World Geomorphological Landscapes

Michel Hermelin *Editor*

Landscapes and Landforms of Colombia

Springer

World Geomorphological Landscapes

Series editor

Piotr Migoń, Wroclaw, Poland

More information about this series at http://www.springer.com/series/10852

Michel Hermelin
Editor

Landscapes and Landforms of Colombia

Springer

Editor
Michel Hermelin (deceased)
Department of Geology
U. EAFIT
Medellín
Colombia

ISSN 2213-2090 ISSN 2213-2104 (electronic)
World Geomorphological Landscapes
ISBN 978-3-319-11799-7 ISBN 978-3-319-11800-0 (eBook)
DOI 10.1007/978-3-319-11800-0

Library of Congress Control Number: 2015945567

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

This book is dedicated to the memory of Benjamín Alvarado Biester, the founding director of the Colombian Geological Survey. About 30 years ago I gave him a copy of the book I had just published, to try to convince architects, urban planners and decision-makers of the necessity to take into account the Earth Sciences in every land development. A few days later, Benjamín responded with this unforgettable comment: "Michel, you put so many arguments in your book to persuade people to study the Earth, but you missed the most important one: it is because it is beautiful."

Foreword

It is a pleasure and an honor to write these introductory words to accompany the book entitled "Landscapes and Geomorphosites of Colombia".

As a botanist by training, I have devoted a good part of my life to carrying out fieldwork in many regions of Colombia. I have always been impressed by the beauty of the country´s landscapes and, as a college professor I tried to impress on my students how, as field biologists, they would be among the luckiest people on Earth because they would have the opportunity to see sites no one else encounters in their regular, day-to-day, city life.

A general geology course, good as it was, did not really give me an appreciation for the geomorphological context in which geological features existed. Therefore, I liked landscapes for what they were, seen by fairly uneducated eyes.

Now, in this book, I find that many of the landscapes I used to visit are being described and analyzed from the geomorphological standpoint. Places like the "Bogotá savanna" (where I have lived most of my life), Chicamocha (one of the first amazing places I visited as a student in the early 1960s), Tatacoa, Guatavita, Tota, Galerazamba, will now have a new meaning for me and for those who read the book. The enthusiasm with which Prof. Michel Hermelin refers to the landscapes of Colombia conveys to the reader the importance and the meaning of these geomorphosites. Professor Hermelin makes it clear that geomorphosites are valuable not only from the scientific point of view, but also from the cultural, aesthetic, and even historical perspectives.

The group of authors that has contributed to the book could not be better. They are experienced scientists who have studied these landscapes in detail and who, therefore, provide first hand insights into their characteristics, scientific value, current state, threats, and opportunities. As an example, Prof. Hermelin himself has devoted his life to the study of geomorphology, environmental geology, and tropical landscapes, among other similarly important subjects.

EAFIT University takes, once again, a leadership role in supporting geological studies of excellent quality, giving Colombia much needed instruments for appropriate decision making as well as for the appreciation of these poorly known treasures. From now on, Colombia will not only be known by its rich biodiversity and diversity of climates and cultures, but also by the beauty and value of its wonderful landscapes and geomorphosites. These two words should become part of the vocabulary of scientists, politicians, students, decision makers, and, most importantly, the general public who will be able to enjoy, respect, protect, and defend them based on scientifically sound arguments.

The Colombian Academy of Exact, Physical and Natural Sciences welcomes with open arms this publication because it increases the level of knowledge of our natural world and because it will play an important role in advancing the understanding and appreciation of science in the country. The book is, no doubt, an important addition to the international series of publications on World Geomorphological Landscapes.

Enrique Forero
President
Colombian Academy of Exact,
Physical and Natural Sciences

Preface

When I was contacted by Edgardo Latrubesse, at that time Latin American representative of the International Association of Geomorphologists, I felt that a dream I had been caressing for several years was becoming real: he proposed that I prepare a book on Colombia for the series **World Geomorphological Landscapes**. The challenge was ambitious and demanding, but it was finally carried out thanks to the generous collaboration of several friendly colleagues and institutions.

Why does the interest for the landscapes of Colombia, a country with such a diversity in climatic and biologic aspects, happen so late?

Several hypotheses can be established. From the historical standpoint, the Spaniards, who conquered the country in the fifteenth century, considered nature an enemy: in fact, mosquito-transmitted fevers and other tropical diseases killed certainly more Spanish soldiers than the brave Indian warriors. On the other hand, these rapacious adventurers were more interested in gold than in landscape inventory or contemplation. Chroniclers' reports tend to confirm this supposition. Furthermore, rules dictated by the Sevilla Council of the Indies obliged Spaniards to live in cities, isolated from the countryside.

The first description of Colombian landscapes came from European travelers, from the end of the eighteenth to the middle of the nineteenth century: Bouguer, Humboldt, Boussingault, Gosselman and later Hettner, Reclus, Crevaux, and others. The middle of the nineteenth century was also the time when a quixotic adventure took place through the inspiration of President T.C. Mosquera and under the able direction of A. Codazzi, an Italian military engineer: the *Comisión Corográfica* (Chorographic Commission), which went across almost the entire country from 1850 to 1859 and left maps, pictures, and reports, was unfortunately published at that time in an erratic manner. This national expedition—like the other travelers—had to face great difficulties to carry on their task: the three jungle-covered cordilleras form tremendous natural barriers. Steamship navigation along the Magdalena River only became reliable at the end of the nineteenth century, when the first railroads were built. At that time, it took about 10 days to travel from Bogotá to Cartagena and 8 days to reach Medellín. It is understandable that airplanes, which started to cover domestic itineraries just after World War I, are considered as the first real integrators of the Colombia nation.

Since the last three decades of the past century, guerrillas and illegal drug-trafficking activities were also an important inconvenience for tourism, a situation that has diminished significantly in recent years. Nowadays, most of the roads can be taken without any risk. This is reflected by the abundance of tourist guides published in English and French.

Little by little, Colombians have learned how valuable their landscapes are through the works of scientists, writers, and painters. And thanks to the development of roads and government efforts to foster domestic and international tourism, many people have begun to enjoy the natural beauties of this country, where not only landscapes are worth seeing but which also possesses attractive cities, such as Cartagena, Popayán, Bogotá, Mompox, and famous archeological sites like *San Agustín* and *Ciudad Perdida* (the Lost City in the Snowy Santa Marta Massif).

The geomorphosites selected are located in the western part of the country. They were selected due to their easy, secure access. Others are missing, such as the *Chiribiquete* Ridge and the *Mavicure* Mounts, which belong to the Amazonian domain. Both deserve aesthetic and scientific interest but require costly air trips to be reached.

During the past 60 years, first as a student and then as a geologist, I have had the privilege to travel across this country using all the possible transports, from walking to mule and canoe to helicopter.

I hope this book may be useful to transmit the very deep enthusiasm I still feel when facing the many beautiful landscapes of Colombia.

August 2014 Michel Hermelin

Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, nature often surprises us creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time to tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. For centuries, and even millennia, they have been shaped by humans who have modified hillslopes, river courses, and coastlines and erected structures that often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology—"the science of scenery"—a part of Earth Sciences that focuses on landforms, their assemblages, surface and subsurface processes that molded them in the past and that change them today. To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume presents the geomorphology of Colombia, a South American country that is home to highly diverse physical landscapes, from tropical coasts and extensive floodplain within equatorial forests, through Andean mountain chains and intramontane plateaux, to numerous volcanoes. The latter are beautiful, but can also be deadly as the famous case of Nevado del Ruiz illustrates. It is the first time ever that landforms and landscapes of this country are presented in a coherent, systematic manner.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists (IAG)—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union (IGU) and the International Union of Geological Sciences (IUGS). Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigor, is the most appropriate means to fulfill these aims and to serve the geoscientific community. Very little of the geomorphological diversity of Colombia has been known so far to the global community and I am extremely grateful that Prof. Michel Hermelin added this book project to his professional agenda and delivered such a fine product, successfully coordinating the large team of authors. I am sure that readers of this volume, after seeing how immensely scenic Colombian geomorphological landscapes are, how many "hidden jewels" exist there, and how surprisingly easy some of them can be accessed, will quickly add Colombia to their list of destinations to go.

Piotr Migoń

Acknowledgments

The preparation of this book was made possible thanks to the Universidad EAFIT Department of Geology, which gave me the permission to use part of my teaching time to complete it. I also express my gratitude to the Nodo Colombiano de Geología (The Colombian Geomorphological Group), which under the direction of Orlando Navas welcomed and supported the project. The Colombian Geological Survey (Servicio Geológico Colombiano) generously permitted the use of its documents and maps. Marta Calvache and Ricardo Méndez from Servicio Geológico Colombiano gave their time and advice as did Gloria Maria Sierra from Universidad EAFIT. J.A. Romero, from Servicio Geologico Colombiano for permission to use his Ph.D. thesis material and Jorge Luis Ceballos from IDEAM for permission tu use one of his photographs Prof. Roberto Vargas, from the Universidad Sur Colombiana made available documents on the Tatacoa Desert. I also thank Enrique Forero, President of the Colombian Academy of Sciences, who kindly accepted to write the forewords. I particularly acknowledge the unfailing assistance of Imelda Nieto, without which this book would not have been possible.

Michel Hermelin

Michel Hermelin Arbaux [1937–2015]

Photo by Miguel Tavera

Dr. Michel Hermelin Arbaux passed away on 15th August 2015 at the age of 78. He was always full of energy, ideas, and questions about nature and humanity from meteorites, soil formation, geo-landscapes, urban geology to ethics in geology, history, social justice, and many other topics.

Dr. Michel Hermelin was General Director of the National Geological Institute of Colombia, and a faculty member at the National University of Colombia. He was also responsible for founding geology as an academic career at the University of Eafit. He was also a distinguished member of the National Academy of Science of Colombia and dedicated most of his multifaceted life to the advancement of geological sciences. He expertly combined the results of basic research with science divulgation, and with the most pertinent applications for the sustainable use of natural resources, a task with big challenges in Colombia. We saw Dr. Michel Hermelin as a generous man, precisely presenting his initiatives at the highest levels, in both national and international forums. We also saw him interacting with solidarity, and without any prejudice towards people from the most disadvantaged places of Colombia.

Those who had the good fortune of working with him and observing his teachings would like to express immense gratitude and also endeavor to continue the ways he showed us. We are certain Dr. Michel liked the poem ‘If’ by Rudyard Kipling, which in many ways describes him very well. We also feel, Dr. Michel, that you are still here, kindly telling us: *thanks very much, it is enough…now, go working boys!*

Iván D. Correa Arango

Contents

Abbreviations

ACCEFyN	Academia Colombiana de Ciencias Exactas, Físicas y Naturales Colombian Academy of Exact, Physical and Natural Sciences
ICP	Instituto Colombiano del Petróleo Colombian Petroleum Institute
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales Institute for Hydrology, Meteorology and Environmental Studies
IGAC	Instituto Geográfico Agustín CodazziGeographical Institute “A. Codazzi”
INGEOMINAS	(until 2013) Institute for Geologic and Mining Research (the Colombian Geological Survey)
INVEMAR	Instituto de Investigaciones Marinas y Costeras Institute for Marine and Coastal Research
SGC	Servicio Geológico Colombiano (Since 2013) The Colombian Geological Survey
UIS	Universidad Industrial de Santander Santander Industrial University (Bucaramanga)
UN	Universidad Nacional National University

Short Biodata of Authors

Blanca Oliva Posada graduated as a Geologist at EAFIT University. She specialized in Remote Sensing applied to Coastal Management in ITC, the Netherlands and obtained her M.Sc. in Earth Sciences at the EAFIT University. For more than 12 years she was with INVEMAR, the National Institute for Coastal Management. She is now with the Ministry of Environment. Her main interests are coastal processes and management and urban geomorphology.

José Humberto Caballero is Associated Professor at the Geosciences and Environment Department of National University of Colombia at Medellin. His main topics of interest are geomorphology in mountain areas and natural risks.

Marta Lucia Calvache is presently the Director of the Department of Geological Hazards of the Colombian Geological Survey. She received her degree in Geology at the National University, Bogotá, and her Ph.D. at Arizona State University. She is widely recognized as one of the first experts in Colombian volcanology, as she has studied the country volcanoes for more than three decades and published many papers and reports on this topic.

Carolina Garcia is a risk management scientist with interdisciplinary focus. She has participated in several multidisciplinary projects on Environmental Geology, Geomorphology, and Risk Management in Latin America and Europe, involving both the academy and NGOs. She is currently a lecturer at different universities in Colombia and also works as a consultant on disaster risk reduction. Her aim is to integrate natural and social sciences to generate useful risk reduction products for multiple stakeholders.

José Henry Carvajal received his B.Sc. in Geology in 1984 from the Universidad Nacional de Colombia–Bogotá, and carried out graduate studies in Remote Sensing applied to Geology at CIAF. He has been working as a geologist at the Colombian Geologic Survey for the past three decades. His main research fields are detailed geological and geomorphological mapping, focused on natural hazard and risk zoning evaluations, in particular, in coastal zones. He participated in several projects and published several papers on hazard urban zoning and emergency prevention. He is currently working on geological processes that impact the Colombian coastal lines' stability. He recently published a proposal in order to standardize geomorphological mapping in Colombia.

Iván Darío Correa Arango is Professor of Coastal Geomorphology in the School of Sciences, Eafit University at Medellín, Colombia. He has a Bachelor degree in Geological Engineering from the National University of Colombia and a Ph.D. degree in Marine Geology from the University Bordeaux I. His primary research interest includes the geological and geomorphological frameworks of the Colombian coasts, including the nature and geological hazards of the southern Caribbean mud-diapiric influenced littorals and the historical breaching of the major barrier island of the Pacific coast related with changes in sediment balances, coseismic subsidence, and positive anomalies related to the El Niño events. He has published over 40 scientific articles and texts.

Domingo Mendivelso graduated as Geologist from the Universidad Nacional in Bogotá. He took several courses in air photo and satellite image interpretation applied to geology at CIAF, Bogotá. He obtained an MSc in Applied Geomorphology from the International Training Center in the Netherlands. He was Assitant Professor at CIAF and in several universities in Bogotá and became full time professional of the Soil Department, National Geographic Institute. After his retirement in 2007 he became consultant and part-time professor in Bogotá.

José Fernando Duque-Trujillo is Professor in the Department of Earth Sciences at EAFIT University. His academic interests are focused on regional tectonic processes using relations between magmatism, deformation, and geodynamics to understand the evolution of continental margins. His work is supported in the use of different tools like structural geology geochronology (U-Pb and ^{40}Ar- ^{39}Ar), geochemistry, and paleomagnetism.

John J. Gallego belongs to the environmental geology research group at National University of Colombia. His research mainly concerns the geomorphology and neotectonics of the eastern and western Antioquia Department, with the majority of his work focusing on the erosion surfaces of "Altiplano Antioqueño" and paleoseismology of active faults in the Cauca River Canyon; geological heritage, environmental geology, and natural hazard zonation for land-use planning.

Georgina Guzmán is Associate Professor of Stratigraphy at the Department of Geology—School of Physicochemical Engineering, UIS Bucaramanga. Her research focus is in the geological mapping of the western Colombian Caribbean and sedimentology of the Middle Magdalena Valley, where she is analyzing Late Cretaceous and Paleocene-Miocene formations.

Michel Hermelin After retiring as Senior Professor from the Universidad Nacional, Medellin, Michel Hermelin founded the Department of Geology and taught Geomorphology and Environmental Geology at Universidad EAFIT, until he retired as Emeritus Professor in 2014. He had been previously general director of the Colombian Geological Survey in Bogotá and private consultant. He served as AGID Executive Committee Member, as Latin American Geological Survey Director Consulting Board Member, as Vice president for Latin America of IUGS COGEOENVIRONMENT, and was president of the Geological Society of Colombia and of the Geology Professional Council. He has edited seven books and published more than 200 scientific articles and book chapters. His main fields of interest are tropical geomorphology, tephrachronology, urban geology, and history of environment.

Ricardo Méndez graduated as a Geological Engineer and took graduate courses in university teaching. For the past three decades he has been at the Volcanologic Observatory of the Colombian Geological Survey in Manizales, working on volcanology and information monitoring and socializing. He has taught several university courses. His present research interests include geoarcheology and its relation to volcanic hazards. He has published several scientific articles and reports related to volcanism.

María Luisa Monsalve is a Senior Geologist at the Colombia Geological Survey. Her research interests include volcanology, volcanic hazard assessment, and geothermics. She has published a number of scientific papers and reports on Colombian volcanic hazards.

Orlando Navas graduated as Geologist from the National University in Bogotá and is a specialist in Remote Sensing applied to geological studies. He worked with the Colombian Geological Survey until his retirement in in 2011. He is presently the President of the Geology Professional Council. He has taught Engineering Geology, Geomorphology and Remote Sensing in several universities and has participated in several research projects on environmental and natural hazard topics; he is the author of several scientific articles and a Manual of Remote Sensing applied to Geosciences.

Juan Felipe Paniagua-Arroyave is a Fulbright scholar sharing affiliations between the Marine Science Research Group at EAFIT University in Medellin, Antioquia, Colombia, and the Geomorphology Laboratory in the Department of Geological Sciences at University of Florida, Gainesville, FL, USA. His research is focused on sediment transport patterns in the inner-continental shelf and surf zone at different timescales. Juan Felipe holds a BEng degree in Civil Engineering and an M.Sc. degree in Earth Sciences both from EAFIT University. He is currently working on his Ph.D. degree in Geology with a minor in Physical Oceanography at University of Florida, focused on the morphodynamics of Cape Canaveral, Florida, shoals.

Bernardo Pulgarín is volcanologist and Coordinator of the Group of Volcano Geology at the Colombian Geological Survey. His research has mainly focused on the stratigraphy, petrology, geochemistry, and geochronology of the Colombian volcanoes, in order to establish their evolutive histories.

Albeiro Rendón is Associate Profesor in the Department of Geosciences at the School of Mines, Universidad Nacional de Colombia—Medellín. His research focuses on environmental geology: geological heritage, paleoseismology, neotectonics, and geological risks.

Ítalo Reyes received his degree in Geology at La Sapienza University in Rome. He was senior geologist at the Acerias Paz de Rio for many years and taught at the School of Engineering Geology of the Universidad Pedagógica y Tecnológica de Colombia in Sogamoso. His main interests in research are related to geological exploration, geological mapping, and structural and economic geology.

Miguel Angel Tavera is presently finishing his work to graduate as a Geologist at the Universidad EAFIT, Medellin. He is particularly interested in geomorphosites and landscape preservation.

Gloria Elena Toro retired professor, at the University EAFIT, has focused her research on the characterization of volcanic deposits which cover most of the Colombian western territory in order to determine the recurrence of major catastrophic events. She is also interested in the thermochronology methods based on the fission track method, especially for zircons.

María Patricia Torres graduated as a Geological Engineer at the National University in Medellin and obtained her M.Sc. in Earth Sciences at Universidad EAFIT, Medellin. She is presently at the Biology Department of the Universidad del Cauca, Popayan. She belongs to the University's GECO (Geology and Ecology) research group and has worked in regional geology, stratigraphy, geochemistry, and geomorphology, particularly in volcanic areas of the Central Cordillera.

Nathalia Vanessa Uasapud graduated as a Geological Engineer at the Colombia National University in Medellin. Her research is related to neotectonics, seismic hazards, environment, and geological heritage. She works presently on mining licensing process and on deformed soft sediment formations and their conservation as geologic heritage in the Cauca River valley near Santa Fe de Antioquia. She has published several articles related to these topics.

Geomorphological Landscapes and Landforms of Colombia

1

Michel Hermelin

Abstract

Colombia is an equatorial country located in the western corner of South America, where young, high mountains permit the existence of a large range of climates: they form sub-desertic to rainy forest in the lowlands to permanent snow and ice in elevations more than 5000 m a.s.l. A complex geological history also contributes to give the country a great diversity of rocks, landscapes, soils, and biota. Numerous natural processes are active including tectonics and volcanism, glacial processes, mass movements, and river erosion and transport. From multiple natural landscapes emerging from this situation, 17 have been selected to give the reader a comprehensive idea of the complexity of the country's natural environment. These geomorphosites are in the mountainous areas and are located from the Caribbean Sea to near the Ecuadorian border.

Keywords

Colombia • Geomorphology • Landscapes • Landforms • Climatic geomorphology

1.1 Introduction

1.1.1 Presentation of the Country

Colombia, located in the northwestern corner of South America, has a continental area of approximately 1,150,000 km^2 and stretches from 12°N to 4°S, with extensive coasts along both the Caribbean Sea and the Pacific Ocean. Its geographic situation and its geological history have produced a complex assemblage of landscapes, which include snow-covered mountains and volcanoes reaching 5800 m above sea level (m a.s.l.), tropical savannas, and Amazonian jungles but also sub-desertic mountain valleys and plains and arid-to mangrove-covered coastal areas. Most of its 46 million inhabitants live in the mountainous zones and in the Caribbean plains, while the eastern part of the country is scarcely populated. About three-quarters of the population now live in urban areas. The country has five cities with a population of more than one million inhabitants, with Bogota—the capital—approaching 9 millions. These cities offer all the modern features found in developed countries. Meanwhile, people in many areas of the remote countryside still live in relatively primitive conditions.

Many aspects of the territory and people of Colombia may thus be summarized in one word, diversity, expressed not only in its topography, climate, vegetation, and animals but also from economic and cultural standpoints. When the Spaniards initiated the conquest of the territory, at the beginning of sixteenth century, they did not find well-established civilizations as were the Incas or the Aztecs. The only important groups were the Chibchas, who lived in the area surrounding Bogota and Tunja. They were integrated in a feudal type of serfdom in which the Spaniards supplanted the existing aristocracy. In most of the other regions, Indian tribes offered fierce resistance and many fled to remote areas or even committed collective suicide instead

M. Hermelin (✉)
Grupo Geología Ambiental e Ingeniería Sísmica, EAFIT University, Medellin, Colombia
e-mail: hermelin@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_1

of submitting to the invaders. One hundred years after the Conquest, the kingdom of *Nueva Granada* was a collection of isolated towns poorly connected by appalling mule trails or a few navigable rivers. Several historians calculate that about 90 % of the indigenous population disappeared during the first century after America's "discovery."

Since then Colombia grew with a strong regional drive, much enhanced by geographical barriers, still expressed in noticeable local accents in the Spanish language spoken in the different parts of the country. Cultural, political, and economic ties improved with time, as expressed by the national saying "Colombia jumped from the mule to the jet plane." Besides its numerous problems, it can be reasonably stated that Colombia is now on the verge of becoming a modern, developed country.

The human impact on the landscape has been extremely variable. Some areas are extremely vulnerable to poor agricultural practices, while other resists much better. Semi-arid zones and *páramos*, for instance, show poor resilience. Humid lowland and Andean forests may also show a poor capacity for recovery. Adding to these facts, exposure to natural hazards, such as earthquakes, tsunamis, volcanic activity, and floods among others, results in an even more strenuous panorama. However, in addition to such a peculiar situation, Colombia offers landscapes that have inspired writers and painters and will enchant most of its visitors, as it did with European travelers during the nineteenth century.

1.1.2 Relief

Colombia can be divided into two main regions: the Andean cordilleras, which stretch in a north–northeastern direction in the western part of the country; and the Eastern Plains which include savannas and Amazonian forest. Several physiographic provinces can be defined as follows (Khobzi and Usselman 1974; Florez 2003) (Fig. 1.1):

(a) The western zone

- The Pacific lowlands, a coastal plain bordering the ocean in the southern part of the country
- The Baudó Cordillera, which forms the northern Pacific coast
- The Darién Range, which reaches the Urabá Gulf western coast
- The Atrato and San Juan River valleys, forming broad, flooded lowlands

(b) The central zone

Parallel to the Atrato–San Juan axis, the cordilleras are separated by rivers that flow following anomalous N–S directions:

- The Western Cordillera, limited in the east by the Cauca River, a broad valley that becomes a canyon in its northern course before its confluence with the Magdalena River. This cordillera is slightly lower than the other two, but it may reach 4000 m at Farallones de Cali and also Farallones de Citará, west of Medellin. Its relief is characterized by steep slopes and narrow valleys. Most of it is still covered by rainforest, except some valleys located in the topographic rain shadows.
- The Central Cordillera, between the Cauca and Magdalena Rivers, with altitudes from 2800 to 3500 m. Three large volcanic massifs rise above 5000 m: Ruiz-Tolima, Huila and Puracé. Toward the north, the cordillera becomes broader and forms several plateaus, which are erosion surfaces carved in crystalline rocks.
- The well-defined Magdalena Valley.
- The Eastern Cordillera, prolongated northward by the Perijá Range and toward the northeast by the Mérida Cordillera in Venezuela. This cordillera is the broadest and it follows a north–northeast direction. Its highest point is the *Sierra Nevada del Cocuy*, with altitudes above 5700 m in its median part. The three cordilleras converge southward before reaching the Ecuadorian border.

