F (2007) Montagnes humides au cœur du Nordeste brésilien semi-aride: le cas du massif de Baturité (Ceará). Apports d'une approche morphopédologique pour la connaissance et la gestion des milieux. Ph.D thesis, Univ Paris-Sorbonne

- Bigarella JJ (1975) The Barreiras Group in Northeastern Brazil. *An Acad Bras Ciên* 47:365–393
- Boillot G, Coulon C (1998) La déchirure continentale et l'ouverture océanique. *Géologie des marges passives*. Gordon and Breach Science Publishers, Amsterdam
- Brandão RL (1995) Mapa geológico da região metropolitana de Fortaleza. Texto explicativo. Sistema de informações para gestão et administração territorial da Região metropolitana de Fortaleza – Projeto SINFOR, CPRM
- Brito Neves BB, Dos Santos EJ, Van Schmus WR (2000) Tectonic history of the Borborema Province, northeastern Brazil. In: Cordani U, Milani EJ, Thomaz Filho A, Campos DA (eds) *Tectonic evolution of South America*. 31st International Geological Congress, Rio de Janeiro, Brazil, pp 151–182
- Caby R, Arthaud M (1986) Major Precambrian nappes of the Brazilian Belt, Ceará, northeast Brazil. *Geology* 14:871–874
- Caby R, Arthaud MH, Archanjo CJ (1995) Lithostratigraphy and petrostructural characterization of supracrustal units in the Brazilian Belt of Northeast Brazil: geodynamic implications. *J South Am Earth Sci* 8(3–4):235–246
- Carneiro CDR, Hamza VM, Almeida FFM (1989) Ativação tectônica, fluxo geotérmico e sismicidade no Nordeste oriental brasileiro. *Rev Bras Geociências* 19(3):310–322
- Carneiro CDR, Monma R, Ferreira FJF, Dehira LK, Magalhães FS (1988) Ensaio de integração geológico-geofísica sobre o Nordeste oriental com base em mapas aeromagnéticos. XXXV Congr Bras Geol, Belém, Pará, Anais 5:2122–2136
- Castro JC, Barrocas SLS, Lima HP (1981) Fácies, diagênese e modelos de acumulação da Formação Açu, parte emersa da Bacia Potiguar. Cenpes, Petrobras
- Claudino Sales V (2002) Evolution géomorphologique de la zone côtière de Ceará (Nord-est du Brésil): du long terme au court terme. PhD thesis, Univ Paris-Sorbonne
- Coimbra JC, Arai M, Carreño AL (2002) Biostratigraphy of Lower Cretaceous microfossils from the Araripe Basin, northeastern Brazil. *Geobios* 35:687–698
- Conrad G, Lappartient JR (1987) Le 'Continental Terminal', sa place dans l'évolution géodynamique du bassin sénégal-mauritanien durant le Cénozoïque. *J Afr Earth Sci* 6:45–60
- Córdoba VC, Castro JC (2002) Análise paleoambiental e diagenética da rampa carbonática Jandaíra, Neocretáceo na Bacia Potiguar. XLI Congr Bras Geol, João Pessoa, Anais, p 264
- Corsini M, Vauchez A, Archanjo CJ, Jardim de Sá EF (1991) Strain transfer at continental scale from a transcurrent shear zone to a transpressional fold belt: the Patos-Seridó system, northeastern Brazil. *Geology* 19:586–589
- Corsino AR, Tiriba VF (1985) Nota sobre a ocorrência de uma pequena bacia sedimentar ao norte do município de Umarizal (R.N) – (Bacia de Gangorra). *Bol DG-CCE/UFRN, Natal* 9:54–56
- Costa MJ, Lins CAC, Bacchiégga JF, Habekost CR, Cruz B (1979) Geologia da Bacia Jaibaras, Ceará, Piauí e Maranhão (Projeto Jaibaras). MME, Geologia Básica 11
