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Jean-Pierre Peulvast  
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# Landforms and Landscape Evolution of the Equatorial Margin of Northeast Brazil

An Overview

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An Overview

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Jean-Pierre Peulvast  
Université Paris-Sorbonne  
Paris  
France

François Bétard  
Université Paris-Diderot  
Paris  
France

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# Preface

This book is the result of more than 15 years of fieldwork in the Ceará and adjoining states (Rio Grande do Norte, Paraíba, Pernambuco, Piauí). Its preparation was undertaken in a period characterized by important progress in the knowledge of the geology and geophysics of Northeast Brazil and, more generally, of passive margins, basement areas, and sedimentary basins. New methods such as thermochronology also contributed to give new insights into topics such as denudation rates and long-term landform evolution models, raising up renewed discussions when confronted to more classical (morphostratigraphic) approaches. Having gathered a wide and original set of geomorphic, morphostructural, pedological, and other data from fieldwork and processing of various types of digital data (digital elevation models, satellite images...), the authors had published their results in many separate articles, but they finally felt the necessity of publishing an integrated work, in the form of what appears as the first and unique synthesis on the landforms and landscape evolution of Northeast Brazil.

More than a simple monograph, the authors present a comprehensive geomorphic overview of a large tropical region where they show how deciphering the long-term landform evolution helps in understanding the present set of landscapes and morphodynamic environments. Illustrated by original maps and more than 80 color photos and 3D images, it is centered on an original analysis of landforms and soils in a key area allowing the understanding of long-term to short term geomorphic evolution on the equatorial passive margin of Brazil. This part of the Brazilian “Nordeste” displays stratigraphic landmarks whose interpretation reveals the age and nature of landforms, leading to a reconstruction of the geomorphic history by the means of combined morphostratigraphic and morphopedological approaches. Beyond the role of differential erosion related to moderate post-oceanic opening uplift, the plain and upland landscape reflects a juxtaposition of landform and soil generations related to a shallow basin inversion, the last stages of which occurred in semi-arid conditions since the Oligocene. These results throw light on old debates on models of long-term landform development in platform areas, and also help in evaluating recent models of denudation and burial based on thermochronological methods. As a whole, this work brings new scientific data that further help in

assessing geodiversity of a large territory, particularly on geomorphodiversity (landforms and processes) and pedodiversity aspects (soils and paleosoils). At a finer scale, it may also help in identifying valuable geomorphological sites (or geomorphosites) whose scientific and other values (cultural, aesthetic, ecological...) might justify their integration into the national network of Brazilian geosites. It also helps in identifying the distribution of hazards and risks related to landforms and geodynamics in northeast Brazil.

# Acknowledgments

This book is the result of more than 15 years of fieldwork in the Ceará and adjoining states (Rio Grande do Norte, Paraíba, Pernambuco, Piauí), which were made possible mainly by financial and technical help of the authors' institutions (Universities of Paris-Sorbonne and Paris-Diderot; Laboratoire de Géographie Physique, UMR CNRS 8591; Laboratoire PRODIG, UMR CNRS 8586) and by the cooperation between the departments of Geography of the University of Paris-Sorbonne and of the Federal University of Ceará (UFC, Programa de Pós-Graduação, Fortaleza). Significant help was also provided by the Federal University of Rio Grande do Norte (UFRN, Natal), the Regional University of Cariri (URCA, Crato), and the Geopark Araripe (Crato). Among the numerous colleagues to whom the authors are indebted for their direct or indirect help, they wish to cite, in chronological order, the Professors and Doctors Vanda Claudino Sales, Jeovah Meireles, Michel Arthaud, Mariano Castelo Branco, Eustógio Dantas, Jean-René Vanney, Francisco Hilario Bezerra, Benjamin Bley de Brito Neves, Rubson Pinheiro Maia, Yanni Gunnell, Gérard Bourgeon, Laurent Caner, Alessandra de Oliveira Magalhães, André Herzog, Francisco Idalécio Freitas, Rosiane Lima Verde, Francisco da Chagas Sousa da Costa, Ana Luiza Coelho Netto. They also wish to thank the numerous students and guides who participated in many fieldwork sessions. The initial versions of various figures were prepared with the help of Florence Bonnaud (University of Paris-Sorbonne). Finally, the authors warmly thank Jorge Rabassa, who, beyond offering them a participation in his research program on paleosurfaces in Argentina, invited them to present this manuscript in the Springer Earth System Sciences collection.