(c) In the north, the Western and Central Cordilleras meet the Caribbean coastal lowlands, prolongated by the Cesar Ranchería Valley and interrupted by the Sierra Nevada de Santa Marta Massif, which rises up to 5780 m a.s.l. The Guajira Peninsula is composed of plains and hills.

(d) The eastern lowlands stretch from the Eastern Cordillera piedmont, formed by extensive alluvial fans. The northern part is occupied by savannas called the *Llanos Orientales* (Eastern Plains), which cover part of Venezuela; the southern part belongs to the Amazonian forest area.

1.1.3 Geology

Since Alexander von Humboldt visited Nueva Granada (the name borne by the territory of Colombia until 1883) at the dawn of nineteenth century, knowledge of its geology has increased due to the contributions of both European travelers and local scientists. The Servicio Geológico Colombiano, which recently replaced the well-known Ingeominas as the National Geological Survey, has been publishing maps and reports since being founded in 1919, and the knowledge of the geology of the country is well advanced, at least for its mountainous part.

Interpretation of Colombia's geological evolution has evolved through the acquisition of new data from fieldwork and remote sensing, but also inspired by new tectonic hypotheses. A very short synthesis of this development will

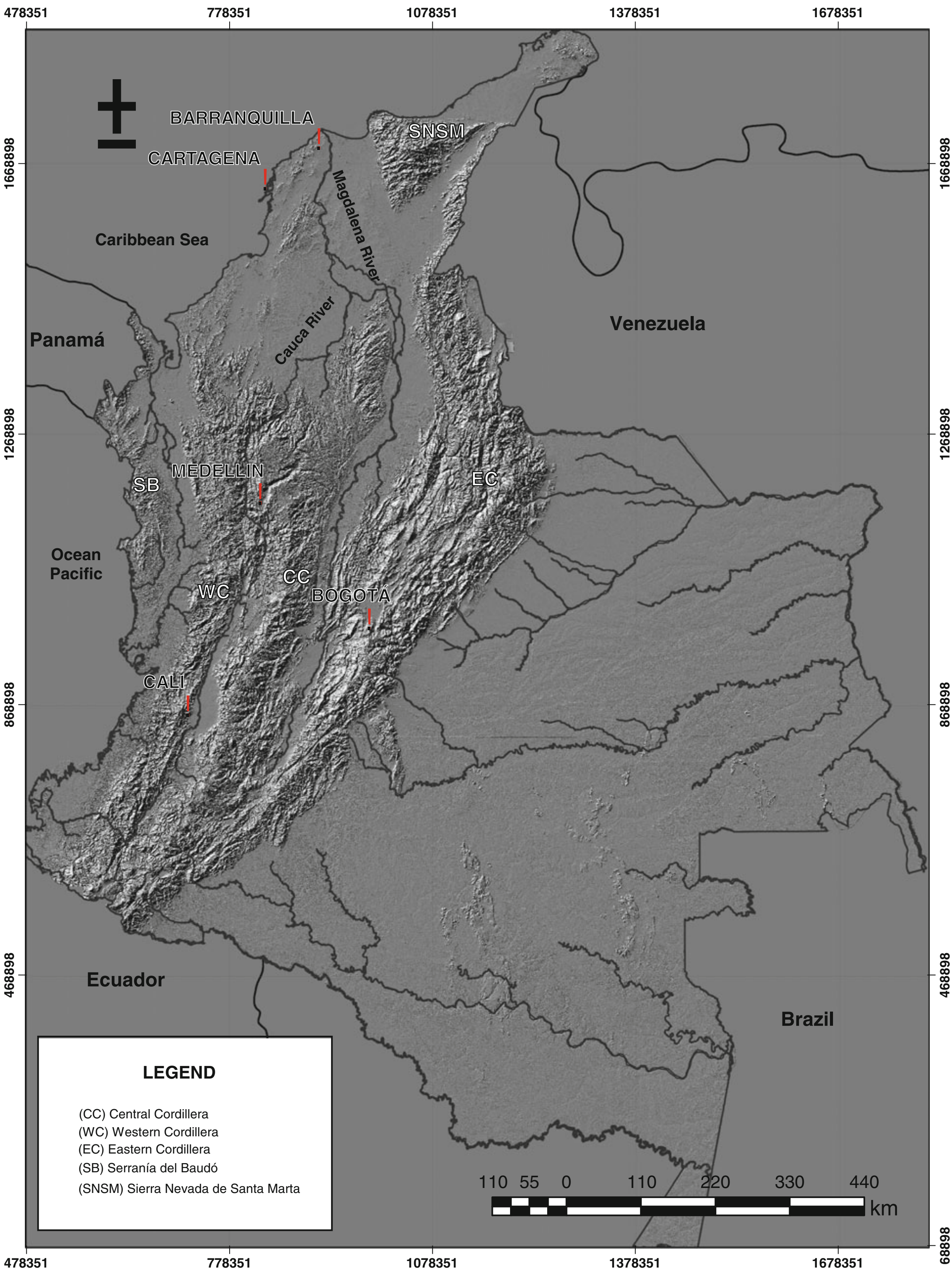


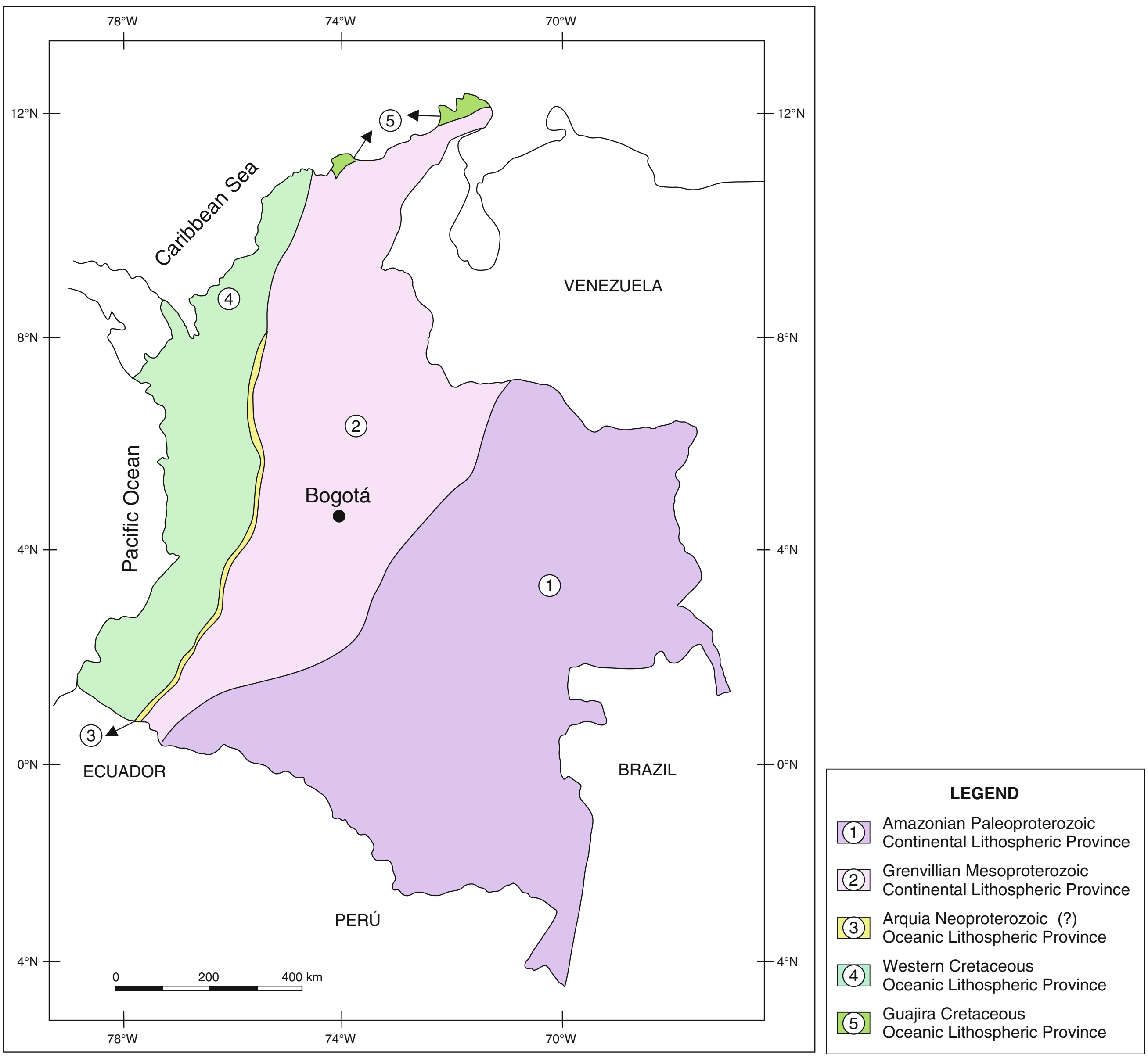
Fig. 1.1 Relief map of Colombia

be presented here; interested readers may refer to more extensive works from authors such as Cediel et al. (1976), Page (1986), Toussaint (1993–1999), Moreno–Sánchez and Pardo–Trujillo (2002), and Gómez et al. (2007).

The Amazonian Precambrian craton is the most stable tectonic element of the northern part of the South American continent, with rocks dated in Colombia from 2200 to 1800 Ma. Toward west of this craton, fragments of continental and oceanic crust have been added by accretion in an irregular, complex form accompanied by sedimentation and volcanism. The precise history of these processes is still being deciphered in light of past movements of tectonic plates.

The most recent official geological map of Colombia produced by the Geological Survey (Gómez et al. 2007) synthesizes these building phases by grouping successive geological formations in lithological provinces as follows (Fig. 1.2):

- The Amazonian Paleoproterozoic Continental Lithological Province, which is part of the Guyana Shield: its western limits are approximately parallel to the Eastern Cordillera eastern border, but more toward the east.
- The Grenvillian Mesoproterozoic Continental Lithological Province: its western limit is the San Jerónimo Fault,



Source: Gómez et al. (Ingeominas), 2007

Fig. 1.2 Geological provinces

which coincides roughly with the location of a subduction zone during the Cretaceous; its basement is formed by metamorphic rocks, which outcrop in the Garzón and Santander Massifs, the La Macarena Ridge, the Sierra Nevada de Santa Marta, and upper Guajira.

- The Arquía Neoproterozoic Oceanic Lithological Province: it consists of a metamorphic belt that was accreted before the Ordovician, as indicated by Devonian and Permo-Triassic sediments and plutons. During the Mesozoic, the western continental margin was associated with oceanic crust subduction, which produced tensional stresses in the east and the formation of a continental basin that was filled with sediments during the Cretaceous.
- The Western Cretaceous Oceanic Lithological Province: the accretion of this oceanic block during the Eocene produced the migration of the subduction zone to its present site. This movement produced the emplacement of the Western Cordillera batholiths and initiated volcanic activity that migrated westward until it reached its present localization.
- The Guajira Cretaceous Oceanic Lithological Province: it is formed by Cretaceous rocks of oceanic origin (Gomez et al. 2007).

A 1:1,500,000 scale geological map of Colombia can be downloaded from www.sgc.gov.co/getattachment/427-4983f-6c67-44ba-a019-8e0283b80b20/Mapa-geologico-de-Colombia.asp.

Active and recent volcanoes have calc-alkaline composition and are located in three segments along the Central Cordillera, in the Cauca-Patía Depression, and in the Western Cordillera (Pennington 1981; Freymuller et al. 1993; Méndez 1997). This volcanic activity is associated with the subduction of the Nazca Plate under the South America Plate, which started in the Pliocene (Fig. 1.3).

Colombia is presently exposed to the direct influence of three tectonic plates, namely the Nazca, Caribbean, and South American Plates. The contact between the first two is quite active, and subduction of the Nazca Plate under the continent proceeds at a rate of about 60 mm a^{-1}; subduction of the Caribbean Plate occurs at a much lower rate. The result is active tectonism, volcanism, and seismicity, mainly in the western part of the country. Due to the east–west stress, the mountainous part of the territory is being forced against the Guyana craton, which forms the eastern part, resulting in active inverse faulting along the Llanos and Amazonian eastern border, and a densely fractured and faulted crust in most of the mountainous part of the country. Displacement velocities obtained from Global Navigation Satellite System (GNSS) stations based on the ITRI-2008 (International Terrestrial Reference Frame) are given in Fig. 1.4.

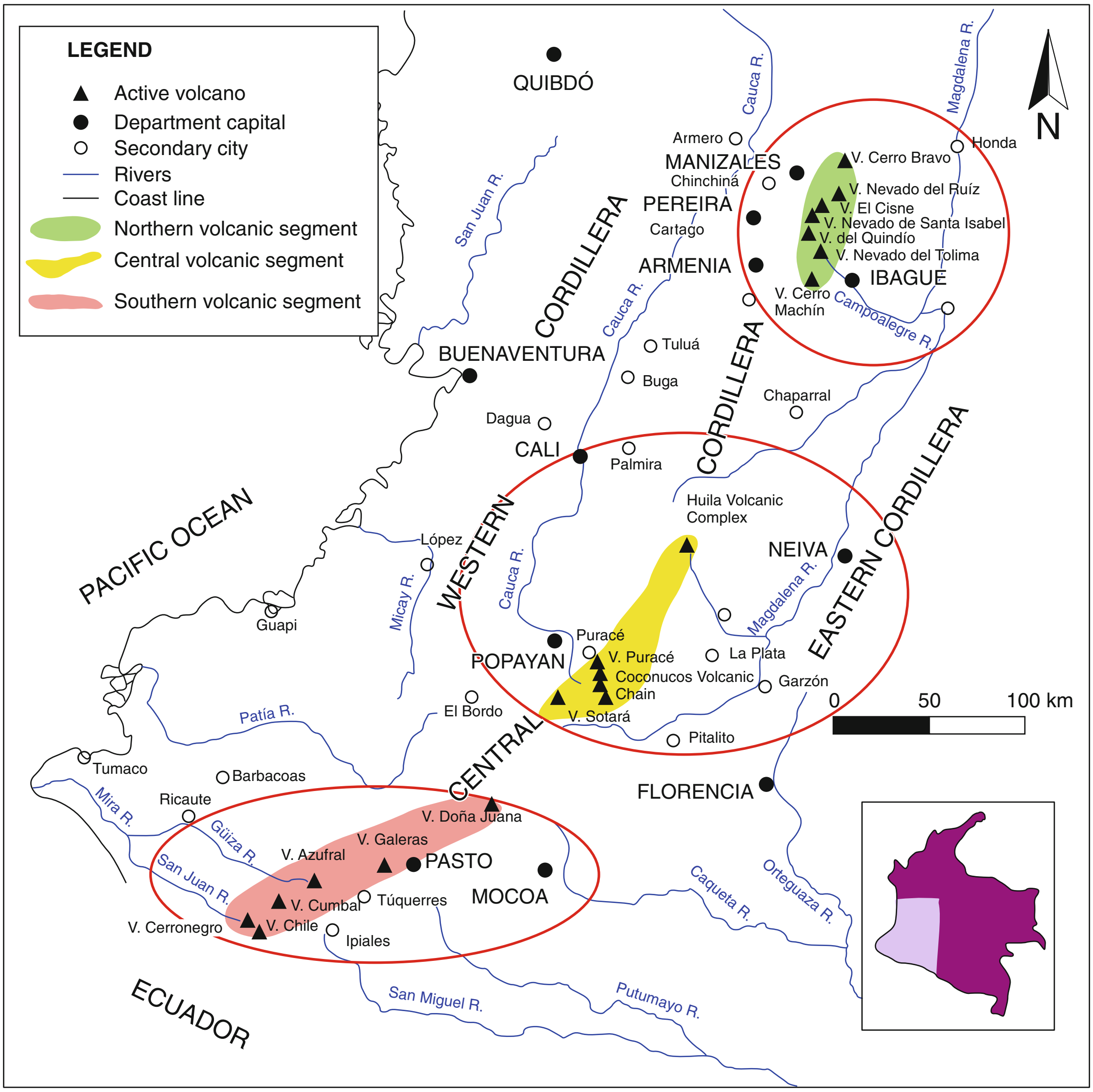
On the basis of palynological studies, van der Hammen (1958) established a sequence of the tectonic activities, which built the present structure of the Andean Cordilleras. The first movement happened in the latest Mastrichtian (pre-Andean Phase I). Some vertical displacements occurred during medium Eocene (pre-Andean Phase II), whereas several plutons were intruded during Oligocene (proto-Andean events). Encompassing the Upper Oligocene-Miocene time bracket, the Eu-Andean Phase I was responsible for building of most of the present large morphostructural units of the northern Andes such as old Western Cordillera, Cauca–Patía Depression, Pre–Central Cordillera, tectonic Magdalena Depression, and Pre–Eastern Cordillera. During the Miocene, an important orogeny occurred, subdivided by van der Hammen (1958) into three different phases, which uplifted the three cordilleras. Modern volcanism started at that time, as evidenced by the composition of sediments deposited in the depression along the cordilleras. The closing of the Panama Isthmus started 12.8–9.5 Ma ago, and much of the Darién region was emergent by ca. 8.6 Ma ago (Coates et al. 2004). This phenomenon affected the planetary oceanic circulation and climates. Migration of animals and plants began between the North and South America continents. The final uplift started in the middle Pliocene and lasted until the Pleistocene, leaving the three main cordilleras with altitudes, which are approximately the present ones.

The previous tectonic movements are related to differences in velocity of the Nazca Plate converging against the South American Plate border. Van der Hammen's data have been confirmed by more recent authors (Restrepo et al. 2009; Horton et al. 2010) working with Apatite U–Th/He thermochronology and detrital Zircon (U–Th)/He ages, respectively.

The uplift of the Eastern Cordillera is well documented by the variation of pollen described by van der Hammen in the sediments deposited in the Bogotá basin, which reflect the initial presence of warm tropical flora and its progressive replacement by species adapted to the present environments. These sediments (Helmens and van der Hammen 1994) also preserve evidence of climatic changes during the Pleistocene, providing an outstanding continental record that coincides with oceanic and glacial observations from the entire planet.

1.1.4 Climate

Being an equatorial country, Colombia does not present seasonal temperature changes. Average daily temperature variation is less than 1 °C both in the coldest (Ipiales, 12 °C) and warmest cities (Mompox, 28 °C). Temperature is controlled by altitude, with a vertical thermal gradient of about 0.6 °C/100 m. The present altitude for snow accumulation is



Source: Servicio Geológico Colombiano, 2014

Fig. 1.3 Active volcanoes

at 4800 m a.s.l.; it used to be about 500 m lower at the end of the Little Ice Age, around 1850 AD. During the Last Glacial Maximum (about 20 ka), the ice accumulation level descended by about 1000 m and the climate was drier than the present one (van der Hammen 1992). A first climatic classification of the territory can be made by dividing it in thermal stages (Table 1.1)

One of the major factors influencing rainfall patterns in Colombia is the movement of the Intertropical Convergency Zone, where trade winds meet. In July, it is located in the north and in December in the south. This movement produces a bimodal type of precipitation in the Andean region, with maximums in April–May and in October–November. In the Caribbean zone and in the eastern plains, rainfall distribution is unimodal and occurs mainly from June to October. The Chocó and Amazonas regions are rainy all year round, the first one with a locality (Lloró) with the world record of 11,000 mm per year. The second important factor in rainfall distribution is mountains, which form barriers to winds carrying humid air. Several valleys are exposed to this type of aridity: Chicamocha and Patía Valleys, for instance. A simplified map showing rainfall distribution in Colombia is represented in Fig. 1.5.

Further important atmospheric phenomena influencing rainfall are as follows:

- Tropical cyclones, locally called hurricanes, may form both in the Caribbean Sea and in the Pacific Ocean,

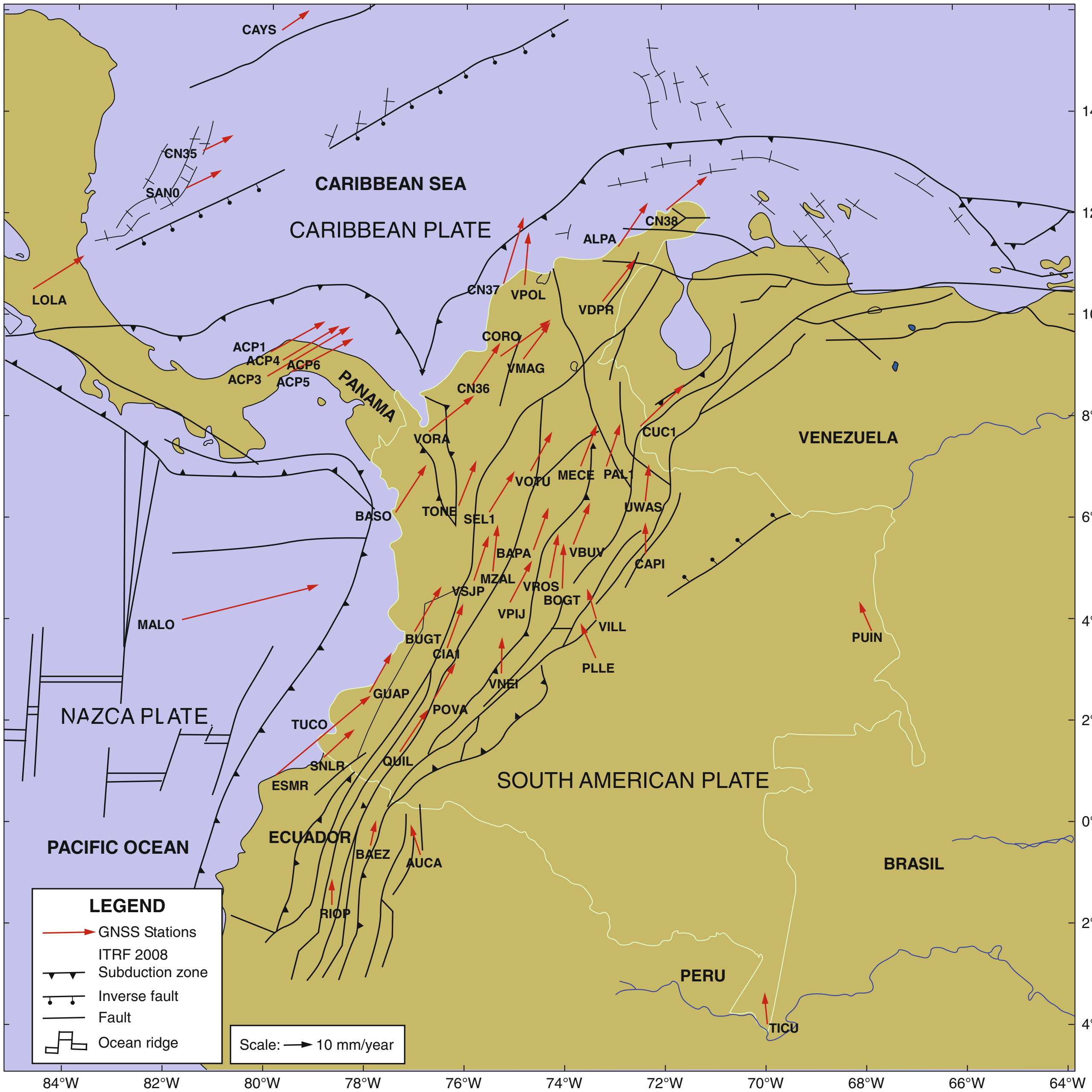


Fig. 1.4 Present geodynamics

Table 1.1 Present thermal stages and vegetation types in Colombia

Temperature (°C)	Altitude (m a.s.l.)	Name	% Area of the country
<0	Above 4800	Permanent snow	0.01
0–10	3300–4800	Very cold to extremely cold	3.67
10–16	2200–3300	Cold	6.88
16–24	1000–2200	Medium	10.04
>24	0–1000	Equatorial	79.40

Adapted from the National Geographical Institute (Instituto Geográfico Agustin Codazzi, IGAC), 1989