- Costa IG, Beltrami CV, Alves LEM (1990) A evolução tectono-sedimentar e o habitat do óleo da Bacia do Ceará. *Bol Geoci Petrobras* 4(1):65–74
- Costa ACD, Hackspacher PC, Dantas EL, Fetter AH (2002) A zona de cisalhamento Patos ou "sutura tectônica Patos" no Domínio da Zona Transversal, Província Borborema: seu significado na colagem neoproterozóica. XLI Congr Bras Geol, João Pessoa, Anais, p 300
- Cremonini OA (1995) A reativação tectônica da Bacia Potiguar no Cretáceo superior. V Simp Nac Estudos Tectônicos, Gramado-RS, Anais, pp 277–280
- Cremonini OA (1996) Evolução tectônica da area de Ubarana, porção submersa da Bacia Potiguar. *Bol Geoci Petrobras* 10(1–4):81–97
- Cremonini OA, Karner GD (1995) Soerguimento termal e erosão na Bacia Potiguar submersa, e seu relacionamento com a evolução da Margem Equatorial brasileira. XVI Simp. Geol. do Nordeste, Recife
- Cremonini OA, Goulart JPM, Soares UM (1996) O rifte Potiguar: novos dados e implicações tectônicas. *Bol 4o Simp sobre o Cretáceo do Brasil, UNESP*, pp 89–93
- Cunha AAS (1991) Reconhecimento dos hiatos da seção terciária da sub-bacia de Mundaú (Bacia do Ceará): um estudo baseado em nanofósseis calcários. *Bol Geoci Petrobras* 8(1):69–82

- Cunha LS, Castelo Branco RMG (2002) Configuração 3-D dos sedimentos quaternários baseada em inverses de dados geofísicos elétricos e eletromagnéticos, região costeira de Cascavel – Ceará. XLI Congr Bras Geol, João Pessoa, Anais, p 85
- Dantas AR, Almeida RB, Sena ES, Bezerra FHR, Oliveira DC (2002) Uso de SIG no estudo da distribuição do evento ígneo Macau, Nordeste oriental, Brasil. XLI Congr Bras Geol, João Pessoa, Anais, p 157
- De Castro DL, Medeiros WE (1997) Afinamento crustal associado à implantação das bacias intracratônicas do trend Cariri-Potiguar. XVII Simp Geol do Nordeste, Fortaleza, Anais, pp 335–338
- De Castro DL, Castelo Branco RMG (1999) Caracterização da arquitetura interna da bacia do Vale do Cariri (NE do Brasil) com base em modelagem gravimétrica 3-D. Braz J Geophys 17:129–144
- De Castro DL, Costa FCN (1999) Mapas gravimétricos do Estado do Ceará. Rev Geologia 12:69–80
- De Castro DL, Castelo Branco RMG, Martins G, Castro NA (2002) Radiometric, magnetic, and gravity study of the Quixadá batholith, central Ceará domain (NE Brazil): evidence for Pan-African/Brasiliano extension-controlled emplacement. J South Am Earth Sci 15:543–551
- De Castro DL, Oliveira DC, Castelo Branco RMG (2007) On the tectonics of the Neocomian Rio do Peixe rift basin, NE Brazil: lessons from gravity, magnetic and radiometric data. J South Am Earth Sci 24:184–202
- De Castro DL, Bezerra FHR, Castelo Branco RMG (2008) Geophysical evidence of crustal-heterogeneity control of fault growth in the Neocomian Iguatu basin, NE Brazil. J South Am Earth Sci 26:271–285
- De Castro DL, Bezerra FHR, Sousa MOL, Fuck RA (2012) Influence of Neoproterozoic tectonic fabric on the origin of the Potiguar Basin, northeastern Brazil and its link with West Africa based on gravity and magnetic data. J Geodyn 54:29–42
- De Castro DL, Fuck RA, Phillips JD, Vidotti RM, Bezerra FH, Dantas EL (2014) Crustal structure beneath the Paleozoic Parnaíba Basin revealed by airborne gravity and magnetic data, Brazil. Tectonophysics 614:128–145