# Contents

<b>1</b>	<b>Introduction</b> . . . . .	1
1.1	General Objectives . . . . .	1
1.2	Limits and Main Physiographic Features of the Study Area . . . . .	3
1.3	The Regional Organization of Landforms: Classical Interpretations . . . . .	6
1.3.1	Morphological Units and Previous Classifications . . . . .	6
1.3.2	Stepped Surfaces: Classical Models of Interpretation . . . . .	7
1.4	The Morphostructural, Morphostratigraphic, and Morphopedological Approaches . . . . .	9
1.4.1	Morphostructural Patterns, Morphostratigraphy and Landform Ages . . . . .	9
1.4.2	Morphopedology and Duricrusts: Chronological Implications . . . . .	11
1.5	A Contribution to the Knowledge of Geodiversity in Northeast Brazil . . . . .	12
	References . . . . .	13
<b>2</b>	<b>Geological Setting: The Borborema Province</b> . . . . .	17
2.1	The Basement . . . . .	19
2.1.1	Structural Framework . . . . .	19
2.1.2	Brasiliano and Late-Brasiliano Structural Heritage . . . . .	22
2.2	Post-orogenic Rocks and Structures: Pre-rift Deposition and Magmatism . . . . .	25
2.2.1	The Post-orogenic Sedimentary Cover . . . . .	25
2.2.2	Early Magmatism and Rifting . . . . .	27
2.3	The Continental Rift . . . . .	27
2.3.1	Limits of the Rift Zone . . . . .	29
2.3.2	The Cariri-Potiguar Rift Zone . . . . .	30
2.3.3	From Continental Rifting to Transtensional Opening of the Equatorial Atlantic . . . . .	33

2.4	The Post-rift Evolution and the Transform Margin . . . . .	35
2.4.1	Onshore Post-rift Covers. . . . .	35
2.4.2	Offshore Basins and Formation of the Transform Margin . . . . .	38
2.5	Post-campanian Sedimentation and Volcanism: The “Drift Phase” . . . . .	40
	References . . . . .	46
<b>3</b>	<b>Morphostructural Patterns: Influence of an Aborted Rift Zone on the Regional Organization of Landforms.</b> . . . . .	<b>53</b>
3.1	The Main Units . . . . .	53
3.1.1	Structural Landforms of the Cariri-Potiguar Rift Zone . . . . .	55
3.1.2	The Northwest Shoulder of the Cariri-Potiguar Rift Zone . . . . .	66
3.1.3	The Borborema Plateau Region: Southeast Shoulder of the Cariri-Potiguar Rift Zone. . . . .	76
3.2	Drainage, Tectonics, and Differential Erosion . . . . .	78
3.2.1	Regional Patterns. . . . .	78
3.2.2	Structurally Controlled River Systems . . . . .	80
3.2.3	Epigeny Phenomena and Their Morphological Meaning . . . . .	83
3.2.4	The Lithological Filter . . . . .	84
3.3	The Determining Influence of Superposed Structural Heritages. . . . .	87
	References . . . . .	89
<b>4</b>	<b>Stepped Surfaces, Palaeolandforms and Morphostratigraphy: Reconstructing the Long-Term Landscape Evolution Since the Mesozoic.</b> . . . . .	<b>93</b>
4.1	Stepped Paleosurfaces and Related Soils as Indicators of Long-Term Landscape Evolution . . . . .	94
4.1.1	The Identification of Stepped Surfaces . . . . .	94
4.1.2	Soils, Weathering Crusts and Superficial Deposits: Chronological Consequences . . . . .	101
4.1.3	Interpretation of the Stepped System of Landforms . . . . .	103
4.1.4	The Araripe Basin, a Keystone for Understanding Post-cenomanian Landscape Evolution . . . . .	106
4.2	Palaeogeography and Chronology of Long-Term Landscape Development . . . . .	107
4.2.1	The Pre-rift Period (Jurassic and Older) . . . . .	107
4.2.2	Intracontinental Rifting (Early Cretaceous) . . . . .	107
4.2.3	Post-rift Stage and Oceanic Opening (Middle to Late Cretaceous) . . . . .	109
4.2.4	Regional Uplift, Erosion and Topographic Inversion (Late Cretaceous to Present) . . . . .	109