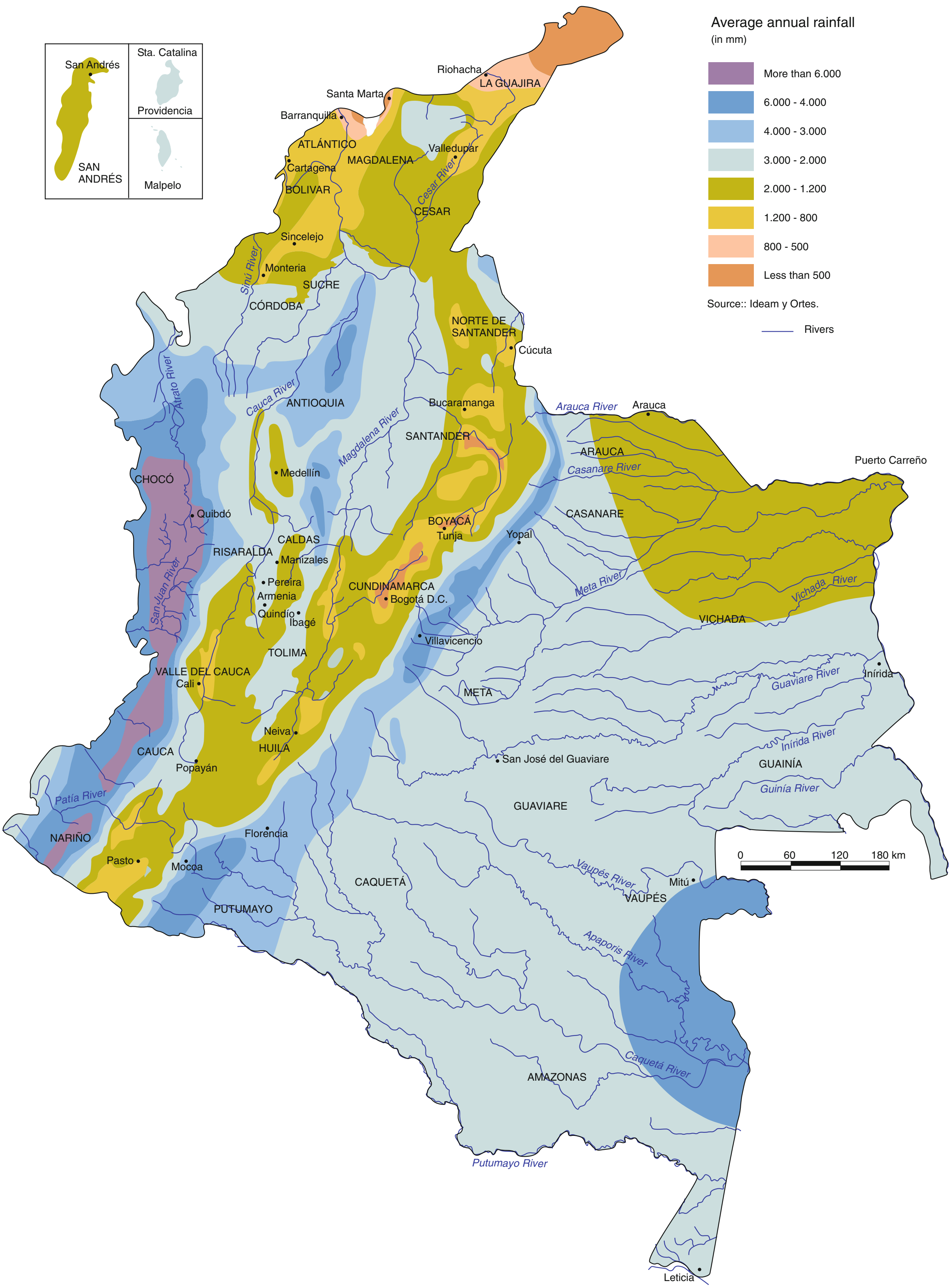


Fig. 1.5 Rainfall distribution (Círculo de Lectores 2004)

mainly between May and November. They have been reported since the Spanish conquest in the San Andres and Providencia Islands and in the Caribbean region, giving rise to strong winds and torrential rainfalls.
- The *El Niño*–Southern Oscillation (ENSO) affects Colombia in two ways: during *El Niño*, Pacific Ocean temperatures become higher near the western coast and the average sea level increases. Precipitation decreases in Andean, Caribbean, and Orinoquian regions but may increase in the southern part of the Pacific coast and in the eastern slope of the Eastern Cordillera and in Amazonía. These events last for 1 year on average and they occur with a frequency of 1–7 years. The opposite situation is called *La Niña*, associated with an increase in rainfall in most of the territory, as happened in 2010 (IGAC 2011).

In order to complete the climate map of the country, a further step is to combine temperature with rainfall distribution; for this purpose, IGAC uses the Caldas–Lang System (IGAC 2011). A recent compilation of climatic data on Colombia can be found in the *Atlas Climatológico de Colombia* (2005) published by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (*Instituto de Hidrología, Meteorología y Estudios Ambientales,* IDEAM) (http://www.ideam.gov.co.publicaciones.openbiblio/Bvirtual/019711/0197117htm).

1.1.5 Hydrology

The area and shape of the main fluvial basins are controlled by relief. The relatively recent uplift of the cordilleras resulted in an anomalous orientation for large rivers like the Magdalena, Cauca, and Atrato, in which they flow in a south–north direction, while most of drainage of the South American continent goes east or westwards.

The great climatic and topographic variations give rise to a large range of discharges and sediment production, the latter being one of the highest in the planet in mountainous areas (Restrepo and Syvitski 2006). Fluvial basin distribution is given in Table 1.2 (IGAC 2011) and Fig. 1.6.

Table 1.2 Fluvial basin distribution in Colombia

Name	% Area
Pacific Ocean	6.8
Orinoco River	30.4
Caribbean Sea (Exc. Magdalena)	9.0
Magdalena–Cauca	23.8
Amazon River	30.3

1.1.6 Geomorphology

Alexander Humboldt gave the first scientific description of Colombian landscapes at the beginning of the nineteenth century. About half a century later, Acosta (1846), a Colombian trained as a geologist in France, gave a precise description of lahars presumably produced by Ruiz Volcano eruptions and analyzed the origin of older deposits of the same volcano. Hettner (1892), the great German geographer, spent 2 years in Colombia traveling extensively in the Eastern Cordillera and left valuable stratigraphic and geomorphological descriptions. Around 1950, French geomorphologist J. Tricart came to Colombia with several collaborators; they carried out several regional studies. Khobzi and Usselmann (1974) published the first classification of Colombian main geomorphic systems. van der Hammen started his research in Colombia in 1957 and kept publishing contributions to the understanding of recent Andean uplifts and Quaternary climatic variations, not only in the *Sabana de Bogotá* but also in most of the country. He and his collaborators studied in detail a 600 m column of lacustrine sediment deposits in the Bogotá basin, which produced one of the best evidences of Quaternary fluctuations and the last Andean uplift (van der Hammen 1992).

The Interamerican Photointerpretation Center (*Centro Interamericano de Fotointerpretación*, CIAF), now a division of IGAC, has produced many regional geomorphological and soil maps since its foundation with Dutch support (ITC, Enschede) in 1960. Thouret (1981) published a morphostructural map of the country in which he classified structural domains and landforms of both endogenic and exogenic origins (Hermelin 1994).

Flórez (2003) proposed a fairly detailed division of the country based on the concept of the Morphogenic System, which includes (a) Morphogenic System Group (larger units), (b) Morphogenic System Subgroup, and (c) Morphogenic Systems (landscape units). Table 1.3 summarizes the first level of this classification.

The same classification was further developed in 2010 with a map 1:500,000 published by IDEAM (2010) (available at www.ideam.gov.co/publications).

A brief description of each one of these groups is as follows:

High Mountain morphogenic group, which can be divided further into

- Ice covered mountain summits, (*nevados*) above 4700 ± 100 m a.s.l., an altitude considered to be that reached by snow at the end of the Little Ice Age, which have been shrinking upward since 1850. They can be underlain by volcanic products, such as Huila, Tolima, Santa Isabel, and Ruiz (Fig. 1.7) or by sedimentary or metamorphic rocks such as *El Cocuy* (Fig. 1.8) and the

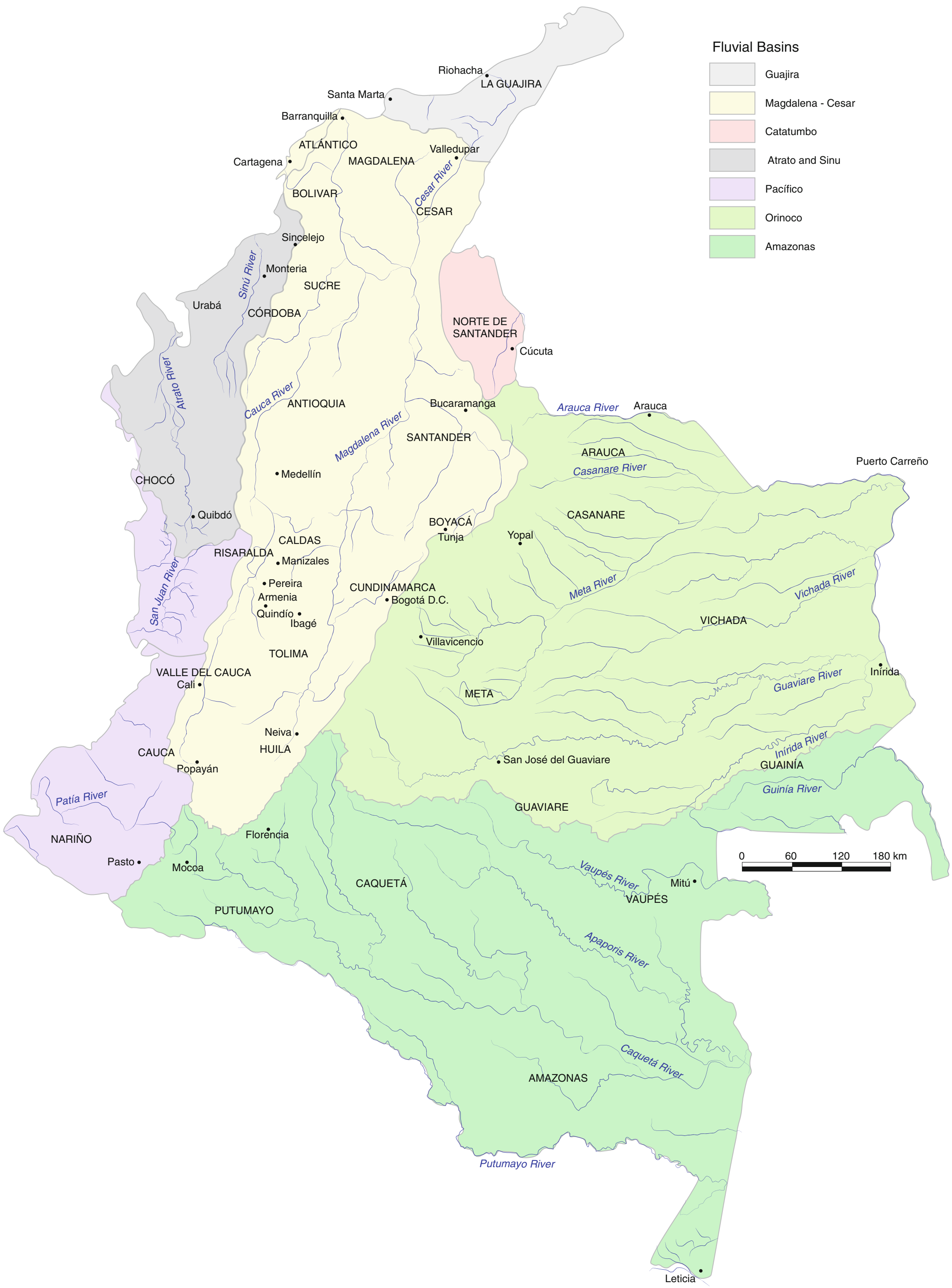


Fig. 1.6 Fluvial basins

Table 1.3 Colombia morphogenic groups (Flórez 2003)

High Mountain
Intermediate Mountain
Low Mountain
Tectonic depressions
Coasts
Amazonian Domain
Orinoquian Domain
Island Systems

Santa Marta Snowy Range. Most of these glaciers will probably disappear in less than a century.

- Periglacial systems which should be stressed that a great difference exists in the meaning of latitudinal periglacial zone and the tropical altitudinal zone, located between the lower ice limit and 3800 ± 100 m a.s.l. in coincidence with the vegetation belt called "*superpáramo*". It is characterized by an almost total lack of vegetation, cryoclastic processes, and eolian activity (Fig. 1.9).
- Inherited glacial system areas which were covered by ice during the last glaciations, located at altitudes from 3000 to 3800 m a.s.l. approximately; they correspond roughly to the present "*páramo*" vegetational floor (Fig. 1.10).
- Middle Mountain group, located between 2700 and 1000 m a.s.l., originally covered by forest and later intensively occupied by humans. The main units that may be distinguished are as follows:

  – Plateaus (*altiplanos*), corresponding to ancient lakes now filled by sediments, as the incorrectly named "*Sabana de Bogotá*" and its northern prolongation in Boyacá, the Tuquerres–Ipiales, Paletara, and Sibundoy plateau in the southern Andes. They may have been exposed to volcanic activity (Fig. 1.11).
  – Slopes on sedimentary or crystalline rocks.
  – Erosional surfaces sometimes covered by volcanic materials as in the Central Cordillera (Fig. 1.12) and characterized by thick saprolites.
  – Canyons, deeply eroded by rivers, generally located along faults.
- Low Mountain group, below 1000 m a.s.l., located on different rocks. With a more restricted temperature range but a large rainfall variation, this category is exposed to the same geomorphic processes: mass movement in the

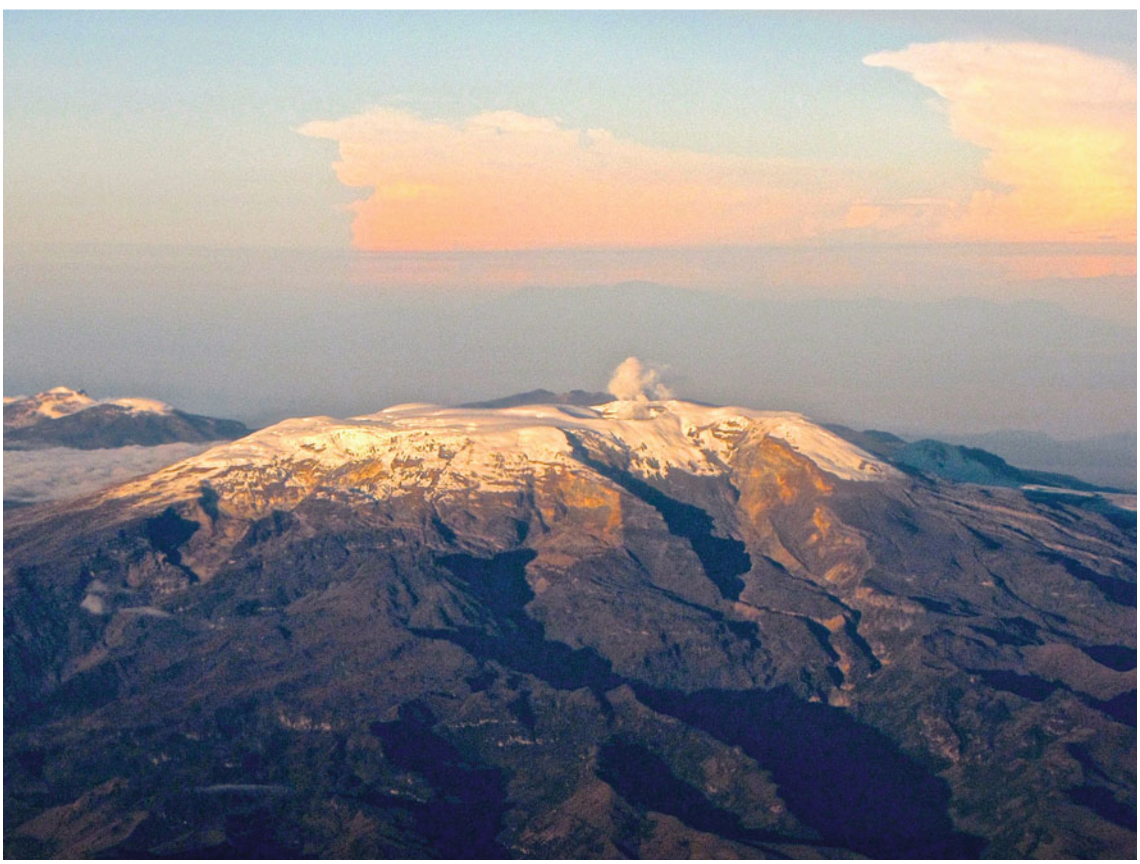


Fig. 1.7 Ruiz Volcano. In the left backgroud; Santa Isabel. *Photo* M. Hermelin

Fig. 1.8 Sierra Nevada del Cocuy. *Photo* M. Hermelin

predominantly humid areas and superficial erosion in the drier areas. Fluvial dynamics is also variable, as much as human occupation.

The Orinoco and Amazonas domains are strongly influenced by precipitation. The former receives rains of 1500–2500 mm per year on a marked monomodal basis and has developed lateritic types of soils and a savanna type of vegetation with forests limited to river vicinity. Main types of geomorphic landscapes are plains, low hills, and paleodunes, now covered by herbaceous vegetation, which have been described in the eastern part of the *Llanos* (Khobzi 1981). The Amazonian forest, with an average precipitation of about 4000 mm, remains humid all year round and its lowlands are frequently flooded.

1.1.7 Soils and Vegetation

The distribution of soils is conditioned by climate, parent material, and organisms and also by topography and time of evolution. As it might be expected from the previous chapters, an enormous variety of soils is found in Colombia (Malagón et al. 2003):

- Entisols are found in the areas drained by the Orinoco and Amazonas Rivers and their tributaries; on the Andean and Sierra Nevada de Santa Marta slopes and in the Caribbean area, including Guajira, they are exposed to erosion.
- Inceptisols are the most extensive soil order and exist in almost the entire country.
- Vertisols have been mapped in the flat areas of the Caribe region and near the Sinú River, in the Cauca Valley, and in the middle Magdalena Valley.
- Aridisols are associated with arid zones in the Guajira, Tatacoa, Cúcuta, and Chicamocha canyons.
- Mollisols and Alfisols have been found in the Caribbean region but also along the Cauca and Magdalena Rivers. Alfisols have been found in Nariño and in the Eastern Cordillera.
- Andisols, as expected from the active and recent volcanism distribution, cover large areas of the three cordilleras from Ecuador up to 7°N (Fig. 1.13).
- Spododols have been reported in the Orinoco region; they occur in sands derived from intensive weathering of the Amazonian Shield crystalline rocks.
- Oxisols and Ultisols are the main soils found in the Amazonian and southern Orinoquian drainage basins.

Fig. 1.9 Superparamo, Ruiz volcano, sand dune, and pebble pavement. *Photo* M. Hermelin

- Finally, Histosols are found in poorly drained areas along the Atrato River and the Pacific coast but also in old lacustrine areas, such as the Sibundoy and some Cundinamarca and Boyacá valleys.

Vegetation, like climate, is distributed vertically. This feature was first noticed by Caldas and by Humboldt in the beginning of the nineteenth century. Humboldt was struck, as were other later European visitors, when he observed that at altitudes higher than 2500 m. a.s.l., where permanent snows start in the Alps, cultivations and forest still flourished in the tropical Andes.

One of the characteristics of the tropical mountains is called diurnal climate by van der Hammen (1992). Considerable differences in temperatures may occur between day and night, but average monthly temperatures remain the same all year round. Areas located above the tree line may endure chilly nights, while during the day temperatures may be relatively high. Snow may fall at night and melt the next morning. This kind of climate has provoked the adaptation of special types of plants like *"frailejones"* (*Espeletia grandiflora*), which grow in a very special ecosystem called a *páramo*, only known in the western hemisphere from Costa Rica to northern Peru.

Other general characteristics of the Andean forest are the increase of vegetation levels and of epiphytes with altitude and humidity. Deciduous tree species are generally confined to regions exposed to more than three dry months per year and altitudes less than 2000 m. Perennifolia vegetation occupies the remnant of the slopes until the "*páramo*" limit (IGAC 2011). One of the first systematic classifications of this distribution was given by Cuatrocasas (1958). Systematic studies on palynology carried out since 1951 by van der Hammen (1992) permitted a classification of these vertical vegetation belts. Figure 1.14 shows a scheme of this distribution for the Eastern Cordillera, which is fairly the representative of the rest of the country.

1. The lowest floor corresponds to three categories:

1.1 Low Tropical forest, also called neotropical, is the most important, with temperatures ranging from 23 to 30 °C and minimum precipitation of 2000 mm per year. In Chocó, on the Pacific coast, rain may reach 11,000 mm per year and the average for the Amazonian area is about 3500 mm per year. This is the unit where biodiversity reaches its maximum (Fig. 1.15)

1.2 Within the same altitude and temperature ranges, some coastal areas like Guajira and the northern

Fig. 1.10 Paramo, Sinscundí near Tota Lake, Boyaca. *Photo* M. Hermelin

peninsula receive only 250–500 mm of rain per year and display a sub-desertic type of shrub (Fig. 1.16).

1.3 A third low vegetation floor is the savanna, found in the Eastern Plains, where at low altitudes, rainfall unimodal distribution is about 1500 mm per year and the extended dry season precludes the growth of trees, except along rivers where water is abundant in the soils and gallery forests exist.

2. A second floor, the sub-Andean forest, is located between 1000 and 2300 m a.s.l., with well-distributed rainfall between 1000 and 4000 mm. It retains the same aspects as the neotropical forest, but has less biodiversity.

3. The Andean forest, between 2300 and 3600 m a.s.l., with average temperatures from 8 to 16 °C and rainfall from 1000 to 4000 mm, is characterized by high atmospheric humidity related to high cloudiness and frequent fog and the presence of orchids and bromelias.

4. The *Páramo*, located from 3500 to 4200 m a.s.l., has some local fluctuations. As mentioned before, this is a very special ecosystem, known only in the Andes (Hofstede et al. 2003). Annual rainfall ranges from 400 to 1600 mm and average temperatures between −1.9 and 10 °C. Low evapotranspiration rates and the capacity to absorb water make the *páramo* an important ecosystem for water conservation. In fact, most Colombian cities located in the Cordilleras depend on *páramos* for their water supply. Among the plants that characterize their vegetation, *frailejón* is the best-known plant (Fig. 1.17). In Colombia, many *páramos* are at risk due to agricultural and cattle grazing activities. van der Hammen (1992) subdivided *páramos* into three levels: *subpáramo*, up to 4000 m a. s. l., consisting of low Andean forest remnants; true *páramo*, from 3500 to 4000/4200 m a.s.l., devoid of trees; and finally *superpáramos*, from 4000 to 4200 m a.s.l., where vegetation is discontinuous.

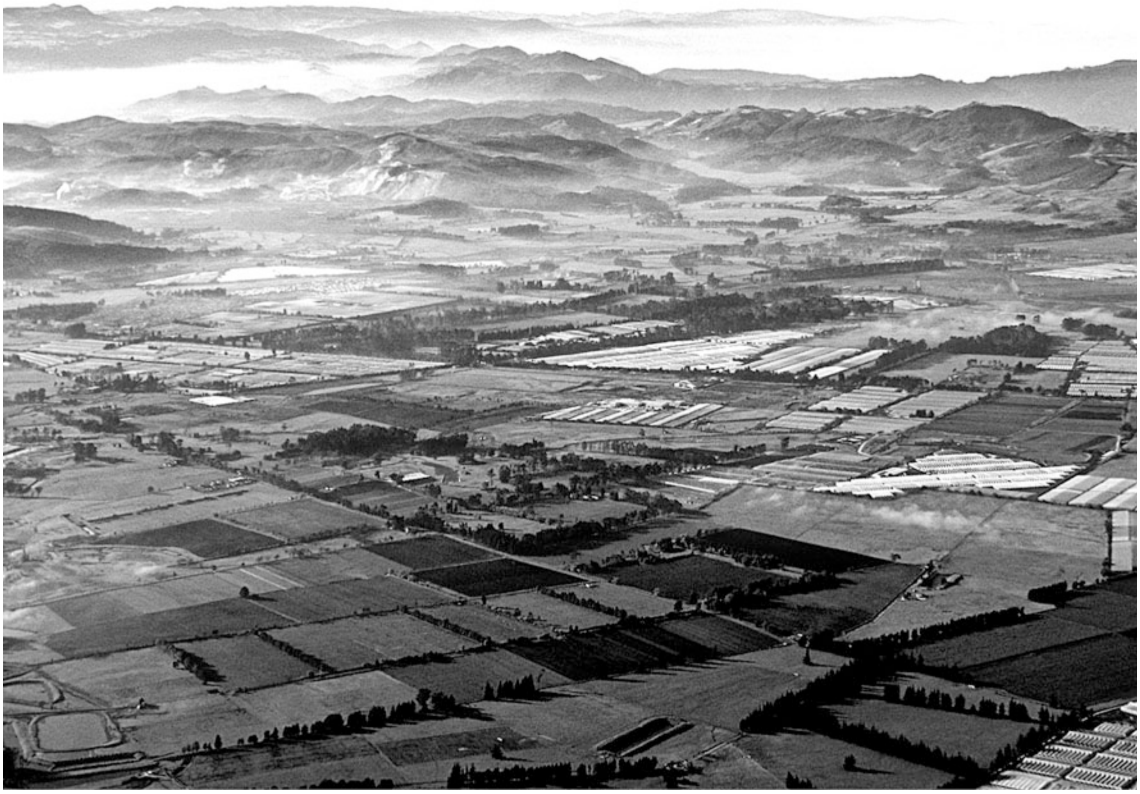


Fig. 1.11 Sabana de Bogota. *Photo* M. Hermelin

Fig. 1.12 Rionegro erosion surface at 2000 m above sea level. *Photo* M. Hermelin

Fig. 1.13 Andisol profile in the Antioquia highlands, Central Cordillera. *Photo* M. Hermelin

Areas located above this altitude are bare of vegetation and permanent snow, and ice starts at about 4800 m.