- De Castro DL, Barbosa VCF, Silva JBC, Medeiros WE (1997) Relevô da interface crosta-manto entre os vínculos de isostasia e suavidade. Congr. Int. SBGf 5, São Paulo, Anais, pp 682–685
- Destro N, Szatmari P, Ladeira EA (1994) Post-Devonian transpressional reactivation of a Proterozoic ductile shear zone in Ceará, NE Brazil. J Struct Geol 16(1):35–45
- Ferreira JM, Oliveira R, Takeya MK, Assumpção MA (1998a) Superposition of local and regional stresses in NE Brazil: evidence from mechanisms around the Potiguar marginal basin. Geophys J Int 134:341–355
- Ferreira VP, Sial AN, Jardim de Sa EF (1998b) Geochemical and isotopic signatures of Proterozoic granitoids in terranes of the Borborema structural province, northeastern Brazil. J South Am Earth Sci 11(5):439–455
- Fetter A, Van Schmus WR, Dos Santos TJS, Arthaud M, Nogueira Neto J (1999) Geocronologia e estrutura do Estado do Ceará : NW da província Borborema, NE Brasil. XVII Simp Geol do Nordeste, Fortaleza, Anais, pp 32–33
- Fetter AH, Van Schmus WR, Dos Santos TJS, Arthaud M, Nogueira Neto JA (2000) U-Pb and Sm-Nd geochronological constraints on the crustal evolution and basement architecture of Ceará State, NW Borborema Province, NE Brazil: implications for the existence of the Paleoproterozoic supercontinent Atlantica. Revista Brasileira de Geociências 30:102–106
- Fetter AH, Dos Santos TS, Van Schmus WR, Hackspacher PC, De Brito Neves BB, Arthaud MH, Wernick E (2003) Evidence for Neoproterozoic continental arc magmatism in the Santa Quitéria Batholith of Ceará State, NW Borborema Province, NE Brazil: implications for the assembly of west Gondwana. Gondwana Res 6(2):265–273
- Françolin JBL, Szatmari P (1987) Mecanismo de rifteamento da porção oriental da margem norte brasileira. Revista Brasileira de Geociências 17(2):196–207

- Françolin JBL, Cobbold PR, Szatmari P (1994) Faulting in the Early Cretaceous Rio do Peixe basin (NE Brazil) and its significance for the opening of the Atlantic. *J Struct Geol* 16(5):647–661
- Galvão CC, Da Silva FCA (2002) Análise microestrutural de um corpo siliciclástico localizado a Nordeste de Santana do Acaraú – CE. *XLI Congr Bras Geol, João Pessoa, Anais*, p 624
- Godard A, Lagasquie JJ, Lageat Y (2001) Basement regions. Springer, Berlin
- Guiraud R, Bellion Y (1995) Late Carboniferous to Recent geodynamic evolution of the West Gondwanian, cratonic, Tethyan margins. In: Nairn AEM et al (eds) *The ocean basins and margins*, vol 8., The Tethys ocean Plenum Press, New York, pp 101–124
- Gunnell Y (1996) Géodynamique d'une moyenne montagne tropicale. La genèse des paysages dans le Ghat occidental du Deccan, sur son revers continental et son piémont maritime. PhD thesis, Univ. B. Pascal, Clermont-Ferrand
- Gunnell Y (1998) Passive margin uplifts and their influence on climatic change and weathering patterns of tropical shield regions. *Global Planet Change* 18:47–57
- Hegarty KA, Morais Neto JM, Karner GD (2002) The enigma of the Araripe plateau: new constraints on its uplift and tectonic history using AFTA. *XLI Congr Bras Geol, João Pessoa, Anais*, p 495