- 4.3 Uplift and Denudation as Driving Factors of Long-Term Landscape Development . . . . . 111
  - 4.3.1 Epeirogenic Deformation and Rates of Uplift and Denudation from Morphostratigraphic Data. . . . . 111
  - 4.3.2 Denudation Depths and Long-Term Erosion Rates: A Discussion of Regional Data . . . . . 113
  - 4.3.3 Interpretation of Discrepancies Between AFTA and Morphostratigraphic Results in the Araripe Basin . . . . . 114
  - 4.3.4 Eustatic Controls on Erosion and Sedimentation . . . . . 117
  - 4.3.5 Basin Inversion and Possible Mechanisms of Regional Uplift . . . . . 118
- References . . . . . 124

- 5 Late Cenozoic Evolution of Landforms: The Influence of Neotectonics and Climatic Changes . . . . . 131**
  - 5.1 Barreiras–Tibau Sediments and Landforms: A Geological Record of the Late Cenozoic Geomorphic Evolution . . . . . 132
    - 5.1.1 Fluvial to Coastal Sediments: Erosion and the Origin of the Late Cenozoic Sediments. . . . . 132
    - 5.1.2 Sedimentation and Sea Level. . . . . 134
  - 5.2 Neotectonics and Landforms: Evidence and Uncertainties . . . . . 135
    - 5.2.1 Seismotectonic Activity, Stress Field and Neotectonics. . . 135
    - 5.2.2 The Coastal Strip: Neotectonic Control on Landforms?. . . 139
    - 5.2.3 Inland Scarps: Weak Evidence of Neotectonics . . . . . 142
    - 5.2.4 Asymmetry of Drainage Basins: The Middle Jaguaribe Basin . . . . . 146
    - 5.2.5 Poorly Characterized Neotectonic Movements in the Interior of Northeast Brazil . . . . . 147
  - 5.3 Late Cenozoic and Present-Day Erosion Dynamics of Scarps and Piedmonts. . . . . 148
    - 5.3.1 Structural Controls on Late Cenozoic Scarp Evolution and Hillslope Dynamics. . . . . 148
    - 5.3.2 Structural and Other Controls on Present-Day Morphodynamics . . . . . 149
    - 5.3.3 Late Cenozoic Climate Change, Hillslope Processes and the Last Stages of Scarp Evolutions . . . . . 154
    - 5.3.4 Conditions of Recent Evolution of Hillslopes and Implications for Hazard Assessment. . . . . 155
  - References . . . . . 157

- 6 Conclusion and Perspectives . . . . . 161**
- 6.1 Structural Geomorphology, Morphostratigraphy  
and Morphopedology in Northeast Brazil: New Ideas  
on Landforms and Landscape Evolution . . . . . 162
- 6.1.1 Great Escarpment or Marginal Escarpment? . . . . . 162
- 6.1.2 Stepped Surfaces and Morphostratigraphic  
Relationships: A Summary . . . . . 163
- 6.1.3 Differential Erosion, Long-Term Landform  
Evolution and Morphopedology . . . . . 164
- 6.1.4 A Discussion of Long-Term Evolution Models . . . . . 168
- 6.2 Toward an Integrated Assessment of Geodiversity  
in Northeast Brazil . . . . . 169
- 6.2.1 Geodiversity in Ceará and Neighboring Regions:  
A Preliminary Assessment . . . . . 170
- 6.2.2 Geoconservation: Why, What, and How? . . . . . 173
- 6.2.3 Geotourism and Geoeducation: New Challenges  
in Northeast Brazil . . . . . 178
- References . . . . . 179
  