1.1.8 Selected Geomorphosites and Landscapes

Sites have been selected as a function of their geomorphic and aesthetic values and are grouped to offer convenient itineraries to visitors (Fig. 1.18)

A. The Caribbean Coast

- La Vela Cape and dune field is situated in a 3 h car drive from Rio Hacha, which can be reached by plane from Bogotá and Barranquilla. A car trip from Santa Marta takes about 3 h; these cities are connected by plane with Bogotá and Medellín (Chap. 2).
- The Galerazamba mud volcano can be reached from Cartagena or Barranquilla in a 1 h car trip. These two

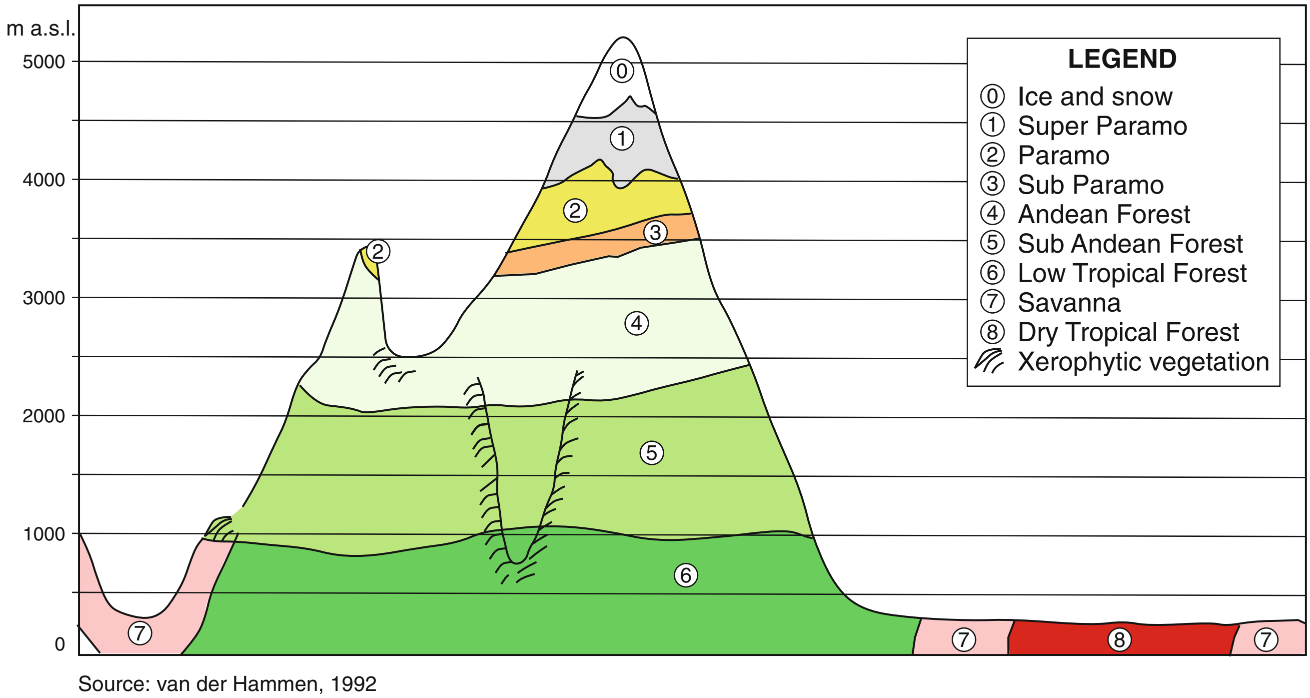


Fig. 1.14 Vertical distribution of vegetation

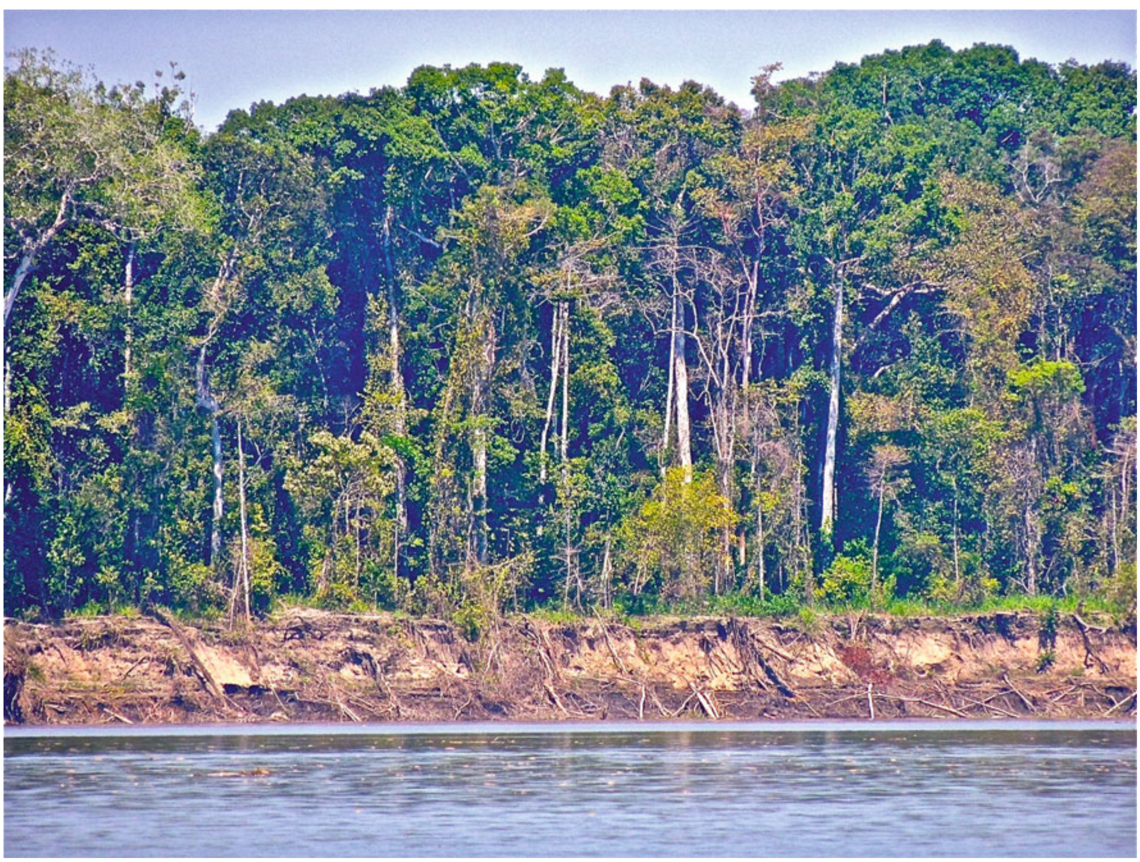


Fig. 1.15 Amazonian forest near Leticia. *Photo* M. Hermelin

Fig. 1.16 Guajira peninsula shuh vegetation. *Photo* M. Hermelin

cities have several daily connections to Bogotá and Medellín (Chap. 3).

- The *Arboletes* mud volcano is a 2 h car ride from Montería, which can be reached by plane from Bogotá, Medellín, or Barranquilla (Chap. 4).

B. The Eastern Cordillera

- *Los Estoraques*, near La Playa de Belén, is the village which is a 1 h car ride from Ocaña, which can be reached by plane from Bogotá or Medellín. It may also be reached from Cúcuta, the Department capital; the trip lasts about 4 h (Chap. 5).
- *Chicamocha* Canyon is reached by car in 1 h from Bucaramanga. This city has air connection with the country's most important cities (Chap. 6).
- *El Cocuy* Snowy Ridge can be reached by road from Bogotá in a 9 h trip (Chap. 7).
- Tota Lake is located 1 h from Sogamoso, a city 3 h away from Bogotá by car (Chap. 8).
- Guatavita Lake is 2 h from Bogotá by car (Chap. 9).
- The Bogotá "savanna" surrounds Bogotá and has abundant roads and transportation; likewise, the Tequendama Waterfall is located 2 h away by car (Chap. 10).
- The Tatacoa Badlands are located near Neiva (a 30-min car ride), which can be reached by plane (30 min) or by road (5 h) from Bogotá (Chap. 11).

C. The Central Cordillera

- The Guatapé and Entrerríos Inselbergs is a 2 h car ride from Medellín, a city connected by air and road with the rest of the country and with an international airport (Chap. 12).

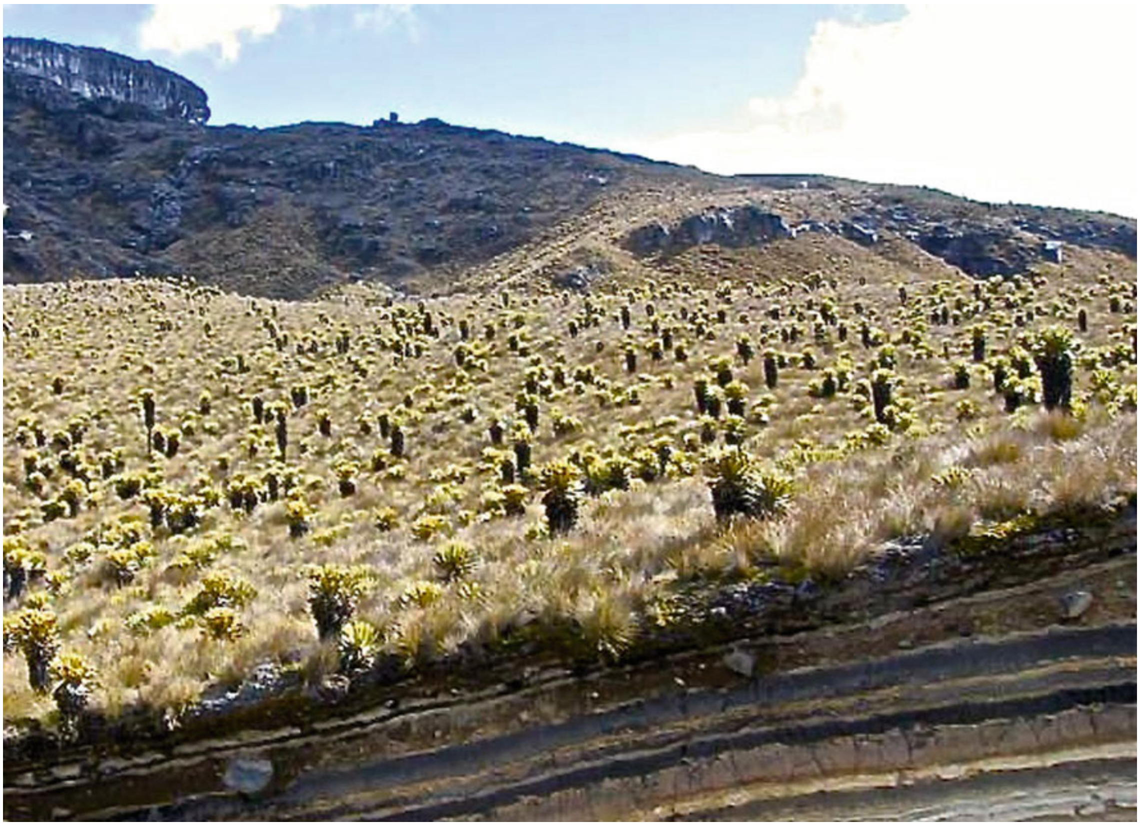


Fig. 1.17 Páramo vegetation growing on andesitic ash layers, Ruiz volcano. *Photo* M. Hermelin

- The Cauca River Canyon is about a 2 h car ride from Medellín. One- or two-day itineraries by car are proposed (Chap. 13).
- The Ruiz Volcanic Park is 2 h from Manizales. This city is connected by air and by road to Bogotá (6 h) and Medellín (3 h) (Chap. 14).

D. The Southern Area

- The Puracé Volcanic Park is located 2 h from Popayán. The city is connected by air with Bogotá and by road with Cali, Pasto and the rest of the country (Chap. 15).
- The Galeras Volcano lies on the outskirts of Pasto, connected by air and road to Bogotá and Cali (Chap. 16).
- *La Cocha* Lake can be reached by car in a 1 h ride from Pasto (Chap. 17).

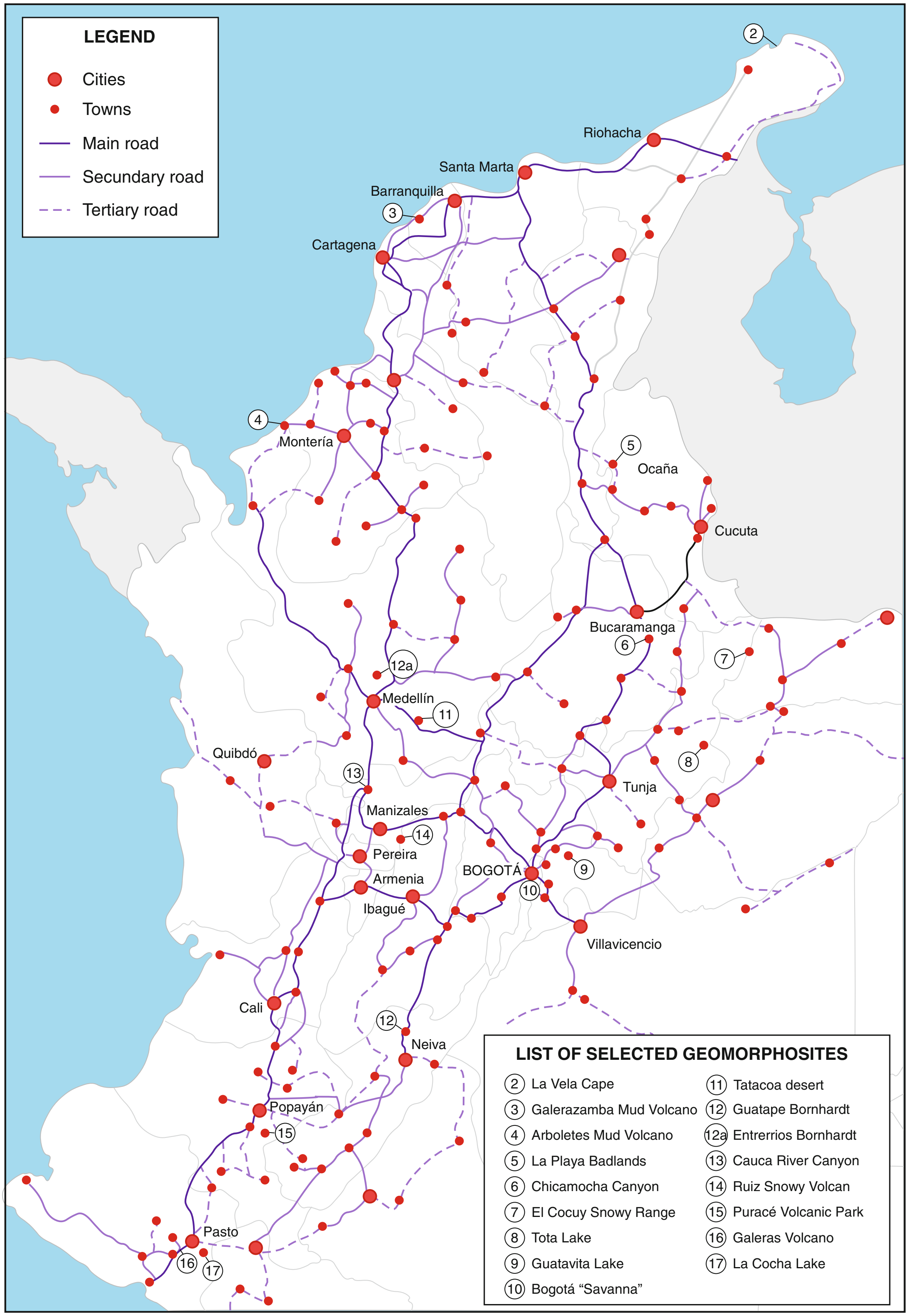


Fig. 1.18 Localization of geomorphosites

References

Acosta J (1846) Relation de l´eruption boueuse sortie du volcan de Ruiz et de la catastrophe de Lagunilla dans la République de la Nouvelle Grenade. C R Acad Sci Paris, Tome 22:709−710

Cediel F, Ujueta G, Cáceres C (1976) Mapa geológico de Colombia, Ed. Geotec, Bogotá

Círculo de Lectores (2004) Gran Atlas y Geografía de Colombia. Intermedio Editores, Bogotá

Coates AG, Collins LS, Aubry M-P, Berggren WA (2004) The Geology of the Darien Panama, and the late Miocene-Pliocene collision of the Panama arc with northwestern South America. GSA Bull 116:1327–1344

Cuatrecasas J (1958) Aspectos de la vegetación natural de Colombia. Revista Academia Colombia de Ciencias Exactas, Físicas y Naturales 10(40):221–264

Etayo-Serna F et al (1983) Mapa de terrenos geológicos de Colombia, No. 14. Publicación Especial Ingeominas

Flórez A (2003) Colombia: evolución de sus relieves y modelados. National University of Colombia, Bogotá

Freymueller J, Kellog J, Vega V (1993) Plate motions in the North Andean region. J Geophys Res 98B(12):21.853–821.863

Gómez J, Nivia A, Montes NE, Jiménez DM, Tejada MI, Sepúlveda J, Osorio JA, Gaona T, Dietrix H, Uribe H, Mora M, Compiladores (2007) Mapa Geológico de Colombia, Scale 1:2 800 000, 2nd ed. INGEOMINAS, Bogotá

Helmens K, van der Hammen Th (1994) The Pliocene and Quaternary of the high plain of Bogota (Colombia): a history of tectonic uplift, basin development and climatic change. Quat Int 22:41−81

Hermelin M (1994) History of Geomorphology in Colombia. International Association of Geomorphologists, Wiley, New York, p. 107−111

Hettner A (1892) (1966) La Cordillera de Bogotá. Resultado de viajes y estudios. Version by E. Guhl. Banco de la República, Bogotá, map

Hofstede R, Segarra P, Mena-Vasconez P (2003) Los páramos del mundo. Global Peatland Initiative/NC.IUCN/Ecociencia.Quito, Proyecto Atlas Mundial de los Páramos

Holdridge LR (1979) Ecología basada en zonas de vida, San José de Costa Rica

Horton BK, Parra M, Saylor JE, Nie J, Mora A, Torres V, Stockli DF, Streecher MR (2010) Resolving uplift of the northern Andes using detrital zircon age signatures. GSA Today, pp 4–9

IDEAM (2010) Sistemas morfogénicos del territorio colombiano. www.ideam.gov.co

Instituto Geográfico Agustin Codazzi (1989) Atlas básio de Colombia, División de Difusión Geográfica, 6a Edición, Bogota

Instituto Geográfico Agustin Codazzi (IGAC) (2011) Subdirección de Geografía y Cartografía, Geografía de Colombia, IGAC, Bogotá

Khobzi J (1981) Los campos de dunas norte de Colombia y de los llanos del Orinoco (Colombia y Venezuela). Revista CIAF 6(1–3):257–292

Khobzi J, Usselman P (1974) Problemas de Geomorfología en Colombia. Bulletin Français d´Etudes Andines V. III(4):59–86

Malagón D, Pulido C, Llinas RD, Chamorro C (2003) Los suelos de Colombia: origen, evolución, clasificación, distribución y uso. Bogotá, IGAC. http://www.sogeocol.com.co/documentos/05/055.pdf

Méndez R (1997) Atlas de los volcanes activos en Colombia. INGEOMINAS, Manizales

Moreno-Sánchez M, Pardo-Trujillo A (2002) Historia geológica del Occidente Colombiano. Geo-Eco-Trop v 26(2):91–113

Murcia LA (1982) El volcanismo Plio-Cuaternario de Colombia: Depósitos piroclásticas asociados y mediciones isotópicas de 87Sr/86Sr, 143Nd/144Nd, δ18O en lavas de los volcanes Galeras, Puracé, Nevado del Ruíz. Publicaciones Geológicas Especiales del INGEOMINAS 10:1–17

Page WD (1986) Geologia Sísmica y sismicidad del Noroeste Colombiano. ISA-Integral-Woodward-Clyde Consultants, Manuscript

Pennington WD (1981) Subduction of the Eastern Panama basin and seismotectonics of northwestern South America. J Geophys Res 86:10753–10770

Restrepo JD, Syvitski JPM (2006) Assessing the effect of natural controls and land use change on sediment yield in a major Andean river: The Magdalena Drainage Basin, Colombia. Ambio 35:65–74

Restrepo–Moreno SA, Foster DA, Stockli DF, Parra–Sánchez LN (2009) Long-term erosion and exhumation of the "Altiplano Antioqueño", northern Andes (Colombia) from Apatite (U-Th)/He thermochronology. Earth Planet Sci Lett. doi:10.1016/j.epsl/2008.09.37

Thouret JC (1981) Mapa geomorfoestructural de los Andes Colombianos. IGAC, Bogotá

Toussaint JF (1993–1999) Evolución geológica de Colombia. National University of Colombia, Medellín

van der Hammen Th (1958) Estratigrafía del Terviario y Maestrichtiano continentales y tectogénesis de los andes colombianos. Published in Boletin Geológico (1960) Tomo VI (1-3):67−128

van der Hammen Th (1992) Historia, ecología y vegetación. Fondo FEN Colombia, Bogotá

Cabo de La Vela ("La Vela" Cape) and Surroundings

2

Blanca Oliva Posada

Abstract

The Cabo de la Vela is located in the Guajira peninsula, in the northernmost Colombia and NE from the Sierra Nevada de Santa Marta, the highest coastal massif in the world (5775 m). It lies in the southern border of the Caribbean tectonic plate, where the relative movement of the plate was responsible for the generation, rotation, and translation of basins and tectonic blocks north of Colombia; one of these blocks is the Jepirra Ridge, to which the La Vela Cape belongs. Before the Campanian, a subduction zone may have formed together with an intra-oceanic arc, represented now by the La Vela Cape; it became a back-arc and then an arc toward the end of Campanian ($\sim$74 Ma), when ultramafic rocks, gabbros, and andesitic dykes formed and were exhumed. From a structural and geomorphological standpoint, the Guajira consists of a broad coastal plain, interrupted north of the Oca and Cuisa Faults by isolated ridges. This results from the evolution of a marine platform, which, from the end of Oligocene to the Pliocene, was flat and stable, interrupted only by islands formed by the Jarara, Macuira, Cosinas, and Carpintero (including Jepirra) Ridges. As a result of Quaternary morphodynamic processes active on the emerged terraces, the great plain gave rise to the present erosional and depositional landforms, which are still under the influence of active processes.

Keywords

Cabo de la Vela • Guajira • Coastal environment • Dunes • Subdesertic environment

2.1 Location

The La Vela (The Sail) Cape is located in the Guajira peninsula, in the northernmost Colombia (N 12°12′20″, W 12° 10′23″). It belongs to the Jepirra Ridge, which—together with the Carpintero, Macuira, Jarara, and Cosinas Ridges—stretches in the northern part of the peninsula (Fig. 2.1).