- Hollanda MHB, Pimentel MM, Oliveira DC, Jardim de Sá EF (2006) Lithosphere–asthenosphere interaction and the origin of Cretaceous tholeiitic magmatism in Northeastern Brazil: Sr–Nd–Pb isotopic evidence. *Lithos* 86:34–49
- Jardim de Sá EF, Matos RMD, Morais Neto JM, Saadi A, Pessoa Neto OC (1999) Epirogenia Cenozóica na Província Borborema : síntese e discussão sobre os modelos de deformação associados. VII Simp. Nac. Estudos Tect., Lençóis – Bahia, Anais, pp 58–61
- Koutsoukos EAM (1992) Late aptian to maastrichtian foraminiferal biogeography and palaeoceanography of the Sergipe basin, Brazil. *Palaeogeogr Palaeoclim Palaeoecol* 92:295–324. doi:10.1016/0031-0182(92)90089-N
- Lang J, Kogbe C, Alidou S, Alzouma KA, Bellion G, Dubois D, Durand A, Guiraud R, Houessou A, De Klasz I, Romann E, Salaré-Chebaldaff M, Trichet J (1990) The continental terminal in West Africa. *J Afr Earth Sci* 10:79–99
- Lappartient JR (1985) Le Continental Terminal et le Pléistocène ancien du bassin sénégalomauritanien: stratigraphie, sédimentation, diagenèse, altération; reconstitution des paléorivages au travers des cuirasses. PhD thesis, Univ Aix-Marseille 3
- Lima MG (2008) A História do Intemperismo na Província Borborema Oriental, Nordeste do Brasil. Implicações paleoclimáticas e tectônicas. PhD thesis, Universidade Federal do Rio Grande do Norte, Natal
- Mabesoone JM, Campos e Silva A, Beurlen K (1972) Estratigrafia e origem do Grupo Barreiras em Pernambuco, Paraíba e Rio Grande do Norte. *Rev Bras Geoc* 2:173–188
- Magnavita LP, Davison I, Kuznir NJ (1994) Rifting, erosion and uplift history of the Reconcavo-Tucano-Jatoba Rift, northeast Brazil. *Tectonics* 13:367–388
- Maia RP, Bezerra FHR (2014a) Tópicos de geomorfologia estrutural. Nordeste brasileiro, Edições UFC, Fortaleza
- Maia RP, Bezerra FHR (2014b) Inversão neotectônica do relevo na Bacia Potiguar, Nordeste do Brasil. *Revista Brasileira de Geomorfologia* 15(1):61–74
- Martill DM (1993) Fossils of the Santana and Crato formations, Brazil (Field Guide to Fossils no. 5). The Palaeontological Association, London
- Martill DM, Bechly G, Loveridge RF (2007) The Crato fossil beds of Brazil: window into an ancient world. Cambridge University Press, Cambridge
- Matos RMD (1992) The Northeast Brazilian rift system. *Tectonics* 11(4):766–791
- Matos RMD (2000) Tectonic evolution of the Equatorial South Atlantic. In: Mohriak W, Taiwani M (eds) *Atlantic rifts and continental margins*. Geophys Monograph 115, American Geophysical Union, pp 331–354
- Matos RMD (2002) Geologia regional da margem equatorial afro-brasileira: evolução cinemática e o contexto paleogeográfico. *XLI Congr Bras Geol, João Pessoa, Anais*, p 272

- Maurin JC, Guiraud R (1993) Basement control in the development of the early Cretaceous West and Central African rift system. *Tectonophysics* 228:81–95
- Mello UT (1989) Controles tectônicos na estratigrafia da Bacia Potiguar: uma integração de modelos geodinâmicos. *Bol Geoci Petrobras* 3(4):347–364
- Menezes MRF, Dantas EP, Caldas LH (1998) Estudos sedimentológicos na formação Tibau, porção emersa da Bacia Potiguar. *Congr Bras Geol, Belo Horizonte, Anais*, p 77