- Index . . . . . 183**

# Abstract

More than a simple monograph, the authors present a comprehensive geomorphic overview of a large tropical region where they show how deciphering the long-term landform evolution helps in understanding the present set of landscapes and morphodynamic environments. The Equatorial margin of the Brazilian “Nordeste” displays stratigraphic landmarks whose interpretation reveals the age and nature of landforms, leading to a reconstruction of the geomorphic history by means of combined morphostratigraphic and morphopedological approaches. Beyond the role of differential erosion related to moderate post-oceanic opening uplift, the plain and upland landscape reflects a juxtaposition of landform and soil generations related to a shallow basin inversion, the last stages of which occurred in semi-arid conditions since the Oligocene. These results throw light on old debates on models of long-term landform development in platform areas, and also help evaluating recent models of denudation and burial based on thermochronological methods. As a whole, this work brings new scientific data that further help assessing geodiversity of a large territory, particularly on geomorphodiversity (landforms and processes) and pedodiversity aspects (soils and paleosoils). At a finer scale, it may also help identifying valuable geomorphological sites (or geomorphosites) whose scientific and other values (cultural, aesthetic, ecological...) might justify their integration into the national network of Brazilian geosites.

**Keywords** Landscape evolution · Morphostratigraphy · Morphopedology · Morphostructural patterns · Northeast Brazil · Passive margin · Geodiversity

# Chapter 1

## Introduction

**Abstract** The equatorial margin of the Brazilian “Nordeste” is especially rich in stratigraphic landmarks that help in understanding the nature of landforms and reconstructing the geomorphic history. It illustrates the interest of combined morphostructural, morphostratigraphic, and morphopedological approaches in the study of a large area ( $\sim 200,000 \text{ km}^2$ ). The objectives are: (1) to propose a review of the geological data; (2) to analyze and revise the morphostructural and morphostratigraphic patterns; (3) to investigate features that might be specifically related to the complex history recorded by a passive margin intersecting a failed rift arm; (4) to show that this type of study is an irreplaceable tool for further geomorphological and geological researches on basement areas, passive margins, and related sedimentary basins; (5) to give a scientific substrate to an inventory of geodiversity in this region particularly rich in remarkable geomorphic and geological features.

**Keywords** Morphostructural analysis · Morphostratigraphy · Morphopedology · Passive margin · Geodiversity · Northeast Brazil

### 1.1 General Objectives

The equatorial margin of the Brazilian Nordeste differs from many uplifted passive margins often poor in Phanerozoic deposits and weathering formations, as it displays lots of stratigraphic landmarks that help in understanding the nature of landforms and reconstructing the geomorphic history. It provides a precious opportunity to illustrate the interest of combined morphostructural, morphostratigraphic, and morphopedological approaches in the study of a large area ( $\sim 200,000 \text{ km}^2$ ).

Recent publications on the structure and morphology of the Brazilian continental margin mainly concern the eastern Atlantic front, a typical rifted margin with Great Escarpments (Ollier 1985a, b; Gallagher et al. 1994; Almeida and Carneiro 1998; Brown et al. 2000; Japsen et al. 2012; Jelinek et al. 2014). Although the structure of

equatorial northeastern Brazil and of conjugate parts of the African margin have also been analyzed in many recent papers (e.g., Popoff 1988; Magnavita et al. 1994; Matos 1992, 2000, 2002), the continental landforms of this region—a transform margin, i.e., resulting from wrench faulting and shearing between two continents before oceanic opening (Boillot and Coulon 1998; Mascle and Basile 1998)—have only partly been reinterpreted until now (Peulvast et al. 2008).

This margin segment strongly differs from those of eastern Brazil, forming a particular case among passive margins with rifted or “type 1” Great Escarpments (Beaumont et al. 2000; Pazzaglia and Gardner 2000). The presence of typical climatic landforms (pediplains, inselbergs...), stepped patterns and related paleo-landforms makes this area a highly representative place for tropical, basement, and margin morphology.

More than a simple monograph, we present a comprehensive geomorphic overview of a large tropical region in order to show how deciphering the long-term landform evolution helps in understanding the present set of landscapes and morphodynamic environments. The Equatorial margin of the Brazilian “Nordeste” displays stratigraphic landmarks whose interpretation reveals the age and nature of landforms, leading to a reconstruction of the long-term geomorphic history by means of combined morphostratigraphic and morphopedological approaches. Beyond the role of differential erosion related to moderate post-oceanic opening uplift, the plain and upland landscape reflects a juxtaposition of landform and soil generations related to a shallow basin inversion, the last stages of which occurred in semi-arid conditions since the Oligocene. The results of this analysis are also expected to throw light on old debates on models of long-term landform development in platform areas, and help in evaluating recent models of denudation and burial based on thermochronological methods (Japsen et al. 2012; Jelinek et al. 2014).