It can be reached by road from Santa Marta (a 7 h drive) or Riohacha (a 3 h drive). Both cities are attended by regular airlines flying to Bogotá and other Colombian cities. Recommended itineraries can be found at the end of this chapter. La Vela Cape is called Jepirra (meaning the sacred place, where the spirits of the dead go) by the Wayúu Indians, who occupied the territory much before the Spanish conquest.

2.2 Regional Aspects

The Guajira Peninsula is located NE from the Sierra Nevada de Santa Marta, the highest coastal massif in the world (5775 m a.s.l.). It is limited by two faults: the Oca Fault (E–W) and the Santa Marta-Bucaramanga Fault (N–S) and the Cesar Rancherias valley at the southeast (IGAC 2009).

B.O. Posada (✉)
Ministry of Environment and Sustainable Development, Bogotá, Colombia
e-mail: boposada@gmail.com

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_2

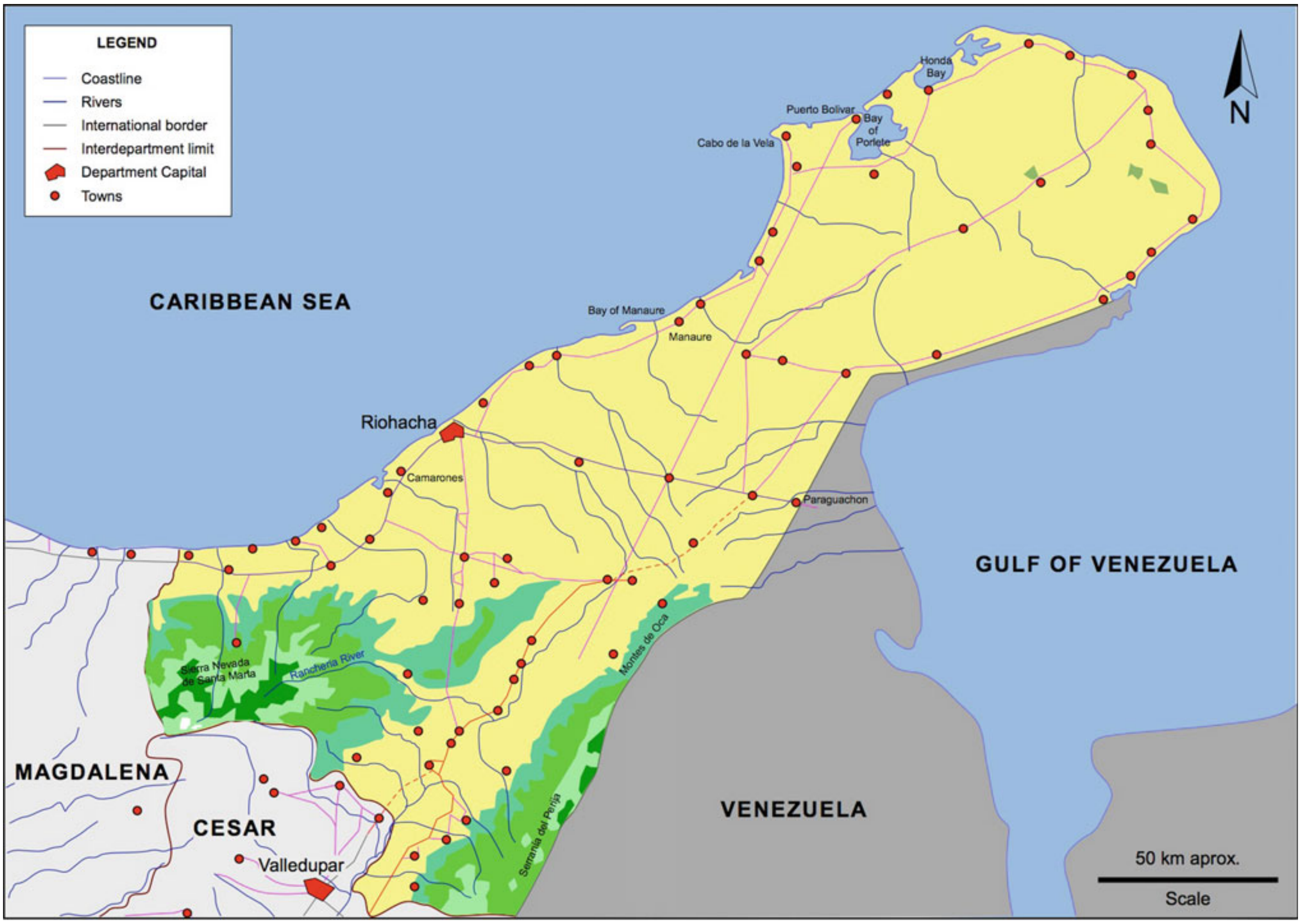


Fig. 2.1 The Guajira Peninsula

The Guajira Peninsula itself is usually divided into two parts: Baja (low) Guajira, the southern part bordering with the Sierra Nevada and the Alta (upper) Guajira, located north of the Rancheria River. The first receives annual rainfalls of 1250 mm and has temperatures of about 27 °C. The second is quite arid, with average rainfall of 150 mm/year, temperatures of 32 °C, and dominant trade winds blowing from NE, with speeds reaching 40 km/h (IGAC 2009). The La Vela Cape receives an average of 339 mm of rain per year. The plain is cut by several morphostructural ridges, such as Macuira, reaching 870 m a.s.l. at the Palúa Mount, covered with humid forest above 550 m a.s.l., which captures humidity directly from the atmosphere, a unique feature in Colombia (IGAC 2009), and the Carpintero Ridge, 200 m.a.s.l., which on the coast becomes the La Vela Cape, characterized by its cliffs. Jarara, Cosinas, and Simarua are other ridges similar to Macuira, but without forest cover (Guerra 2003) (Fig. 2.1).

The region has five main urban centers (Table 2.1) and smaller villages, with a total population of almost 650 000 inhabitants, of which 50 % are native indigenous, mainly from the Wayúu ethnic group (IGAC 2009).

2.3 Geology

The La Vela Cape lies in the southern border of the Caribbean tectonic plate, north of the Oca fault (Nova et al. 2011), where some isolated structural blocks were uplifted; one of these blocks is the Jepirra Ridge, to which the La Vela Cape belongs (Figs. 2.2 and 2.3).

The evolution of the La Vela Cape area is bound to the change in tectonic trend, which occurred during Jurassic–Lower Cretaceous, when the proto-Caribbean oceanic crust was generated during the separation of the North and South America plates (Weber et al. 2009). The relative movement of the Caribbean Plate was responsible for the generation, rotation, and translation of basins and tectonic blocks north of Colombia. Before the Campanian, a subduction zone may have formed together with an intra-oceanic arc, represented now by the La Vela Cape. It became a back-arc and then an arc toward the end of Campanian (~74 Ma), when ultramafic rocks, gabbros, and andesitic dykes were formed and exhumed. (Fig. 2.4).

Table 2.1 Guajira Municipality Population (*Alcaldía Municipal* of Dibulla (2012), *Alcaldía Municipal* of Riohacha (2012), *Alcaldía Municipal* of Manaure (2012), *Alcaldía Municipal* of Maicao (2012), *Alcaldía Municipal* of Uribia (2012))

Municipalites	Total population	Urban population	Indigenous population (%)
Dibulla	29.446	4.761	33
Riohacha	222.354	186.733	26
Manaure	92.232	37.999	68
Uribia	156.496	11.071	95
Maicao	148.427	101.567	26

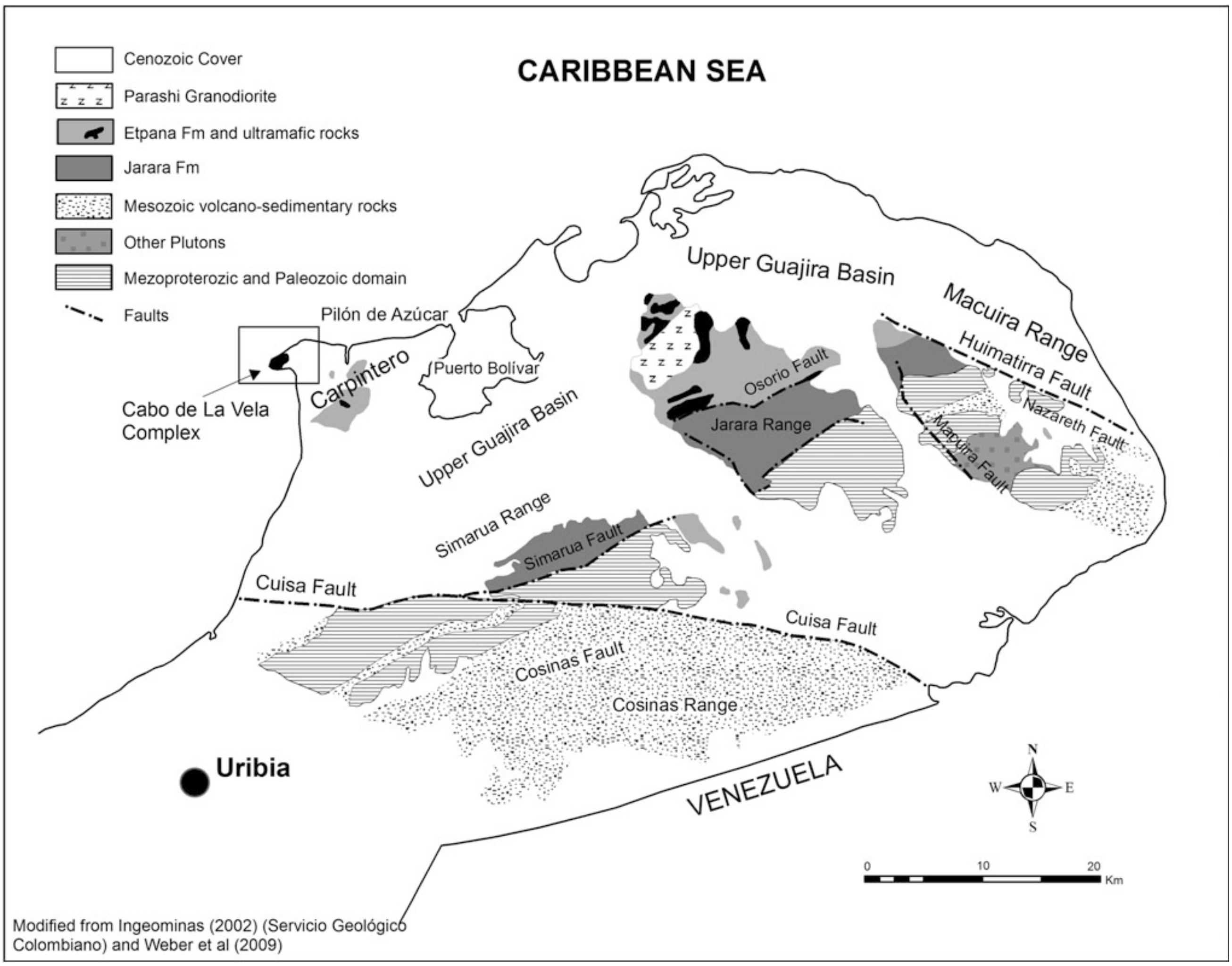


Fig. 2.2 Geologic map of the Guajira Peninsula

Associated with this evolution, the Etpana Formation was formed in place of the rift zone, while the Jarara Formation originated near the arc. During the Late Cretaceous and Paleocene, the proto-Caribbean Plate and the South American passive margin collided, and subduction of the former under the latter began (Hernandez et al. 2003; Cardona et al. 2007; Weber et al. 2009). During Paleocene and Early Eocene, sedimentation did not occur (IGAC 2009). During the Eocene, shallow marine sedimentation began in the Guajira, depositing marine to continental sedimentary sequences (Chicangana 2011). The Cuisa Fault began to displace the Alta Guajira block from the Sierra Nevada-Baja Guajira block. During the Oligocene, the Guajira Peninsula started its northeastward translation, which could explain its present geographical position, despite having been formed tens of kilometers away (Hernandez et al. 2003) (Fig. 2.4).

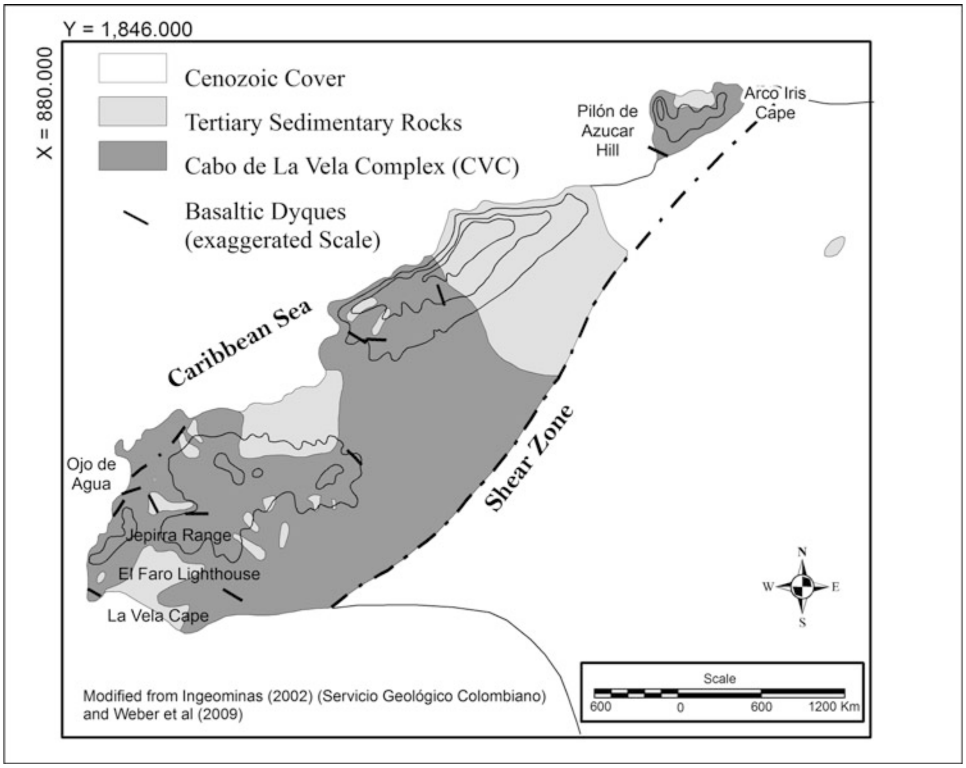


Fig. 2.3 Geologic map of the Cabo de la Vela area

Weber et al. (2009) called "La Vela Cape ultramafic complex" the rock assemblage which includes principally serpentinized ultramafic rocks, gabbros, and andesitic dykes and forms low hills, sometimes covered by Cenozoic sediments and separated by extensive plains formed on other Cretaceous rock massifs, which apparently present some similarities (Ingeominas 2002). The Etpana and Jarara Formations are associated with these rocks, both from chronological and geological standpoints (Weber et al. 2009).

Ultrabasic rocks are mainly serpentinites. Gabbros occur as small lenses in serpentinite bodies, which are coarse grained to pegmatitic and, as serpentinites, show foliation, banding, and polygonal granoblastic texture, characteristic of high-temperature crystallization. Hornblendites are found near the borders of gabbro dykes or in serpentinites (Cardona et al. 2007; Weber et al. 2009). These mineral assemblages suggest that these rocks were formed under greenschist and pumpellyte-prenhite facies (Weber et al. 2009). Mafic volcanic dykes cross the other rocks and show thicknesses of up to 2 m. They possibly consist of basalts, andesites, and phaneritic to small-grained aphanitic, with a green to greenish-gray color and porphyritic texture (Weber et al. 2009).

The Etpana Formation is a Cretaceous low-grade meta-volcanic-sedimentary body, consisting of phyllites, greenschists, serpentinites, gabbros, and rodingites intruded by the Parashi Stock, which consists of quartz diorites and porphyritic rocks (Zapata et al. 2010). It is unconformably overlain by Palaeogene–Neogene conglomerates (Ingeominas 2002). The Jarara Formation is formed by phyllites, which grade into muscovite schists, chloritic schists, metamorphosed quartz, and locally quartzites, gneisses, and hornblende rocks. Its contact with the Etpana Formation is faulted in the Jarara Ridge, along the inverse Osorio Fault, and it is overlain unconformably by Paleogene and Neogene sediments (Ingeominas 2002).

Cenozoic Macarao, Siamana, Uitpa, Mongui, and Castillete Formations, the latter bordering the La Vela Cape shore, were deposited during a transgressive–regressive marine cycle between the end of Eocene and part of Oligocene. Tectonic activity interrupted sedimentation and is expressed by small folds, faults, and unconformable contacts between the Macarao and Siamana Formations. Sedimentation was interrupted again at the end Pliocene due to the beginning of Andean orogeny; in north of the Oca Fault, sedimentary units were slightly folded and the platform was lifted several meters above sea level (Ingeominas 2002).

Quaternary deposits which cover these formations include thick to very thick deposits of materials mainly derived from the surrounding ridge erosion and were considered by Ingeominas (2002) as partially erosional and depositional terraces formed during the Pliocene and Pleistocene. Alluvial plain deposits consist of gravels, sands, and clays in variable proportions and in part of Aeolian deposits, cover flat, sunken areas (Ingeominas 2002; Khobzi 1981). Aeolian sands, which cover large areas of the Guajira

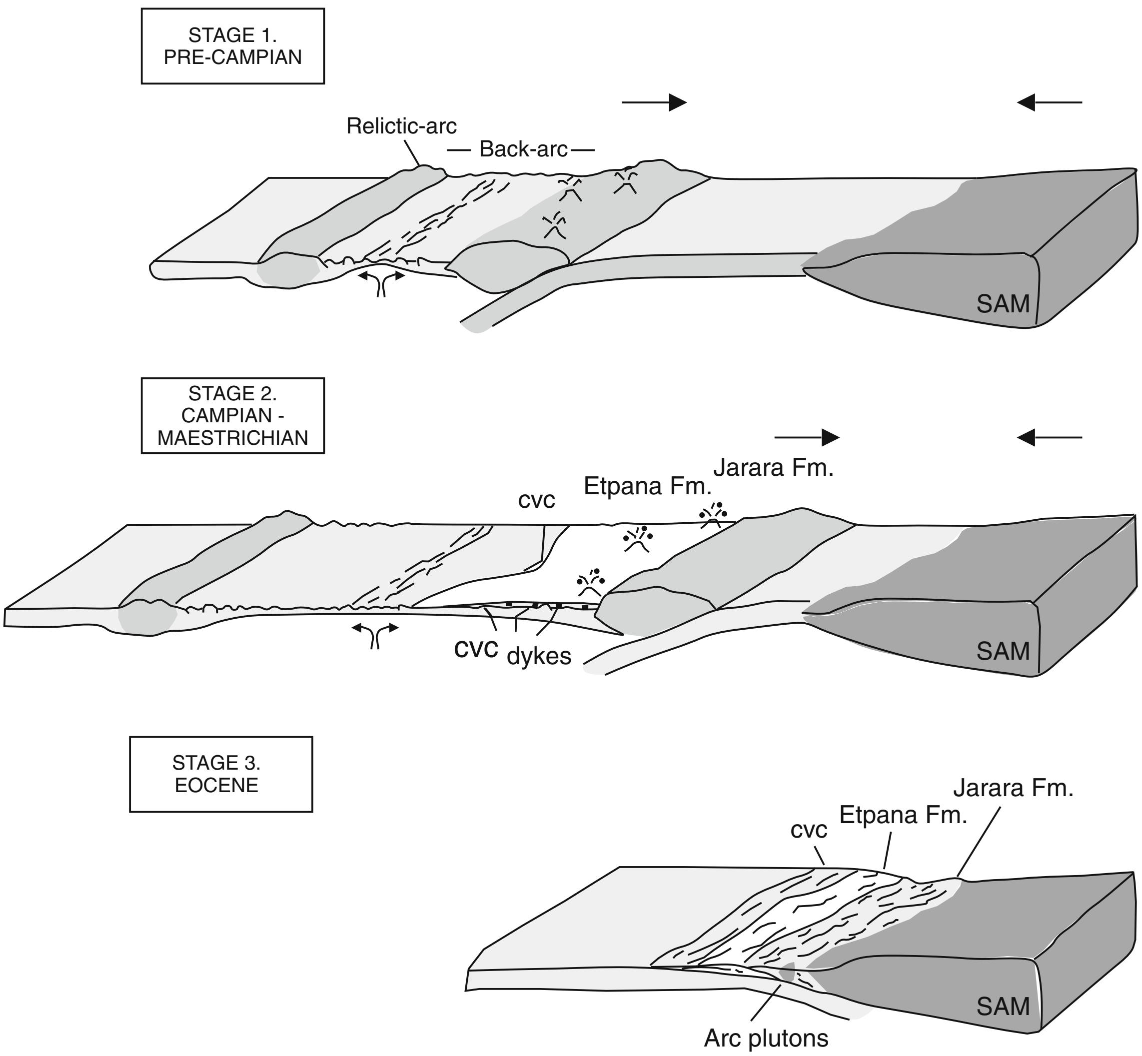


Fig. 2.4 Tectonic evolution

Peninsula and which in Alta Guajira cover the N–NE slopes of the ridges, have been interpreted as products of a large plain stretching in the N–NE coast, as a consequence of a Pleistocene marine regression (Ingeominas 2002). Beach and coastal deposits, as well as alluvial bed deposits, are also widely distributed (Fig. 2.5).

From a structural standpoint, the Guajira peninsula is located north of the Oca Fault, which together with Cuisa Fault, located northward, belong to the same E–W fault system that cuts an older N–NE regional trend, and caused vertical and eastward movements of the blocks which make the different ridges of the peninsula (Ingeominas 2002).

The EW Cuisa fault stretches for more than 80 km and separates pre-Mesozoic Cretaceous metamorphic rocks and Cenozoic sediments of the northern block from pre-Mesozoic Cretaceous metamorphic rocks and Mesozoic sediments form the Cosinas area. It is covered by Oligocene sediments in the west and by recent materials in the east. Ingeominas (2002) suggests two kinds of movement: a right-lateral strike, with a displacement of 28 km, and another along the dip, which uplifted the southern block with respect to the northern one.

2.4 Geomorphology

In north of the Sierra Nevada de Santa Marta, the Guajira consists of a broad coastal plain, interrupted north of the Oca and Cuisa Faults by isolated ridges (Fig. 2.2). This pattern results from the evolution of a marine platform, which—from the end of Oligocene to the Pliocene—was flat and stable, interrupted only by islands formed by the Jarara, Macuira, Cosinas, and Carpintero (including Jepirra) Ridges. These islands acted as wave breakers and enabled

Fig. 2.5 Alluvial deposits. *Photography* Michel Hermelin

development of reefs and sedimentation in a relatively quiet sea and a stable tectonic environment (Ingeominas 2002), As a result of morphodynamic processes which were active during the Quaternary on the emerged terraces, the great plain gave rise to the present erosional and depositional landforms which are now under the influence of the active processes (Fig. 2.6).

The coastal zone is flat or slightly undulated and consists of Cenozoic sedimentary rocks partially covered by Aeolian deposits (dunes) (Figs. 2.7 and 2.8) and alluvial and marine deposits (beaches, bars, lagoons). It is cut by numerous streams, most of them were seasonal. Altitudes do not exceed 100 m a.s.l. Sands were originated by the erosion of the sedimentary beds during a drier period, prior to river and creek cutting (IGAC 2009). Sea level lowering during the Pleistocene uncovered large plains in the N–NE coast, which supplied sand that is now stored in the northern ridges.

Dune fields, mainly parabolic, are found along the coastline, in the salt flat areas, and along the valleys between ridges (Ingeominas 2002); they can be clearly observed on the NE slopes of La Vela Cape or limited by alluvial plains. Their distribution obeys to bioclimatic rather topographic factors; the principal orientation is 63° NE, related with trade winds, which have conserved the same orientation at least since the beginning of Holocene, as evidenced by old and recent dunes (Khobzi 1981). These dunes exist together at Arco Iris (Rainbow) Point and Pilón de Azúcar (Sugar Loaf) and may reach heights ranging from centimeters to meters. Emerging dunes are very common on the plain, and their distribution may cause partial vegetation burial. The extensive development of dune systems in the area around the La Vela Cape might be an indicator of dryer climates during Holocene, perhaps associated with lower sea level. Slightly more humid phases could explain the presence of certain types of soils. Dune sands are quartz, possibly because the original carbonates dissolved after the formation of soil related to marine regression.