- Menezes MRF, Lima Filho FP (1997) Estudo faciológico na Formação Serra do Martins, Serra de Portalegre - RN. *XVII Simp Geol do Nordeste, Fortaleza* 15:193–198
- Menezes MRF, Lima Filho FP, Farias PRC (2002) Fácies e sistema deposicional da Formação Serra do Martins nos platôs terciários do Rio Grande do Norte. *XLI Congr Bras Geol, João Pessoa, Anais*, p 387
- Mizusaki AMP, Thomaz-Filho A, Milani EJ, De Cesero P (2002) Mesozoic and Cenozoic igneous activity and its tectonic control in northeastern Brazil. *J South Am Earth Sci* 15:183–198
- Monié P, Caby R, Arthaud M (1997) The Neoproterozoic Brazilian orogeny in northeast Brazil: $^{40}\text{Ar}/^{39}\text{Ar}$ and petrostructural data from Ceará. *Precambrian Res* 81:241–264
- Morais Neto JM (1999) As coberturas sedimentares terciárias do interior da Paraíba e do Rio Grande do Norte e gênese da antecrise da Borborema. *MSc thesis, Univ Federal de Ouro Preto, Ouro Preto, Brazil*
- Morais Neto JM, Alkmim FF (2001) A deformação das coberturas terciárias do Planalto da Borborema (PB-RN) e seu significado tectônico. *Rev Bras Geociências* 31(1):95–106
- Morais Neto JM, Green PF, Karner GD, Alkmim FF (2008) Age of the Serra do Martins Formation, Borborema Plateau, northeastern Brazil: constraints from apatite and zircon fission track analysis. *Bol Geoci Petrobras* 16(1):23–52
- Morais Neto JM, Hegarty KA, Karner GD, Alkmim FF, Matos RMD (2000) Uplift and erosion in the Borborema Province, northeast Brazil: insights from apatite fission track analysis. *XXXI Int Geol Congr, IUGS/SBG, Abstract Volume, Rio de Janeiro*
- Morais Neto JM, Menezes MRF, Szatmari P, York D (2002) Datação Ar/Ar do plug basáltico «Serrote Preto» e seu significado para a cronologia de Formação Serra do Martins. *XLI Congr Bras Geol, João Pessoa, Anais*, p 499
- Neumann VH (1999) Estratigrafia, sedimentología, geoquímica y diagénesis de los sistemas lacustres apte-albienses de la Cuenca de Araripe (Nordeste de Brasil). *PhD thesis, Univ Barcelona*
- Neumann VH, Borrego AG, Cabrera L, Dino R (2003) Organic matter composition and distribution through the Aptian-Albian lacustrine sequences of the Araripe basin, northeastern Brazil. *Int J Coal Geol* 54:21–40
- Neves CAO (1989) Análise regional do trinômio geração-migração-acumulação de hidrocarbonetos na sequência continental eocretácica da Bacia Potiguar. *Bol Geoci Petrobras* 3(3):131–145
- Neves SP (2002) Considerações sobre a evolução termomecânica das faixas Orós, Piancó-Alto Brígida e Seridó, Província Borborema, Nordeste do Brasil. *XLI Congr Bras Geol, João Pessoa, Anais*, p 322
- Neves SP (2015) Constraints from zircon geochronology on the tectonic evolution of the Borborema Province (NE Brazil): Widespread intracontinental Neoproterozoic reworking of a Paleoproterozoic accretionary orogen. *J S Am Earth Sci* 58:150–164. doi:[10.1016/j.jsames.2014.08.004](https://doi.org/10.1016/j.jsames.2014.08.004)
- Nogueira JF, Morales N, Nogueira Neto JA (1997) A estrutura interna do batólito de Quixadá – CE: dados preliminares. *XVII Simp Geol Nordeste, Fortaleza, Anais*, pp 297–301