Therefore, the book is organized around the following objectives: (1) to propose a review of the geological data that are necessary for understanding inland morphology; (2) to analyze morphostructural and morphostratigraphic patterns of this vast area whose only large morphological outlines are hitherto described; (3) to investigate features that might be specifically related to the complex history recorded by a passive margin intersecting a failed arm; (4) to show that, generally speaking, this type of study is an irreplaceable tool for further geomorphological and geological researches on basement areas, passive margins, and related sedimentary basins, for instance, by deciphering the respective influences of superposed structural heritages on the relief, discriminating tectonic, climatic, and other factors of geomorphological differentiation, giving bases for reconstructing the morpho-tectonic evolution or understanding the recent or current morphodynamic evolution; (5) to give a scientific substrate to an inventory of geodiversity which, in this region particularly rich in remarkable geomorphic and geological features, is still far from to be completed, in spite of the existence of various types of preservation units (Geopark Araripe, National Parks) and of the SIGEP preliminary inventory (Bétard et al. 2011).

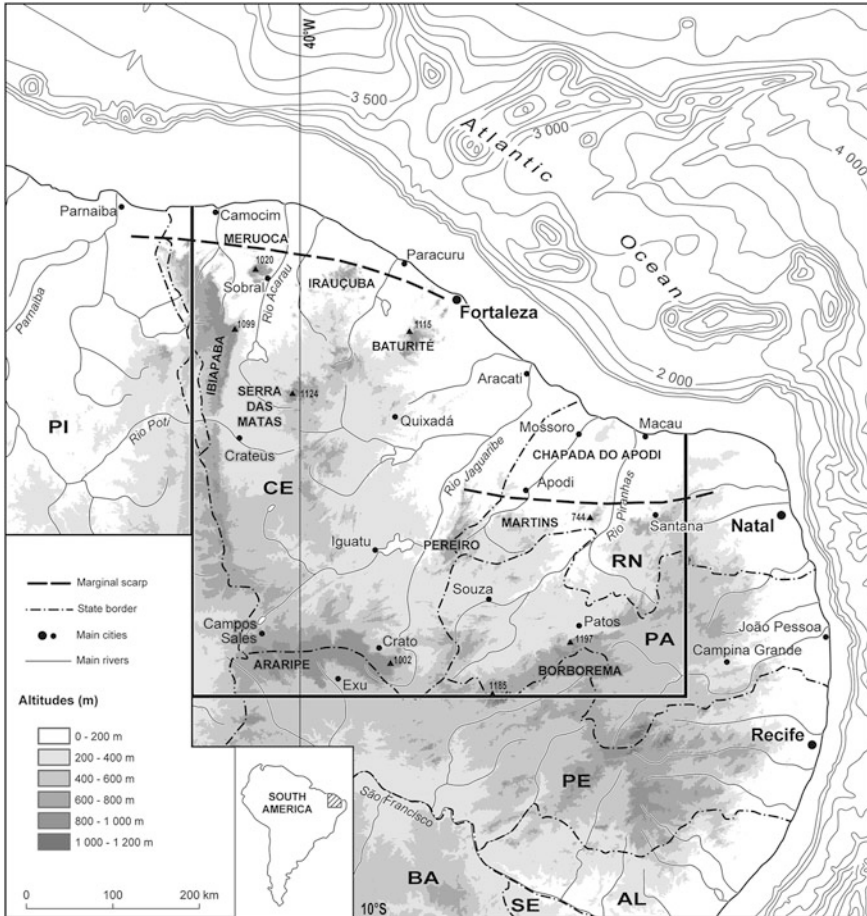
## 1.2 Limits and Main Physiographic Features of the Study Area