Alluvial valleys related to the Rancheria River watershed include many wadis capable of producing erosion and transport during rainfalls. The first part of the road to *La Vela* Cape follows one of the wadis; a thin-stone desert pavement in formation can be observed in its walls and a crust several millimeters thick covers the soil (Fig. 2.9). The wadis dissect the soil forming channels which may reach a width of four meters (IGAC 2009). Deep incisions of the wadis form terraces, which were carved in the recent alluvial and aeolian deposits but also in Paleogene and Neogene sedimentary formations. Two levels have been identified.

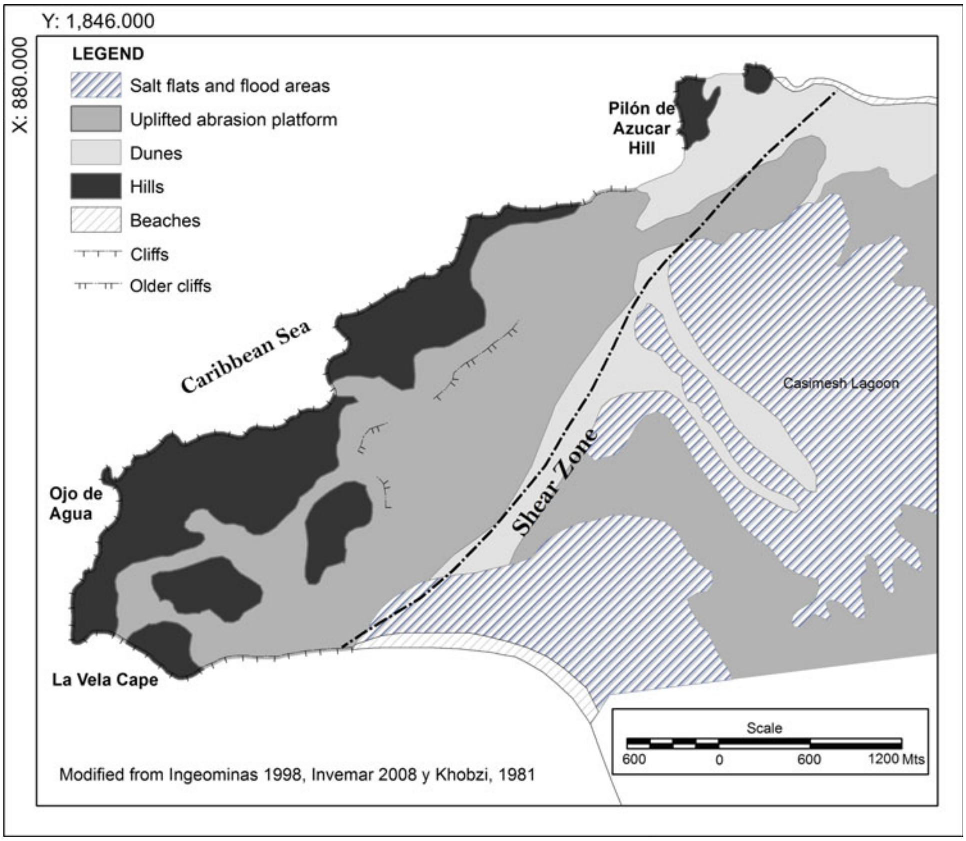


Fig. 2.6 Local geomorphological map of the Cabo de la Vela site

Fig. 2.7 Dunes. *Photography* Michel Hermelin

Fig. 2.8 Vegetated dunes, in the ore ground, desert pavement. *Photography* Michel Hermelin

Floodplains, which include salt flats, are extensive; following the rainy season, water evaporates or drains very slowly due to poor soil permeability. The Kasimesh Lake, around the Vela Cape, is considered by Khobzi (1981) a sebkha and has a considerable extension during rainy periods, while during dryer periods, the most of its area is a sebkha.

Bars, beaches, lagoons, salt flats, and dunes form along the coastline. Beaches measure from 2 to 15 m in width approximately, formed of terrigenous and biogenic sands, and also of quartz, feldspars, oxides, and rock fragments from neighboring rocky formations and shell fragments. Locally, longitudinal dunes cover the back beach. Beach barrier systems with widths reaching tens of meters can be observed behind the beaches. They are used to build houses; behind the barriers are flood areas with salt flats and lagoons, and coastal dunes reach height of 3 m and show no vegetation.

Ridges

The coast around La Vela Cape is characterized by rocky points, bays, and small islands associated with the Japira Ridge, commonly considered as part of the Carpintero Ridge. La Vela Cape (Figs. 2.10 and 2.11) and Pilón de Azúcar (Sugar Loaf) (Fig. 2.12) are small mounts formed on ultramafic rocks, which show terraces and old reddish dunes, pediments, and uplifted abrasion platforms related to recent sea level changes (Holocene thermal optimum, Ingeominas 2002; IGAC 2009; *Alcaldía Municipal Uribia of* 2012). Gullies produced by seasonal wadis are common on deeply weathered rocks, with scarce vegetation mounds and high slopes.

A good example of abrasion platform can be seen at the Arco Iris Point, NE of Pilón de Azúcar. It lies about 4 m a.s.l. and was formed from sedimentary rocks of the Castillete Formation, consisting in fossiliferous limestones resistant to erosion, intercalated with slightly compacted calcareous sandstones (*Alcaldía Municipal of Uribia* 2012). The upper part of this sequence apparently corresponds to beach rocks, as deduced from its composition of sands, typically found in beaches, its slight seaward dip, its low angular lamination, and lapiez-type erosional relief. It would coincide with the shallow marine environment origin attributed to this formation. In the Pilón de Azucar lower slope, several older reddish dunes occur, some protected by vegetation and other partially destroyed, and undulated to flat areas are covered by desert pavement (Fig. 2.13).

Fig. 2.9 Desert pavement. *Photography* Michel Hermelin

Fig. 2.10 La Vela Cape looking toward SW. The old lighthouse is visible. *Photography* Michel Hermelin

Fig. 2.11 La Vela Cape. *Photography* oriented toward NW, Michel Hermelin

Fig. 2.12 Pilon de Azucar, a promontory formed of ultramafic rock. *Photography* Michel Hermelin

Fig. 2.13 Vegetation. *Photography* Michel Hermelin

2.5 Vegetation and Land Use

The La Vela Cape lies in the life zone called "subtropical desert scrub" (Holdridge 1967), characterized by low vegetation cover with cactus and spiny bush scrub. Isolated bushes with rounded crowns oriented by the wind are dominated by *trupillo* (*Prosopis juliflora*) and giant cactus (*Lemaire ocereus griseus*). In a lower proportion, *dividivi* (Caesalpinia coriaria) and *palo verde* (*Cercidium praecox*) are found. Tuna (small cactus, O*puntia wentlana*) is the most aggressive species during colonization of degraded areas due to overgrazing. Species like *Sesuvium portulacastrum*, *Heterostachys ritteriana*, *Batis maritima*, *Philocene vermicularis*, *Lycium tweedianum,* and *Castela erecta* occupy recent dunes, while salt flats have no vegetation. When soils are sandy, a homogeneous community of *Castela erecta* grows sometimes in combination with other species such as *Jatropha gossypifolia* (IGAC 1978 in *Alcaldía Municipal of Uribia* 2012) (Fig. 2.13).

In the Carpintero Ridge, vegetation is also very scarce. Near wadis, small trees such as *trupillo, palo verde, dividivi,* and *guamacho* remain green even during the dry season. Land use is reduced to extensive grazing by small flocks of goats and sheep. Agriculture is practically absent and food is brought from Venezuela and other regions of Colombia.

Fishing activity has been carried out by industrial fishing fleet. Artisanal extraction of marine salt, gypsum, and talc exists; pearl fishing was an important activity at the beginning of the colonial time (IGAC 1978 In *Alcadía Municipal of Uribia* 2012).

2.6 Cultural Aspects

The northern Guajira (Alta Guajira) is a territory belonging to the Wayúu community, characterized by its strong ties to traditions, a social organization based on family clans, and a high dispersion in the territory. They live on grazing and fishing activities; water is scarce and health conditions are precarious; education is limited and electricity exists only in large population centers. They speak their own language (*Wayuunaiki*).

Wayúus proceed from a pre-Colombian society of food collectors without chiefdoms, which is now divided into fishermen and cattle raisers. The organization is based on matriarchy: family tradition is transmitted by women. They live in small groups of houses (*rancherías, pichipala*) with communal water wells and cemetery.

Wayúus believe in a supreme being, *Maleiwa*, the Creator, together with secondary gods. Several places have a special significance, like Jepirra, a ridge in the La Vela Cape, which is considered sacred because this is where the Wayúu souls rest. In this place, Wayúus may live and goats may graze, but the land cannot be sold and white people cannot live there. A *Wayúu* dies twice: the first when death occurs, the soul is liberated from the body and lives in Jepirra; then he dies for the second time 5 or 6 years later, and the body remains are exhumed and carried to the cemetery of the locality where the deceased was born. Then the soul starts its definitive travel through the cosmos toward the Milky Way, signaled as the Dead Way (EPM 2002).

2.7 Further Recommendations

In the Guajira Peninsula, secondary roads are sometimes poorly defined and road signals are scarce. The best way to reach Cabo de la Vela is through a travel agency in Riohacha, which will provide a four-wheel-drive vehicle with a native driver and arrange lodging and food at one of the "hotels" in the village. Magnificent sunsets can be observed from the Cape and it is worth spending the night there.

The Tayrona National Natural Park is located 10 min by car from Santa Marta. It offers spectacular beaches made of white sands, many of them dangerous for swimmers due to strong waves and currents. The beaches alternate with rocky shores consisting of enormous granitic blocks forming tors, which deserve a visit. Interesting archeological remnants can be visited at *Ciudad Perdida* (Lost City) located in the Sierra Nevada slopes. Excursions lasting 5–6 days can be organized from Santa Marta or Bogotá. With clear weather, the road from Riohacha to Santa Marta offers a magnificent view of the Sierra Nevada de Santa Marta. The best time is during the early morning hours.

References

Alcaldía Municipal of Dibulla (2012) Plan de desarrollo municipal 2012–2015. Todos por el cambio. http://dibulla-laguajira.gov.co/apc-aa-files/36613366636532653934333065633636/plan-de-desarrollo-final-1.pdf. Accessed 12 April 2013

Alcaldía Municipal of Maicao (2012) Plan de Desarrollo. Maicao con la gente, rumbo al centenario. 2012–2015. http://www.maicao-laguajira.gov.co/apc-aa-files/62306434343132353932663863663238/PDMJUNIO.pdf. Accessed 12 April 2013

Alcaldía municipal of Manaure (2012) Proyecto de Acuerdo. Plan de Desarrollo Municipal. Municipio de Manaure, La Guajira. 2012–2015. http://www.manaure-laguajira.gov.co/apc-aa-files/35346465396630316261313435653934/plan-de-desarrollo-2012-2015.pdf. Accessed 12 April 2013

Alcaldía Municipal of Riohacha (2012) Plan de desarrollo. Municipio de Riohacha 2012–2015. http://riohacha-laguajira.gov.co/apc-aa-files/38393262636535666639653330326234/Plandedesarrollo2012_2015_Proyecto_de_Acuerdo.pdf. Accessed 12 April 2103

Alcaldía Municipal of Uribia (2012) Plan Municipal de Desarrollo. Comprometidos con Uribia. http://www.uribia-laguajira.gov.co/apc-aa-files/61373734653263366234393535663234/plan_municipal_de_desarrollo_de_uribia_2012_2015.pdf. Accessed 12 April 2013

Cardona A, Weber M, Wilson R, Cordani U, Muñoz CM, Paniagua F (2007) Evolución tectono-magmática de las rocas máficas-ultramáficas del Cabo de La Vela y el Stock de Parashi, Península de la Guajira: registro de la evolución orogénica cretácica-eocena del norte de Suramérica y el Caribe. XI Congreso Colombiano de Geología, Bucaramanga, August 14–17, 2007

Chicangana G, Kammer A, Vargas C, Jiménez CA, Ordóñez CI, Mora H, Ferrari AL, López SA (2011) El posible origen de la sismicidad somera que se presenta en la región que corresponde a la Sierra Nevada de Santa Marta, la Serranía de Perijá y la Península de La Guajira, noreste de Colombia. www.capycua.com.co Vol. 6, Noviembre 2011. Accessed 16 April 2013

EPM - Empresas Públicas de Medellín (2002) Proyecto de aprovechamiento eólico Jepirachi. Plan de gestión social para la etapa de estudios. 344 p

Guerra CW (2003) La Guajira. Colombia, Imeditors 157p

Hernández R, Ramírez V, Reyes JP (2003) Evolución Geohistórica de las Cuencas del Norte de Colombia. VIII Simposio Bolivariano – Exploración Petrolera en las Cuencas Subandinas. 256 p

Holdridge LR (1967) Life zone ecology. Tropical Science Center San José, Costa Rica 260p

IGAC - INSTITUTO GEOGRÁFICO AGUSTÍN CODAZZI (2009) Estudio general de suelos y zonificación de tierras del departamento de La Guajira. Medio Biofísico. 86 p

IGAC - INSTITUTO GEOGRÁFICO AGUSTÍN CODAZZI (1978) Estudio General de Suelos Alta y Media Guajira. Vol. XIV, N° 1, Bogotá

INGEOMINAS (2002) Mapa Geológico Del Departamento de La Guajira. Geología, recursos minerales y amenazas potenciales. Scale 1:250.000. Versión 2. Informe técnico preparado por Gabriel Rodríguez, Ana Cristina Londoño. 259 p

Khobzi J (1981) Los campos de duna del norte de Colombia y de los Llanos del Orinoco (Colombia y Venezuela) Revista CIAF 6(1–3):257–292

Nova G, Montaño P C, Bayona G, Rapalini A, and Montes C (2011) Análisis Paleomagnético en Unidades del Mesozoico en la Alta Guajira. Latinmag Letters, Volume 1, Special Issue (2011), B30, 1–5, Proceedings Tandil, Argentina

Weber MB, Cardona A I, Paniagua F, Cordani U, Sepúlveda L, Wilson R (2009) Cabo de la Vela Mafic-Ultramafic Complex, Northeastern Colombian Caribbean region: a record of multistage evolution of a Late Cretaceous intra-oceanic arc. In: the origin and evolution of the Caribbean, Plate, Geological Society, London, Special Publication 328, pp 549–568

Zapata S, Weber M, Cardona A, Valencia V, Guzmán G, Tabón M (2010) Provenance of Oligocene conglomerates and associated sandstones from the Siamaná formation, Serranía de Jarara, Guajira, Colombia: Implications for Oligocene Caribbean-South American Tectonics. Bol. Ciencias Tierra no. 27 Medellín

3 Mud Diapirism in the Central Colombian Caribbean Coastal Zone

José Henry Carvajal

Abstract

The western part of the Colombian Caribbean coast is associated with Cenozoic accretionary prisms and influenced by mud diapirism, originated by density contrast between high-pressure muddy mass material containing gases and denser surrounding overburden, and by tectonic compression associated with oblique plate convergence. Mud diapirism surface manifestations are associated with land risings and differential tilting, locally called “mud volcanoes,” land mudflows, mud, and intermittent gas bubbles and accumulation of mud on the surface. These manifestations have been considered as curious and picturesque phenomena. However, paroxysmal phases constitute a geologic risk for the inhabitants and the infrastructure of the region. The region of Cartagena displays numerous examples of these phenomena and deserves a visit by the scientific community which will also appreciate the beauty of this well-preserved colonial city.

Keywords

Mud diapirism • Coastal geomorphology • Caribbean coast • Cartagena

3.1 Introduction

Mud diapirism originates due to both the density contrast between plastic high-pressure muddy materials charged with gases and their denser overburden, and tectonic compression associated with oblique tectonic plate convergence. The muddy diapíric material moves upward through fractures, generating uplift and rock fracturing, and results in mud and gas expulsion through mouths of varied shapes and sizes. This phenomenon is common along Cenozoic folded belts associated with convergent plate boundaries. It is found in Venezuela, Trinidad and Tobago, Ecuador, Panamá, as well as in Spain, Sicily, around the Caspian Sea, in Azerbaijan, Taiwan, and many other localities (Higgins and Sanders 1974; Kopf 2002).

Mud diapirism is a process of land deformation and it is partly responsible for the configuration of the central Colombian Caribbean coastal line (Carvajal 2011). Landforms such as homoclinal ridges, pressure ridges, cuestas, hogbacks, anticline and syncline ridges, marine terraces and islands, located near the continental shelf, owe their origin to mud diapirism that locally favors differential rising of the land, generated by the oblique convergence of the Nazca, Caribbean and South American plates (Vernette 1985; Vernette et al. 1992; Carvajal et al. 2010 in Carvajal 2011).

Mud volcanoes are attractive manifestations of mud diapirism, and they are locally considered as picturesque landforms of the Colombian Caribbean coast. In 1801, Humboldt A. and Fidalgo visited the area and the former described it (ACCEFYN 1999, Fidalgo 1794 in Mantilla and Cuadros 1958) (see Fig. 3.1, taken from Humbolt 1804, in MacGuillivray 2005) in the following words:

J.H. Carvajal (✉)
Servicio Geológico Colombiano, Bogotá, Colombia
e-mail: jcarvajal@sgc.gov.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_3

Fig. 3.1 Mud volcanoes at Turbaco. Drawing made by Louis de Rieux, during a visit made in the company of Humboldt in March 1801. From Humboldt 1804 in Mac Guilvray (2005)

> The volcanoes of Turbaco are a deserted and lonely place amid the forest, where no bush grows in an extension of about 800 feet, the nearest is the *Bromelia Karatas*. This desert place is made of greyish mud, clay that (according to the theory of Basalt of Werner) is, everywhere, cracked by desiccation in figures of 5 and 6 sides. On this clay layer, many big and small cones rises in wonderful ways. The isolated one that is located farther toward the south part (in fact the one that the young Louis de Rieux drew so well), rises little by little on an extremely wide base to a height of 3 or 4 "toises" (1 toise = 1,946 m). In the summit of the cone there is a circular hole with a crater shape border, some inches wide and it is full water, from it spring up enormous bubbles of air in irregular lapses, approximately five times every 2 min, with a great deaf noise (Humboldt, in ACCEFYN 1999).

Mud diapirism is found from Barranquilla to the Urabá Gulf, including offshore and onshore areas. It is related to the Sinú and San Jacinto fold belts (Fig. 3.2), which are two wedges of sediments, accreted to the South American Plate, as products of the oblique convergence of the Nazca and Caribbean Plates (Duque 1979, 1984; Vernette et al. 1992; Kellogg et al. 2005). The region described here is located between Galerazamba and the Dique channel. It is characterized by a medium-dry tropical climate, with annual average temperatures of 28 °C, softened by the incidence of the trade winds between January and April.

3.2 Geological Framework

The northwestern Colombian Caribbean coastal zone is framed by two areas with different geological characteristics. A stable platform is separated from an unstable region located west of the Romeral fault system, considered as a major paleosuture, which defines a clear boundary between continental and oceanic basements (Duque 1979, 1984; Toto and Kellogg 1992; Flinch 2003). The stable area is underlain by unfolded continental crust and defined at the surface by the lower Magdalena River basin. The unstable area is formed by two structural sedimentary wedges, defined by Duque (1979) as San Jacinto and Sinú fold belts, in the east and west, respectively. They have been considered as two sedimentary prisms, accreted to the northwestern Colombian margin and they are separated by the Sinú lineament, which defines an evident structural change (Duque 1979, 1984; Obando 2011 in Carvajal 2011).

The San Jacinto fold belt is structurally complex, associated with northwest-verging folds and thrust faults trending northeast. From south to north, it is divided into three structural elements: San Jerónimo, San Jacinto and Luruaco anticlinoriums, respectively (Fig. 3.2), formed by Upper Cretaceous pelagic rocks, a thick sequence of Tertiary rocks

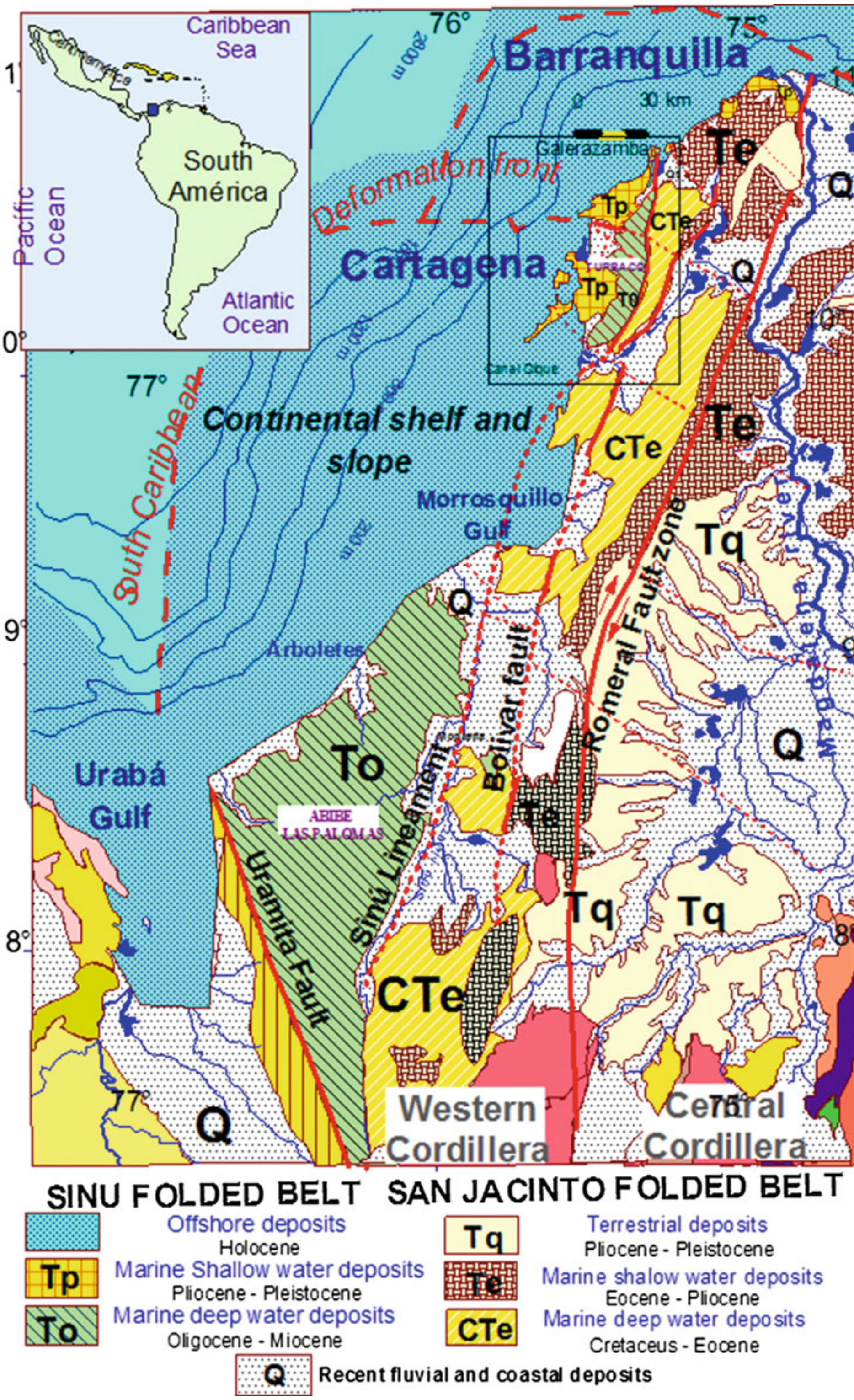


Fig. 3.2 Geological and structural framework of the northwesten Colombian Caribbean coastal region. Modified from Duque (1979), (1984) and Guzmán et al. (2004)

of turbiditic origin and coral reef limestones, locally covered by Quaternary fluvial and lacustrine deposits (Duque 1979, 1984). This fold belt presents locally some mud volcanoes with transcurrent faulting trending NW–SE.