- Nogueira FCC, Marques FO, Bezerra FHR, De Castro DL, Fuck RA (2015) Cretaceous intracontinental rifting and post-rift inversion in NE Brazil: insights from the Rio do Peixe basin. *Tectonophysics* 644–645:92–107. doi:[10.1016/j.tecto.2014.12.016](https://doi.org/10.1016/j.tecto.2014.12.016)
- Oliveira DC, Gomes CJS (1996) A expressão de reativações pós-intrusão do enxame de diques Rio Ceará Mirim (Mesozóico): implicações na evolução tectônica da Bacia Potiguar. *Bol Geoci Petrobras* 10(1–4):121–145

- Oliveira CG, Maas MVR (2002) Modelo descritivo das brechas quartzo-hematíticas do sudoeste do Cinturão cuprífero Orós-Jaguaribe, Província Borborema. XLI Congr. Bras. Geol., João Pessoa, Anais, p 459
- Oliveira DC, Mohriak WU (2003) Jaibaras trough: an important element in the early tectonic evolution of the Parnaíba interior sag basin, Northern Brazil. *Mar Pet Geol* 20:351–383
- Oliveira RG, Medeiros WE (2012) Evidences of buried loads in the base of the crust of Borborema Plateau (NE Brazil) from Bouguer admittance estimates. *J S Am Earth Sci* 37:60–76
- Pessoa Neto OC (1999) Análise estratigráfica integrada da plataforma mista (siliciclástica-carbonática) do Neogeno da Bacia Potiguar, nordeste do Brasil. MSc thesis, Univ Fed Rio Grande do Sul, Porto Alegre, Brazil
- Pessoa Neto OC (2003) Estratigrafia de seqüências da plataforma mista neogênica na Bacia Potiguar, margem equatorial brasileira. *Rev Bras Geociências* 33:263–278
- Peulvast JP, Bétard F (2015) A history of basin inversion, scarp retreat and shallow denudation: the Araripe Basin as a keystone for understanding long-term landscape evolution in NE Brazil. *Geomorphology* 233:20–40. doi:[10.1016/j.geomorph.2014.10.009](https://doi.org/10.1016/j.geomorph.2014.10.009)
- Peulvast JP, Claudino Sales V, Bétard F, Gunnell Y (2008) Low post-Cenomanian denudation depths across the Brazilian Northeast: implications for long-term landscape evolution at a transform continental margin. *Global Planet Change* 62:39–60. doi:[10.1016/j.gloplacha.2007.11.005](https://doi.org/10.1016/j.gloplacha.2007.11.005)
- Ponte FC, Appi CJ (1990) Proposta de revisão da coluna litoestratigráfica da Bacia do Araripe. In Congresso Brasileiro de Geologia 36, Anais, Natal, SBG, pp 211–226
- Ponte FC, Ponte-Filho FC (1996) Estrutura geológica e evolução tectônica da Bacia do Araripe. MME/DNPM, Recife
- Rossetti DF, Bezerra FHR, Góes AM, Brito Neves BB (2011) Sediment deformation in Miocene and Post-Miocene strata, Northeastern Brazil: evidence for paleoseismicity in a passive margin. *Sed Geol* 235:172–187
- Rossetti DF, Bezerra FHR, Dominguez JLR (2013) Late Oligocene-Miocene transgressions along the equatorial and eastern margins of Brazil. *Earth-Sci Rev* 123:87–112
- Saadi A, Torquato JR (1992) Contribuição à neotectônica do Estado do Ceará. *Rev Geologia* 5: 5–38
- Santos TJS, Fetter AH, Hackspacher PC, Van Schmus WR, Neto JN (2008) Neoproterozoic tectonic and magmatic episodes in the NW sector of Borborema Province, NE Brazil, during assembly of Western Gondwana. *J S Am Earth Sci* 25(3):271–284
- Sénant J, Popoff M (1991) Early Cretaceous extension in northeast Brazil related to the South Atlantic opening. *Tectonophysics* 198:35–46