The study area belongs to the Borborema Province (Almeida et al. 1981) and forms the northern part of the Brazilian northeast, or “Nordeste.” This eastern segment of the Brazilian Equatorial margin is a passive margin whose counterpart, on the opposite side of the Equatorial Atlantic Ocean, is the northern shore of the Gulf of Guinea between Cameroon and Ghana (Popoff 1988; Maurin and Guiraud 1993; Matos 2000). Situated between 3°15' and 7°30'S, and 37° and 41°W (560 × 520 km), it includes the Ceará state and the western parts of the Rio Grande do Norte and Paraíba states, as well as a northern fringe of the inner Pernambuco state, to the south (Fig. 1.1). Its western and southern limits, respectively, coincide with high plateaus, the Serra de Ibiapaba and the Chapada do Araripe (ca 1000 m a.s.l.). To the southeast and the east, it is bounded by the Borborema massif (1200 m a.s.l.), which separates it from the lower São Francisco valley and from the stepped plateaus and lowlands of the east coast, south of the São Roque Cape. The region belongs to the semi-arid Nordeste, but the coastal strip and the inner mountains are characterized by more humid tropical climates, with forest environments (Figueiredo 1997; Cavalcante 2005; Bétard 2007).

Along the ca 600 km long, WE to NW–SE coastline, the continental shelf is relatively narrow (from 100 km wide in the west to 41 km in the east: Freire et al. 2002) and shallow (50–80 m at the continental edge; Figs. 1.1 and 1.2). Most coastal landforms are low, with long tracts of sand beaches and barriers, dunes and narrow coastal plains locally interrupted by estuaries or by low rocky promontories and short active sea-cliffs (eastern Ceará), and often bounded inland by low abandoned cliffs (Claudino Sales 2002; Fig. 1.3a). Inland, a 10–80 km wide strip of low sedimentary plateaus called “tabuleiros” (10–60 m in altitude) is almost interrupted near Fortaleza, where coastal mountains rise up to 800 m, only a few kilometers far from the shoreline (Serra de Camara, Fig. 1.3b). Including a calcareous “chapada” east of the Jaguaribe River, these slightly dissected lowlands form the transition between the coast and the vast erosion plains—the so-called «Sertaneja Depression»—which extend far inland on the Precambrian basement, up to the foot of remote scarps and inselbergs.

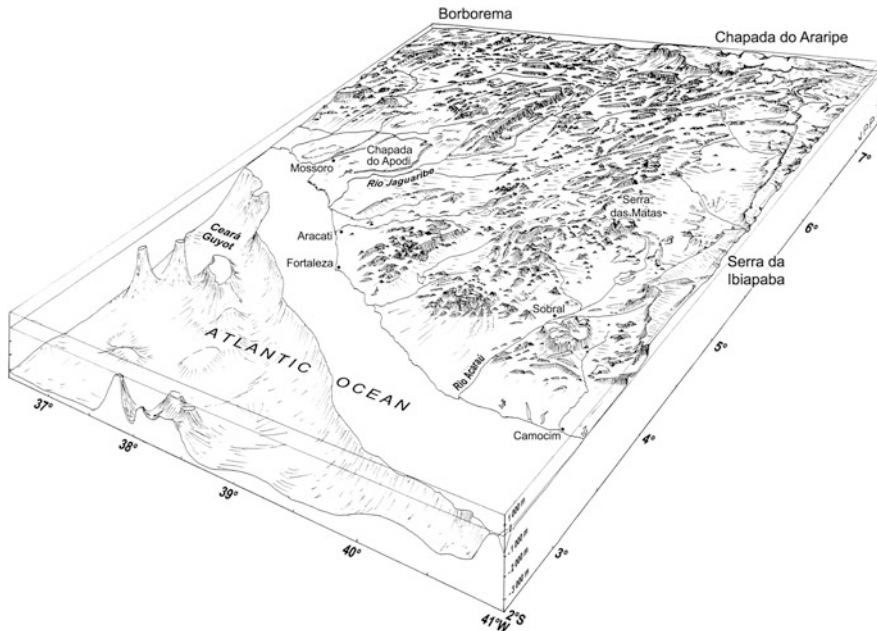
The regional relief is organized around a large depression drained by the lower Jaguaribe river and its tributaries. To the west, a wide highland zone drained by shorter rivers oriented to the north is characterized by summit altitudes around 1000 m a.s.l. To the north of the Borborema plateau, the eastern upland zone is narrow, with lower summits (700–900 m a.s.l.). At regional scale, the inland area, or “sertão,” exhibits the roughly concentric pattern of a huge hemicycle (Fig. 1.4), here named “the Jaguaribe-Piranhas hemicycle,” intersected by two discontinuous and offset EW alignments of mountain slopes forming a highly dissected escarpment