The Sinú fold belt, which extends from the Gulf of Urabá to the north of Barranquilla, includes the present offshore and onshore areas (Fig. 3.2). It is formed by a series of narrow mud-cored, NNE trending anticlines that limit wide

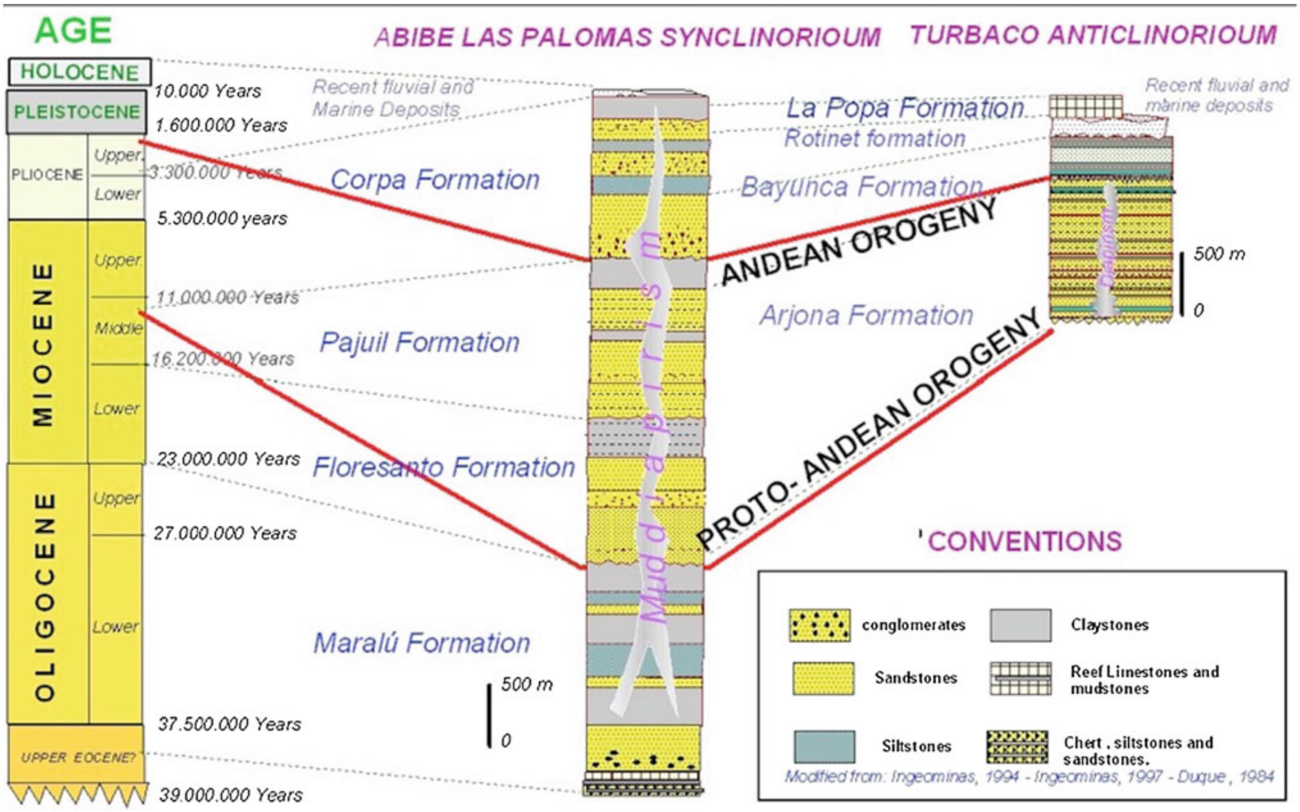


Fig. 3.3 Generalized stratigraphic columns of the Sinú fold belt for the Cordoba–Antioquia and the Turbaco region (Carvajal 2001)

and gentle synclines, particularly in their southern region (Duque 1979, 1984; Mantilla et al. 2009).

The region analyzed in this chapter is located in the Turbaco anticlinorium of the Sinú fold belt (Duque 1979, 1984). It is limited to the east by the San Jacinto fold belt, by the Sinú River lineament (Villanueva fault in the Totumo region, north from Cartagena), whereas to the west, it is bounded by the south Caribbean deformation front and to the south by the Rocha lineament, associated with the Dique channel (Fig. 3.2).

The region from Galerazamba to Cartagena is characterized by broad and gentle synclines (troughs), curved in plan view and wedged eastward against the Villanueva—El Totumo fault; they are limited locally by narrow and tight anticlines associated with NW-verging thrust faulting, which bear mud volcanoes. This structural framework, trending NNE–SSW and NEE–SWW, was formed by transpressional–transtensional processes, and it is locally bounded by left-lateral strike-slip faults trending NW–SE (Toto and Kellog 1992; Vernette et al. 1992; Cediel et al. 2003; Ordoñez 2008).

The Sinú fold belt, which was formed during the orogenic Andean phase, from the late Miocene to Pliocene, includes a 5000 m thick sequence of Oligocene, Miocene, and Pliocene pelagic and hemipelagic sediments and turbidites south of Las Palomas synclinorium. At the Turbaco anticlinorium, sandstones, claystones, and siltstones of turbiditic origin (Arjona Formation) are found tectonically affected by transpressive convergence between the Caribbean and South American Plates (Fig. 3.2) (Duque 1979, 1984; Geotec and Ingeominas 2000; Guzmán et al. 2004).

In the structural troughs and highs, these rocks are locally overlain by 4000 m of shallow marine Miocene to Pleistocene–Holocene fluvial and carbonates facies. These sedimentary sequences are made up of claystones, sandstones, gravels, and sands and locally of calcareous sandstones and reef limestones (La Popa Formation) that give to the Cartagena region its attractive landscape (Duque 1979; Reyes et al. 2001; Guzmán et al. 2004). Quaternary deposits present in the region are clays, sands, and clastic and bioclastic gravels of alluvial, aeolian, and marine origin (Fig. 3.3).

3.3 Geomorphological Characteristics

Landforms genetically related with mud diapirism are common in the Sinú folded belt. Mud diapirism is considered as a geological deformation process, being at least partly responsible for the morphological configuration of the coastline.

This province has been also modeled by denudational and accumulation processes and has been subdivided into hills and coastal plains, mainly of denudational, marine, fluvial, and aeolian origins (Carvajal et al. 2010 in Carvajal 2011; Carvajal and Mendivelso 2011) (Fig. 3.4).

3.3.1 Landforms Associated with Mud Diapirism

Morphostructural landforms such as cuestas, hogbacks, anticline ridges, homoclinal ridges, and pressure ridges represent different stages of tilting and deformation (Fig. 3.4). Link (1927) had already documented the morphological expression of numerous shore features along this coast, such as elevated Quaternary coral reefs, wave cut cliffs, elevated residual fluvial gravels, raised, superimposed and diverted streams, and explained their occurrence as the succession of strandline oscillations through stages of erosion, submergence, and emergence. Recent geomorphological mapping indicates that mud diapirism and "mud volcanoes" associated with regional faulting provide evidence of neotectonic activity (Martínez et al. 2010; Carvajal 2011) (Fig. 3.4).

Typical cuestas and hogbacks with sharp to rounded crests, defined by tilting of hard sedimentary rock, with inclinations smaller than 15° and larger than 35º, respectively, are associated with vertical tectonic movement and with mud diapirism. Some examples of this process are the Turbaco cuesta associated with a recently tilted reef coral platform, the considered self paleo-atoll of the Albornoz hill and the highest hill of Cartagena, La Popa (Figs. 3.5, and 3.6).

Pressure ridges develop through an advanced folding process, which begins with the formation of anticline folds, differentially deformed along the structure, called offshore turtle anticlines by Vernette (1985) and may contain positive and negative flower structures (Fig. 3.7). As a result of this process, both local verticality of the sedimentary sequences and "mud volcanoes" on top of the structure occur. The Punta Canoas pressure ridge, 4 km long and 60 m high, developed on folded sandstones and claystones of the Arjona Formation. It trends NE and is characterized by hilly morphology. It is fractured and dissected with a N30ºE trend due to dextral strike-slip movements, which facilitated mud volcano occurrence on the summit (Fig. 3.8).

Offshore the Cartagena coastal zone, the effect of convergent tectonics and mud diapirism facilitates the formation of anticlinal ridges (turtle anticlines) and pressure ridges, in whose summits mud volcanoes may form. When these structures reach photic zones, they are colonized by corals, and form islands. This is the origin of the Rosario's islands, Salmedina banks, Tierrabomba island, and Cascajo, and Arena Islands (Fig. 3.8). Processes associated with mud diapirism in continental shelves have been well-documented by Sheppard et al. (1968), Vernette (1985), Vernette et al. (1988, 1990, 1992), Briceño and Vernnete (1992), Martínez et al. (1990), Carvajal (1992), Correa et al. (2005), GIO (2005), Vinnels et al. (2010) and Carvajal (2011). Vertical tectonic activity in onshore areas has been evidenced by monitoring stations with GPS–GNSS (Mora 2010 in Carvajal 2011). Preliminary results indicate differential uprising in Tierrabomba and Cartagena (6–7 mm/year) and subsidence in Galerazamba (2 mm/year). It is important to signal a much higher subsidence (17–35 mm/year) in the stations located on top of "volcanic" buildings of Pueblo Nuevo (V-6) and Totumo (V-7), which had been previously associated with expansive clays.

Currently, a similar process occurs at the Arenas Island, located NE of the Cascajo island. This island is rising possibly due to mud diapirism, and causes wave refraction and diffraction processes, producing the progradation of the beach to the island (Fig. 3.8).

3.3.2 Mud Volcanoes

The most spectacular manifestations of mud diapirism are undoubtedly "mud volcanoes" located both onshore and offshore (Figs. 3.4, 3.5, 3.7, and 3.8). These mud volcanoes cause the verticality of the sedimentary sequences and facilitate mud movement through fractures and equally between friable and porous sandy layers or strata (Carvajal 2011; Carvajal and Mendivelso 2011). This situation has been evidenced by geophysical data (gravimetry, magnetometry, and profile geoeletric tomography) obtained in the sector of Pueblo Nuevo—El Totumo (Bolívar) (Obando and Vásquez 2010 in Carvajal 2011). Most mud volcanoes are located on the summits of either anticlines, homoclinal ridges, or pressure ridges associated with transpressional–transtensional tectonics (Fig. 3.7). Locally, they can be found isolated along right-lateral strike-slip faults (Carvajal 2011). In the Cartagena area, the "volcanic" buildings have dome morphology with convex slopes between 15° and 20°, diameters 0.8–1 km, and heights of 50 m, but they may even reach 4.5 km in diameter (Carvajal 2011).

Craters may reach diameters of 500 m and display several mouths, which may also occur in the flanks of the structures (Figs. 3.9, 3.10, 3.11, 3.12, and 3.13). Mud volcano buildings are formed both by muddy material accumulation produced by eruptions, and by land deformation generated by the upward push of mud (hydrofracturation) (Fig. 3.14). Locally, they may show raised rims caused by the subsidence into the void left by the extruded material (Cañaveral "mud volcano", Fig. 3.12).

Surface materials that constitute the mud volcano edifices are dark to brownish gray plastic clays, with dispersed clasts

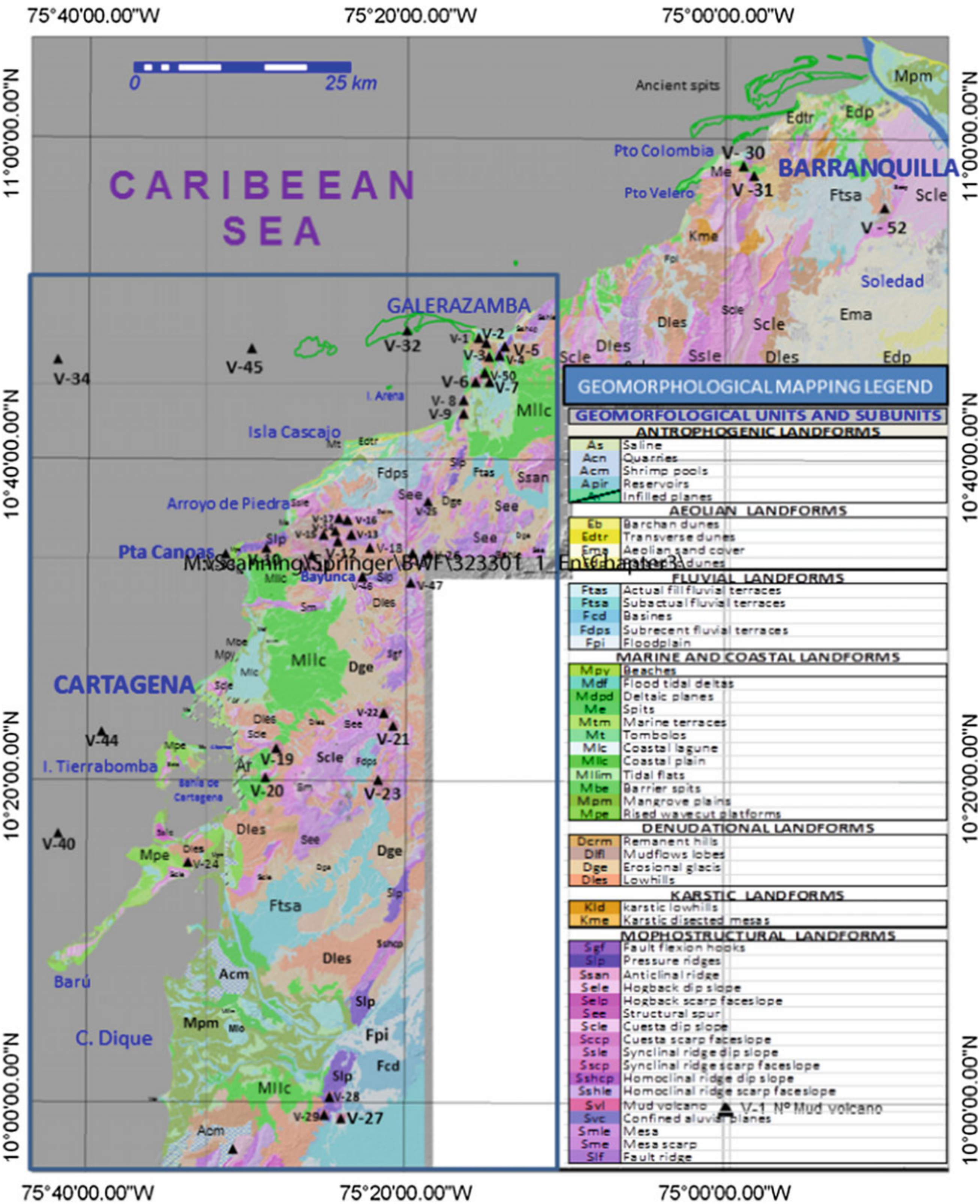


Fig. 3.4 Geomorphological map of the area showing the "mud volcano" locations. Note their common occurrence on and offshore, particularly in the Cartagena zone (*blue line*). Modified from Carvajal (2011)

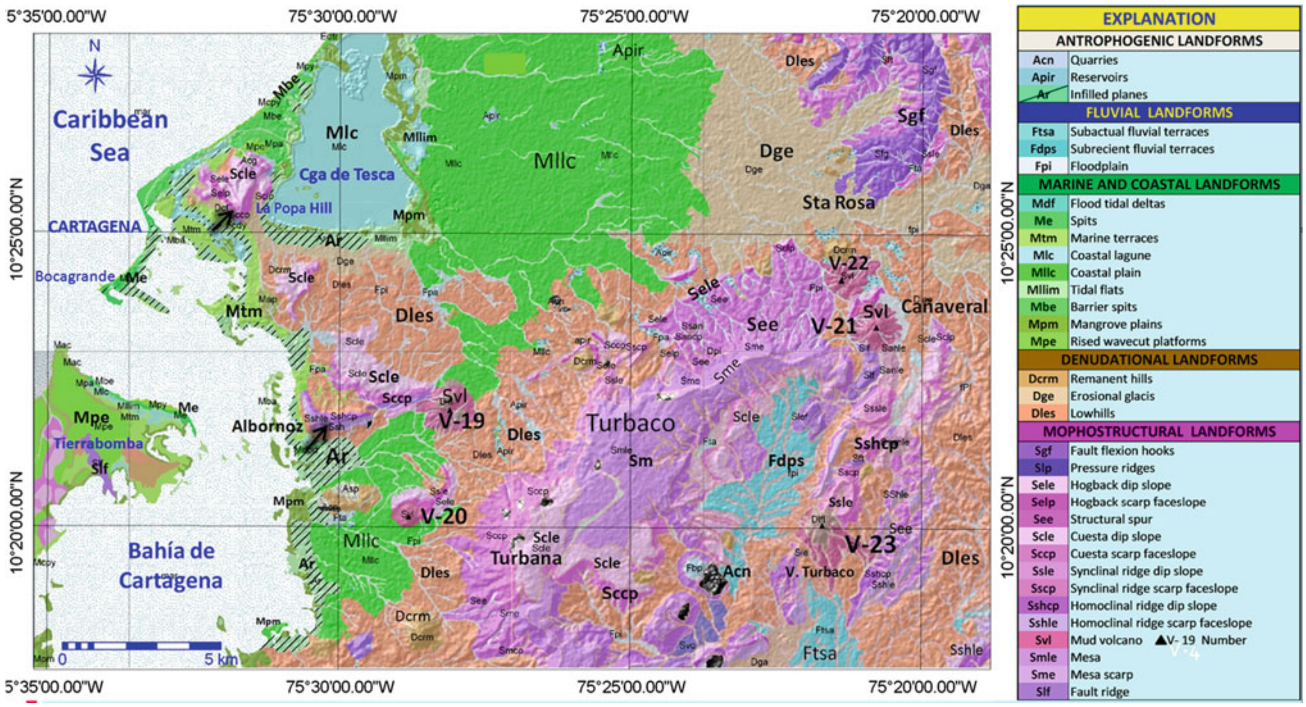


Fig. 3.5 Detailed geomorphological map of the Cartagena area. La Popa and Albornoz Hills are signaled by *black arrows* as El Rodeo, Membrillal, Cañaveral, and Turbaco mud volcanoes. Adapted from Carvajal (2001)

Fig. 3.6 North-looking view of the La Popa hill. Note the conical shape of the cuesta scarp, the accentuated surface erosion processes, and the presence of landslides

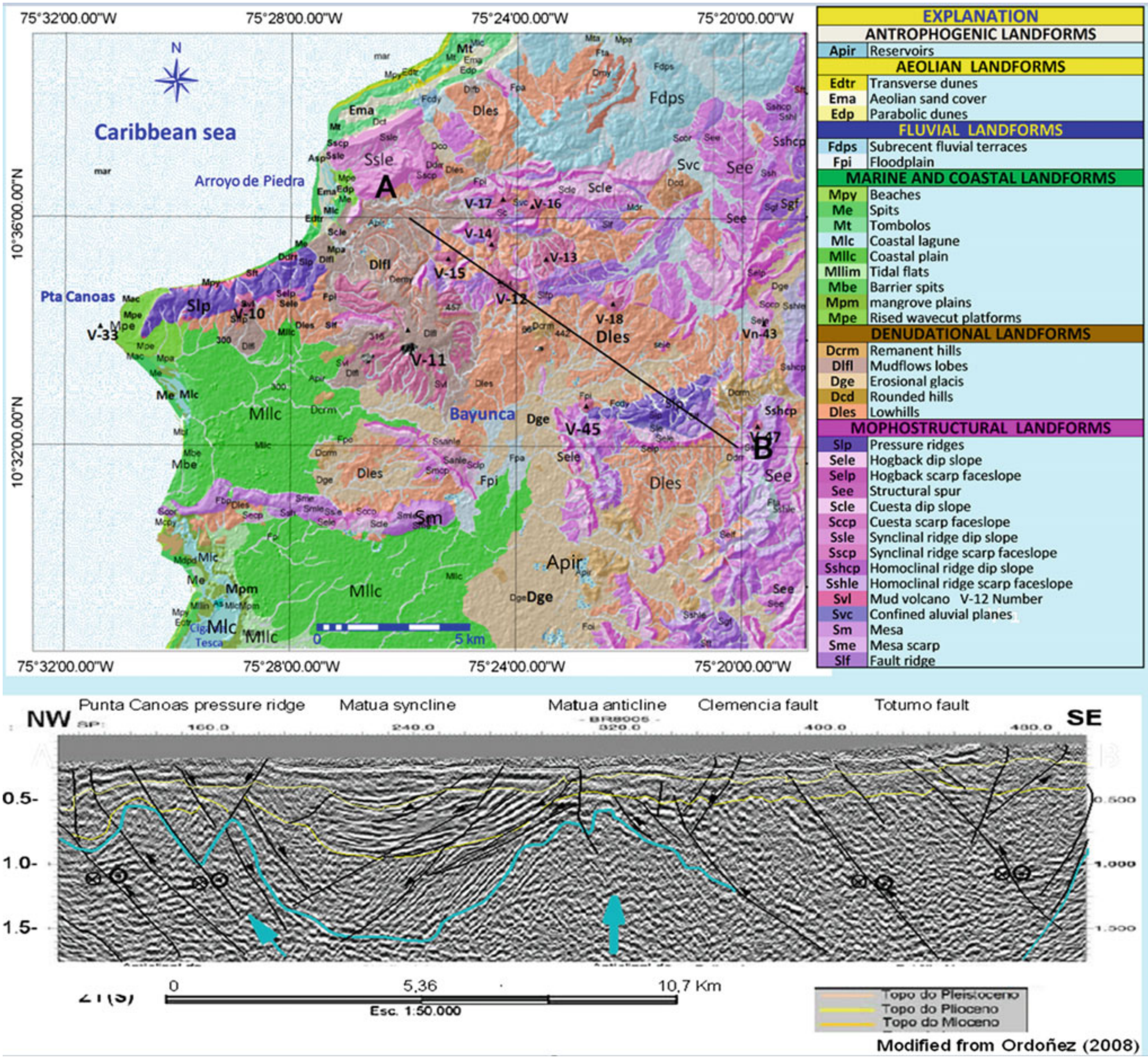


Fig. 3.7 Geomorphological map of the Punta Canoas–Bayunca zone. Mud volcanoes are located on the top of pressure ridges. Seismic cross-section, modified from Ordoñez (2008)

and blocks with diameters up to 1 m. These materials were produced by ancient eruptions which produced mudflows or mud breccias, predominantly composed of quartz feldspatic sandstones, claystones, siltstones, reef limestones and calcareous sandstones, calcite, and locally pyrite blocks (Carvajal and Mendivelso 2010, 2011; Carvajal 2011, 2012).

The main characteristic of the rocky blocks expelled violently during mud eruptions is their high fracturing. This situation results from the high-gas content at depth and its expansion near the surface (Carvajal 2001, 2011). The source of these materials is considered the oldest rocks of Oligocene to Miocene age (Maralú Formation) south of Sinú folded belt, while in the north there is uncertainty about the origin; however, rock fragments of the Arjona, Bayunca, and Rotinet formations are incorporated.

In the Totumo area, Obando and Vásquez 2010 in Carvajal (2011), based on detailed gravimetric, magnetometric, and geoelectric measurements, indicate two sources of origin for the extruded materials. One is located at depth and is associated with the Miocene turbidites (Arjona Formation), while the second, shallower source, is related to Pleistocene materials of the ancient Magdalena River delta.