- Sial AN, Long LE, Pessoa DAR, Kawashita K (1981) Potassium-argon ages and strontium isotope geochemistry of Mesozoic and Tertiary basaltic rocks, northeastern Brazil. *Acad. Brasileira de Ciências*, 53, 115–122
- Sial AN, Ferreira VP, Almeida AR (2002) C- and O isotope fluctuations in carbonates of the Freicheirinha Formation, NW Ceará, northeast Brazil. XLI Congr Bras Geol, João Pessoa, Anais, p 508
- Silveira FV (2006) Magmatismo cenozóico da porção central do Rio Grande do Norte, NE do Brasil. Dissertation, Universidade Federal do Rio Grande do Norte, Natal
- Sousa DC, Jardim De Sá EF, Matos RMD, Oliveira DC (1999) Deformação sin- e pós-Formação Barreiras na região de Ponta Grossa (Icapuí, CE), litoral ocidental da Bacia Potiguar. VII Simp Nac Estudos Tect, Lençóis – Bahia, Anais, pp 90–93
- Sousa DC, Jardim de Sá EF, Antunes AF (2008a) Deformação neógena e suas implicações na estruturação dos campos de petróleo na região de Icapuí-Ponta Grossa (CE), Bacia Potiguar emersa. *Revista Brasileira de Geologia* 38(2-suplemento):97–110
- Sousa DC Jardim de Sá EF, Vital H, do Nascimento MAL (2008b) Falésias na praia de Ponta Grossa, Icapuí, CE. Importantes deformações tectônicas cenozóicas em rochas sedimentares da Formação Barreiras. In: Winge M, Schobbenhaus C, Souza CRG, Fernandes ACS, Berbert-Born M, Queiroz ET (eds) Sítios geológicos e paleontológicos do Brasil. Published in Internet 24/09/2008. <http://www.und.br/ig/sigep/sitio120.pdf>

- Souza SM (1982) Atualização da litoestratigrafia da Bacia Potiguar. XXXII Congr Bras Geol 32, Salvador, Anais 5, pp 2392–2406
- Srivastava HK, Lima MS, Nogueira AM, Martins G, Pereira MA (1989) Geologia e estratigrafia das bacias de Pau dos Ferros e do Rio Nazaré (Rio Grande do Norte). XII Simp Geologia do Nordeste, Fortaleza, Anais, pp 157–161
- Teixeira AL, Gaucher C, Paim PSG, Fonseca MD, Parente CV, Silva Filho WD, Almeida AD (2004) Bacias do estágio da transição da Plataforma Sul-Americana. In: Mantesso Neto V, Bartorelli A, Carneiro CDR, Brito-Neves BB (eds) Geologia do Continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida, Beca, pp 487–537
- Torquato JR (ed) (1989) Granitóides do Ceará. Região de Quixadá-Solonópole. Rev Geologia 2 (1–2):1–143
- Trompette R (1994) Geology of Western Gondwana (2000–500 Ma). Pan-African-Brasiliano aggregation of South America and Africa. Balkema, Rotterdam
- Valença LMM, Neumann VH, Mabesoone JM (2003) An overview on Callovian-Cenomanian intracratonic basins of Northeast Brazil: onshore stratigraphic record of the opening of the southern Atlantic. Geol Acta 1(3):261–275
- Vaucher A, Neves S, Cabry R, Corsini M, Egydio-Silva M, Arthaud M, Amaro V (1995) The Borborema shear zone system, NE Brazil. J S Am Earth Sci 8(3–4):247–266
- Vieira TM, Martins G, Oliveira DC, De Castro DL, Castelo Branco RMG (2002) O magmatismo alcalino de idade terciária das bacias Potiguar e Ceará: uma revisão comparativa preliminar. XLI Congr Bras Geol, João Pessoa, Anais, p 399

Landforms and Landscape Evolution of the Equatorial
Margin of Northeast Brazil

An Overview

Peulvast, J.-P.; Betard, F.

2015, XIII, 186 p. 59 illus., 35 illus. in color., Hardcover

ISBN: 978-3-319-18202-5