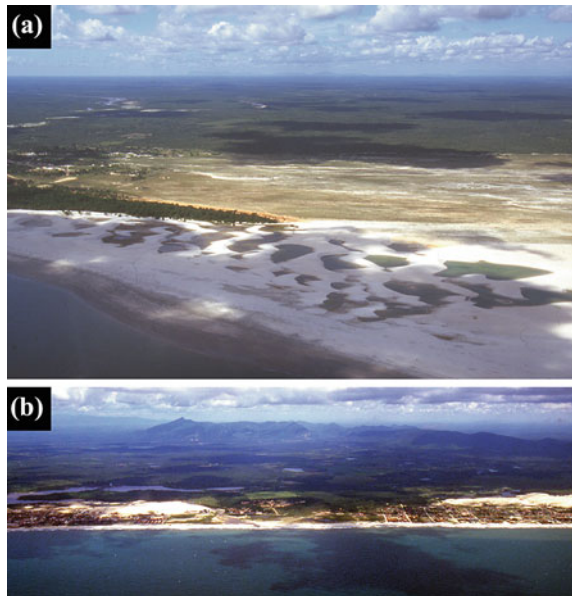
**Fig. 1.1** Location map of the study area. Topography derived from the SRTM DEM (shuttle radar topography mission digital elevation model)

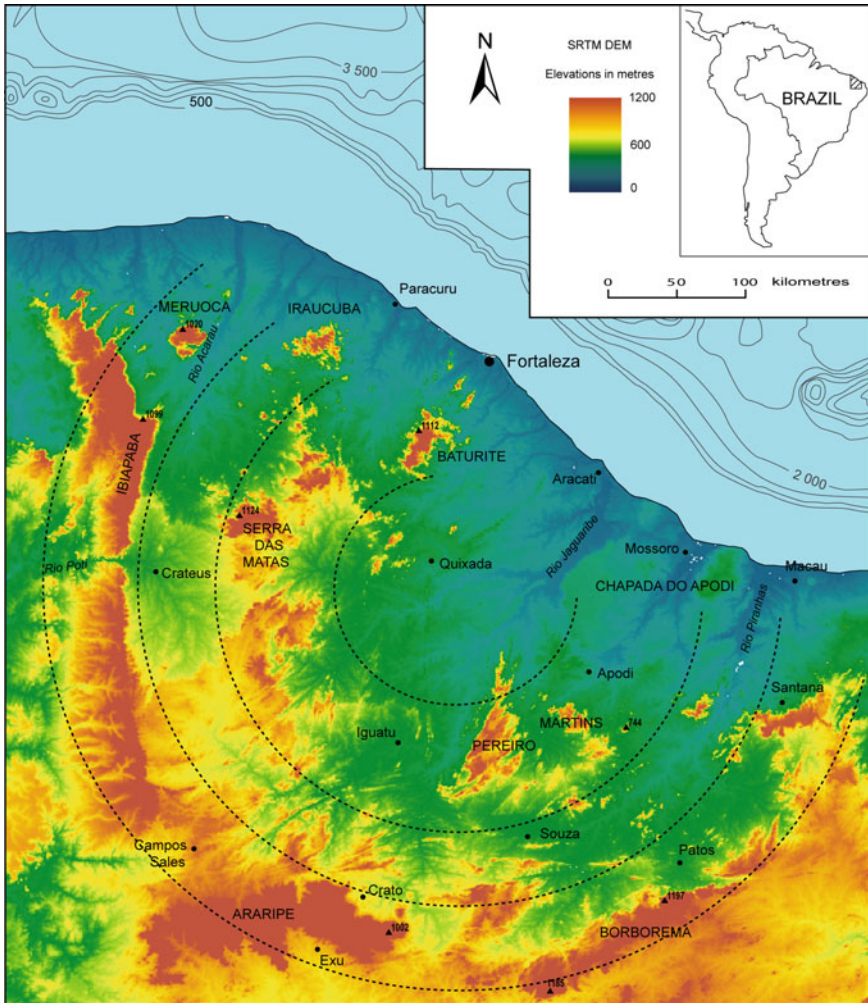
along the margin, perhaps a low and very discontinuous version of a Great Escarpment (in the sense of Ollier 1985a). The offset area corresponds to the lower Jaguaribe valley and plain, and opens on a SE-trending segment of the continental margin (Fortaleza - Potiguar). The highlands are arranged in two concentric half rings around the central plain which widens toward the Aracati Platform and the Potiguar Basin (Fig. 1.4). Historically, less attention has been paid to this geographical pattern than to the stepped patterns described or postulated by many authors (Peulvast and Claudino Sales 2004).



**Fig. 1.2** Sketch block-diagram of the Jaguaribe—Piranhas amphitheater, showing the main topographic features

**Fig. 1.3 a** Guriú, west of Jericoacoara: wide tabuleiros interrupted over the sea by a low abandoned sea-cliff (left) widely overridden by mobile dunes (barchanoids). **b** Icarai de Caucaia (western outskirts of Fortaleza): narrow coastal plain fringed by sandy shore and dunes, and overlooked to the south by residual mountains exceptionally close to the coast (Serra de Juá, Serra da Conceição).  
 Photographs J.P. Peulvast





**Fig. 1.4** Topography of the study area. Note the concentric patterns of landforms, organized in two half rings of highlands around a wide central plain—the so-called “Sertaneja Depression.” Topography derived from the SRTM DEM

### 1.3 The Regional Organization of Landforms: Classical Interpretations

#### 1.3.1 Morphological Units and Previous Classifications

In the literature, the morphological features of the study area are either described on the basis of stratigraphic and topographic criteria or in relation to tectonics. One of the most detailed descriptions and partitioning of the regional morphology was

proposed in the Radambrasil Project (Moreira and Gatto 1981; Prattes et al. 1981). Here, these authors identify the following morphostructural units:

1. the coastal plain,
2. the coastal plateaus or “tabuleiros” underlain by the soft sandstones of the Barreiras Formation,
3. the low Sertaneja Surface, widely developed inland around 350 m a.s.l. and lower, and considered to be the fundamental topographic level,
4. the residual massifs or plateaus, above 700 m a.s.l., which correspond to the mountains of the inner half ring of highlands, and to the marginal escarpment,
5. the Ibiapaba Plateau.

Strong structural controls appear in parts of the outlines of these units and in the dissected landforms.

Another classification of morphological domains, proposed for the Ceará state (Souza 1988, 1997), reflects the underlying lithological and chronostratigraphic units:

- the domain of Cenozoic deposits (fluvial plains, coastal landforms, tabuleiros or “Glacis pré-litorâneos”),
- the domain of Paleo-Mesozoic sedimentary basins, with related structural landforms (Chapada do Araripe, Chapada do Apodi, Ibiapaba plateau),
- the basement units, comprising the dissected residual mountains and the Sertaneja depressions, slightly dissected and strewn with inselbergs.

The classification proposed by Saadi and Torquato (1992) also concerns the Ceará state. It opposes “peripheric” sedimentary basins (in fact at the periphery of the state) and a “Central crystalline block or nucleus” (the western part of the inner mountain half ring). The Sertaneja surface and the “residual mountains” would register a regional updoming north of the EW Patos shear zone, between NE-trending depressions or grabens located in northwest (Jaibaras) and southeast Ceará (Senador Pompeu, Orós and Jaguaribe fault systems). These descriptions do not account for the roughly concentric patterns described above.

### ***1.3.2 Stepped Surfaces: Classical Models of Interpretation***

The morphological patterns of northeast Brazil are classically considered as a result of regional uplift induced by break-up of the Gondwana supercontinent, interfering with climatic fluctuations in the Cenozoic (Mabesoone and Castro 1975). The uplift would have triggered the shaping of successively lower planation surfaces and the incision of a centrifugal drainage pattern (Fig. 1.5).

As in the Guiana Shield (McConnell 1968; Zonneveld 1985, 1993), all authors agree on the existence of stepped erosion surfaces in this region, related to Mesozoic and Cenozoic sediments deposited on the continental margin. Landscape patterns have been interpreted as (i) the erosional response to updoming of a large crustal