The mud that constantly emanates in a periodic way from the mouths is constituted predominantly of kaolinite (>40 %) and smectite type clays (10–40 %), and in smaller proportion of chlorite, illite, and pyrophyllite. Very fine quartz and low

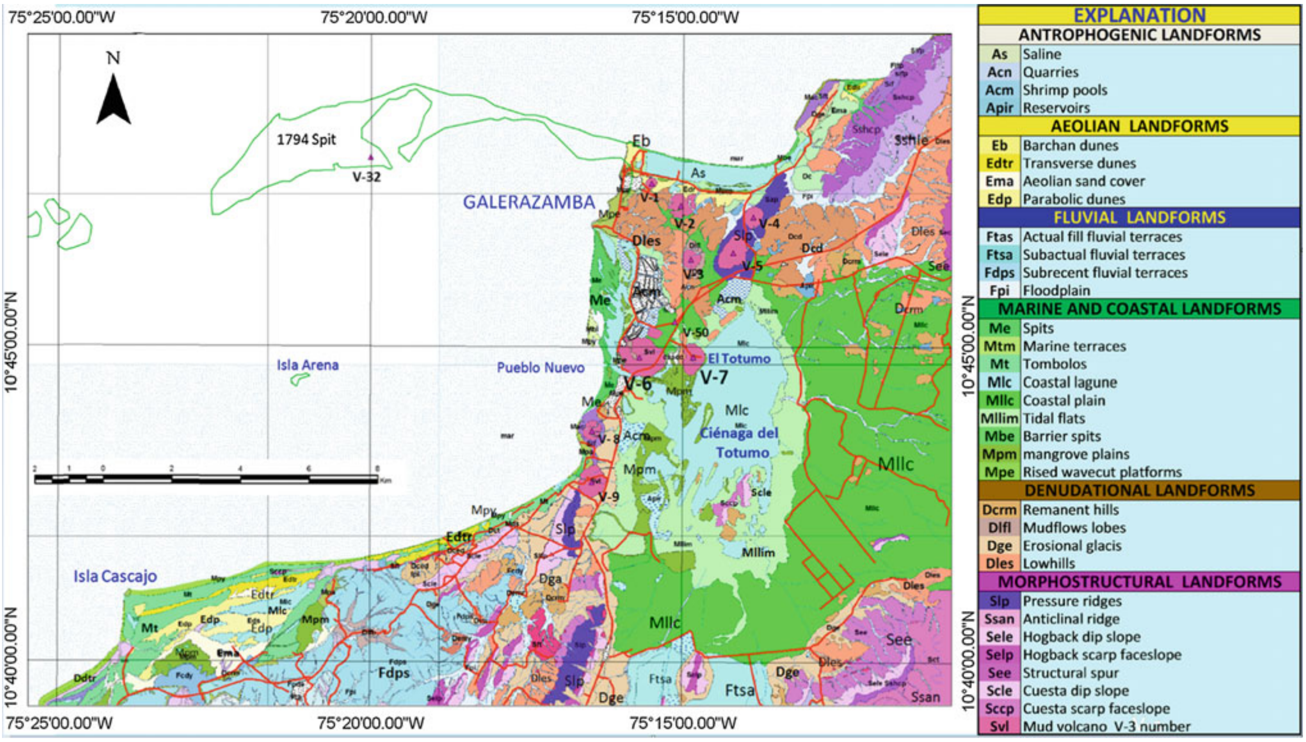


Fig. 3.8 Geomorphological map of the Galerazamba zone, showing both the tombolo of the Cascajo Island and the geomorphic processes associated with wave diffraction and refraction at the Arena Island. From Carvajal (2001)

Fig. 3.9 East-looking view of the Pueblo Nuevo mud volcano. Note the *dome-like* shape and the channelized 1999 mudflow. *Image* downloaded from Google Earth (2012)

Fig. 3.10 Panoramic westward view of the Totumo mud volcano. Note in the foreground the touristic *cone-shaped* mouth. Downloaded from Google Earth (2012)

percentages of feldspar, pyrite, gypsum and halite area are also present. Mud is constituted predominantly of silica, alumina, and smaller proportions of ferrous oxides and of calcium, potassium, magnesium, manganese, and titanium oxides. On the other hand, gases emanating continuously from springs are predominantly methane and in smaller proportion carbon dioxide of biogenic origin (Carvajal and Mendivelso 2010; Carvajal 2011).

The differences in density, viscosity, and degree of fluidity of these materials, when reaching the surface, control the shape of the holes or suckers of varied sizes (from 0.5 to 60 m in diameter) and the dimensions of cones (from 0.6 to 20 m high and from 1 to 30 m in base diameter). According to Higgins and Saunders (1974), mud mouths or springs of this type of "volcanoes" can be classified according to their form and the flank slope of the cones, in the following way (Figs. 3.15, 3.16, 3.17 and 3.18):

Type A = Cone with slopes >20º
Type B = Cone with slope from 5 to 20º
Type C = Cone with slopes <5º
Type D = Boiler shape or crater of several meters in diameter, and
Type O = Holes measuring few cm in width.

On those mud volcano slopes where piping processes occur and lead to collapse in an advanced stage, gullies up to 2.5 m deep may form. According to Carvajal et al. (2010) in Carvajal (2011), the common occurrence of these processes obeys to the low-degree consolidation of the expelled material, associated with gas oversaturation, and later percolation of runoff.

3.3.3 Natural Resources Associated to Mud Volcanoes

Mud volcanoes are one of the best tourist attractions of the region, not only for their landscape expression and the panoramic views they offer, but also for therapeutic and medicinal use of the muddy materials, taking advantage of

Fig. 3.11 East-looking view of the El Rodeo mud volcano located toward SE of Cartagena of Indias. Note the advanced urbanization of the flanks of the structure. Downloaded from Google Earth (2012)

Fig. 3.12 Panoramic view toward SW of the Cañaveral mud volcano. Notice the through or rim syncline around the "volcanic" structure. Downloaded from Google Earth (2012)

the their compositional and physicochemical characteristics. Their mineralogical composition is characterized by wetting properties, given by humidities between 1 and 5 % and pH between 7 and 8. They have fine to very fine textures, dark gray color, locally with stains of brown oil, which confers them good skin adherence (Carvajal and Mendivelso 2011).

The only place where this resource is used for these purposes is at the El Totumo mud volcano. According to Bernal et al. (2000), treatments and empiric massages are given with the expelled material from this mud volcano, consisting in total immersion in mud, while cleaning is done in waters from the nearby coastal lagoon. According to the

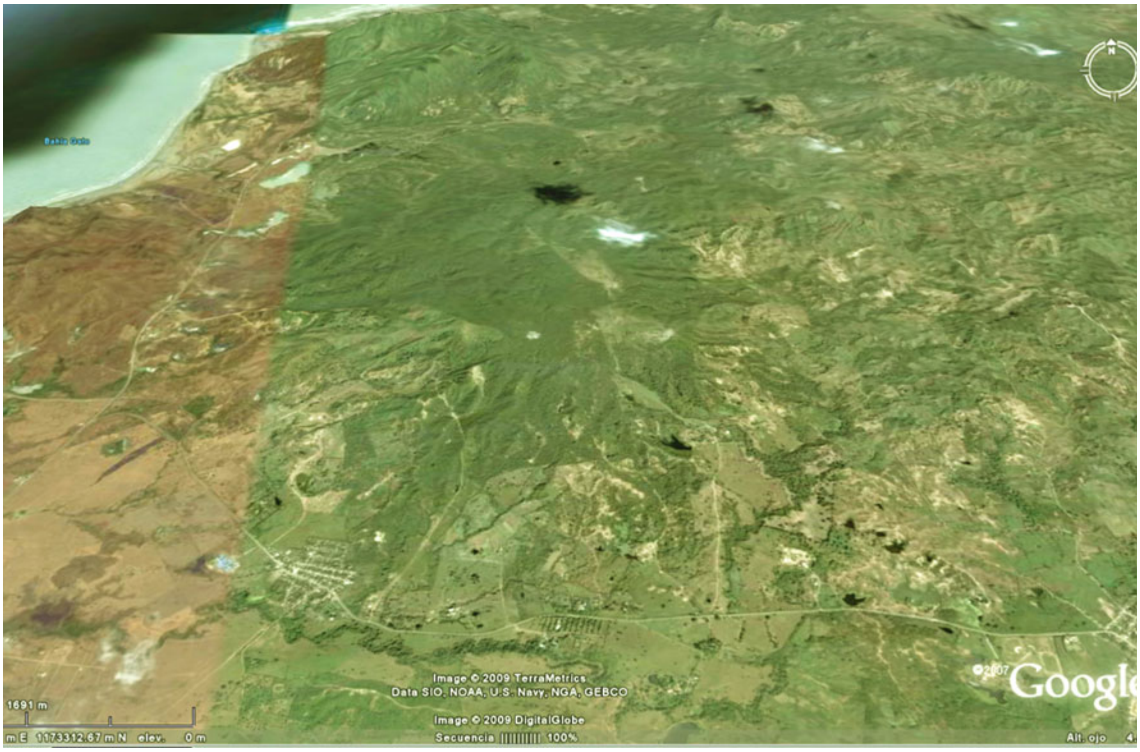


Fig. 3.13 Oblique aerial view toward the north of the Yerbabuena Mud volcano. Note details of the mud emission places associated with *white spots*. Downloaded from Google Earth (2012)

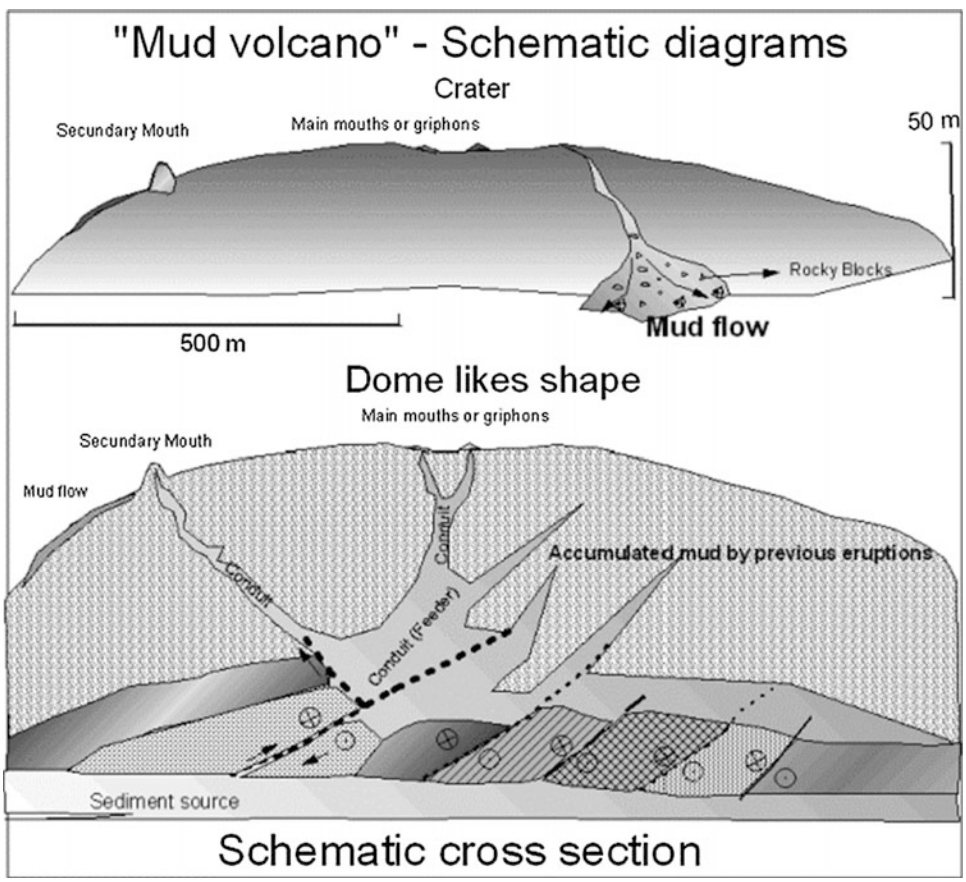


Fig. 3.14 "Mud volcano" schematic diagram. Mudflows were generated during the eruptive process

Fig. 3.15 View of a type A mouth at El Totumo mud volcano. *Cone* is about 16 m high

Fig. 3.16 Type B mouths located in the crater of El Reposo mud volcano. Mud is released slowly and mud cracks are conspicuous

Fig. 3.17 Type C mouth of mud volcano El Rodeo. Mud fluidity is conspicuous

Fig. 3.18 Panoramic view toward the NW of type D mouth of the Arboletes mud volcano. The mouth diameter exceeds 50 m

residents, people have obtained good results in the treatment of skin and articulation pathologies.

The sector with more perspectives to exploit this geo-touristic potential is the Galerazamba region (INGEOMINAS-CARDIQUE 1999; Carvajal and Mendivelso 2011).

3.4 Geological Hazards Associated to Mud Volcanism

Although areas where "mud volcanoes" are present can be exploited for touristic and medicinal purposes, it is important to take into account geologic hazards associated with them. Periodic and violent extrusion of muds, more or less every

Fig. 3.19 Type O mouth details (*left*), a few centimeters in diameter, located in the main crater of the Totumo mud volcano. In the *top right*, the touristic type A, mouth shown in detail in Fig. 3.15

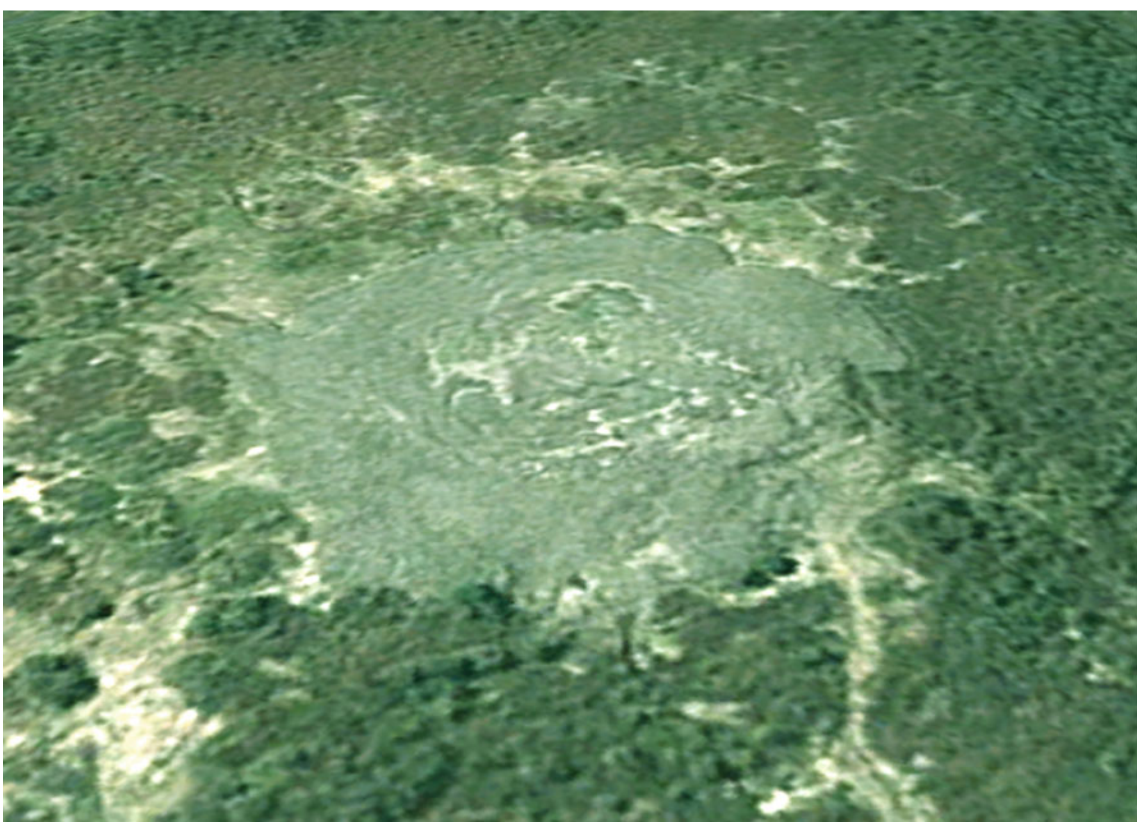


Fig. 3.20 Panoramic view of the *pan-shaped* mudflow 90 m in diameter, formed during the late 2012 eruption of the El Rodeo mud volcano. Downloaded from Google Earth (2013)

Fig. 3.21 Aspects of mudflows and fire generated during the October 2010 Santa Fe de Platas mud volcano eruption. Photo Juan Guillermo Cano

Fig. 3.22 Panoramic view of channeled mudflows at the northern part of the Santafe de Platas mud volcano during October 2010 eruption

15–20 years, can constitute a risk for people and man-made structures located close to the eruption centers. According to Kopf (2002), eruptive processes are triggered by one or more of the following factors: tectonic compression, high content of gases or density inversion associated with difference in densities among the materials confined in depth and the denser upper sedimentary cover.

The common behavior of mud volcanoes is characterized by slow mud emanation, accompanied by intermittent gas bubbling. This mud is dispersed slowly and laterally several meters around, and locally it is interdigitated with flows from other mouths. If eruptions are violent and throw out mud and rockblocks to an approximate height of 15–20 m, they become dangerous.

Carvajal (2001) gives the following list of dangerous manifestations:

– Violent expulsion of mud and rocky blocks.
– Mud flows, channeled by drainages, or forming small mesas several tens of meters in diameter and 1–3 m in height.
– Fracturing of the surrounding terrain

Fig. 3.23 Sinkhole and graben structures generated in the SW sector of the El Reposo mud volcano crater, during the May 2012 eruption

Fig. 3.24 View of the pan-shaped mudflows generated during the December 2000 eruption of El Totumo mud volcano, which obstructed the road leading to the touristic mouth

– Emission of gases and local generation of fires by the ignition of methane (Carvajal 2001, 2011, 2012; Carvajal and Mendivelso 2010, 2011) (Figs. 3.19, 3.20, 3.21, 3.22, and 3.23).

The historical eruptive activity of these mud volcanoes have been well documented by Ramírez (1959), Carvajal and Mendivelso (2010, 2011), Carvajal (2011, 2012), and Carvajal and Calderón (2013). Although in Colombia significant steps have been taken to define the hazards associated with mud volcanism, it is fundamental to improve the knowledge on this topic. Areas influenced by mud volcanism have been considered as risk terrains (Fig. 3.24).

Acknowledgments The author would like to thank the Colombian Geological Service (before INGEOMINAS) for allowing the use of information from the project "Colombian marine and coastal investigations." The author thanks Michel Hermelin and Domingo Mendivelso for the revision and improvement of the manuscript.

References

Academia Colombiana de Ciencias Exactas Físicas y Naturales ACCEFyN (1999) Alexander Von Humboldt en Colombia. Extractos de sus diarios. www.comunidadandina.org/bda/docs/co-ca-0004 . Biblioteca Luis Ángel Arango. Bogotá. Colombia

Bernal N, Carvajal J H, Peláez R, Reyes G (2000) Informe preliminar del reconocimiento de los "volcanes de lodo de la costa Atlántica Colombiana y de aguas minerales del Municipio de Usiacurí, departamento del Atlántico (preliminar). Informe INGEOMINAS Inédito, I-2690. 17 p. Bogotá

Briceño L, Vernette G (1992) Manifestaciones del diapirismo arcilloso en el margen colombiano del Caribe. Geofísica Colombiana vol 1, pp 21–30. ISSN 0121-2974. Bogotá

Carvajal JH (1992) Características sedimentológicas de la plataforma continental frente a Galerazamba. Informe 2173 INGEOMINAS Cartagena de Indias

Carvajal JH (2001) Amenazas geológicas asociadas al volcanismo de lodos. Memorias del VIII Congreso Colombiano de Geología. CD aparte de Volcanes. 15 páginas. Manizales

Carvajal JH (2011) Características del "volcanismo de lodo" del Caribe central Colombiano. Informe Servicio Geológico Colombiano en proceso de publicación. 82 p. Bogotá

Carvajal JH (2012) Características de la actividad eruptiva del 11 de mayo de 2012 en el "volcán de lodo" El Reposo o Bajogrande. Bayunca – Municipio de Cartagena de Indias. Informe de atención de emergencias. 50 p. Servicio Geológico Colombiano. Bogotá

Carvajal JH, Mendivelso D (2010) Características de las erupciones "volcánicas de lodo" – "volcán de lodo" de Santafé de Las Platas. Municipio de Arboletes, departamento de Antioquia. Informe de Atención de emergencias. 44 p, INGEOMINAS, inédito. Bogotá

Carvajal JH, Mendivelso D (2011) Catálogo de "Volcanes de lodo". Caribe Central Colombiano. Informe en proceso de oficialización en INGEOMINAS. 54 p, INGEOMINAS, inédito. Bogotá

Carvajal JH, Calderón Y (2013) La actividad aruptiva del volcan de lodo El Rodeo al sureste del casco urbano de Cartagena de Indias. Informe de atención técnica. Servicio Geológico Colombiano. 60 p. Bogotá

Cediel F, Shaw R, Cáceres C (2003) Tectonic assembly of the northern Andean block. In: Bartolini C, Buffer RT, Blickwede J (eds) The circum—Gulf of Mexico and the Caribbean: hydrocarbon habitats, basin formation and plate tectonics. AAPG Memoir, vol 79, pp 815–848.l

Correa I, Alcantara-Carrio JJ, González RD (2005) Historical and recent shore erosion along Colombian Caribbean coast. J Coast Res (Proceedings of the 2ª Meeting in Marine Science), 52–57. Valencia. Spain

Duque H (1979) Major structural elements and evolution of Northwestern Colombia. In: Watkins JS, Montadert L, Dickerson PW (eds) Geological and geophysical investigations of continental margins. American Association of Petroleum Geologists Memoir, vol 29, pp 329–351

Duque H (1984) Structural style, diapirism and accretionary episodes of the Sinú-San Jacinto terrains. Southwesten Caribbean borderland. In Bonini WE, Hargraves RB, Sagham R (eds) The South American—Caribbean plate boundary and regional tectonic. Geological Society of America Memoirs vol 162, pp 303–316. Version en español en Boletín Geológico INGEOMINAS vol 27 No. 2, pp 1–29. Bogotá

Flinch JF (2003) Structural evolution of the Sinú lower Magdalena area (Northern Colombia). In: Bartolini CR, Blickwede J (eds) The Gulf of Mexico and Caribbean region: hydrocarbon habitats, basin formation and plate tectonics. AAPG, memoir in press, chapter 35. 22 p and 20 figures

GIO Grupo de Investigaciones en Oceanología (2005) Estudios oceanográficos de los bancos de Salmedina. Caribe Colombiano, 108 p. Escuela Naval Almirante Padilla. Cartagena

Google Earth (2011, 2012 and 2013) Google Earth Images Northwestern Colombian Caribbean region. Downloaded from www.google.com. Google earth

GEOTEC and INGEOMINAS (2000) Cartografía geológica de la región del Sinú – noroeste de Colombia. Planchas escala 1: 100000 (50- 51 - 59 - 60 - 61 – 69- 70- 71- 79 - 80). Volumen 1 _ texto. 160 p. Santafé de Bogotá. Colombia

Guzmán G, Gómez I, Serrano S (2004) Geología de los Cinturones Sinú San Jacinto y borde occidental del valle inferior del Magdalena. Un mapa escala 1: 300 000. INGEOMINAS – Université de Liège. Belgique. Bogotá

Higgins GE, Saunders JB (1974) Mud volcanoes—their nature and origin. Verh Naturforsh. Ges. Basel, pp 101–152

INGEOMINAS-CARDIQUE (1999) Evaluación del potencial ambiental de los recursos suelo, agua, mineral y bosques en el territorio de la Jurisdicción de Cardique. Convenio Interadministrativo Ingeominas - Cardique, Nº 095/98. 132 p. Cartagena

Kellogg J, Toto E, Cerón J (2005) Structure and tectonics of the Sinú – San Jacinto accretionary prism in Northern Colombia. X Congreso Colombiano de Geologia. pp 1–10. Bogotá

Kopf AJ (2002) Significance of mud volcanism. Rev Geophys 40 (2):50, 1005. doi:10.1029/2000RG000093

Link ThA (1927) Post - Tertiary strand-line oscillations in the Caribbean coastal area of Colombia, South America. J Geol 35:58–72

MacGuillivray W (2005) Von Humboldt personal narrative of travels during the years 1799–1804. A condensed narrative of his journeys in the equinoctial regions of America and Asian Russia, together with analysis of his more important investigations. Ann Arbor, Michigan. University of Michigan Library, Michigan.

Mantilla A, Cuadros A (1958) Localización del volcán de la Galera de Zamba. Reconstrucción del perfil costanero y puntos prominentes efectuada con base en el relato, posiciones, rumbos y distancias de la Expedición Fidalgo de 1794. Escala 1:80 000. Instituto Geográfico Agustín Codazzi. Bogotá

Mantilla AMJ, Kley J, Pava C (2009) Configuration of the Caribbean margin: Constraints from 2D seismic reflection data and potencial fields interpretation. In: Lallemand S, Funicielo F (eds) Subduction zones geodynamics. Springer, Berlin, pp 247–271

Martinez JO, Pilkey O, Neal W (1990) Rapid formation of large coastal sand bodies after emplacement of Magdalena River jetties, northern Colombia. Environ Geol Water Sci 16(3):187–194 (Springer, New York)

Martínez I, Yokoyama Y, Gómez A, Delgado A, Matsuzaki H, Rendon E (2010) Late Holocene marine terraces of the Cartagena Region, southern caribbean: the product of neotectonism or a former high stand in sea level? J South Am Earth Sci 29:214–224 (Elsevier)

Ordoñez C (2008) Controle neotectónico de diapirismo de lama na regiao de Cartagena, Colombia. Tesis de maestría presentada a la Universidad Federal Fluminense, Área de Geología y Geofísica Marina. 208 p. Brasil

Ramírez JE (1959) El volcán submarino de Galerazamba. Revista de la Academia Colombiana de Ciencias Exactas y Naturales. vol X, N° 41. Bogotá. Colombia

Reyes GA, Guzmán G, Barbosa G, Zapata G (2001) Geología de las Planchas 23 Cartagena y 29-30 Arjona, Escala 1:100000. Memoria Explicativa INGEOMINAS: 1-69

Shepard F, Dill R, Heezen B (1968) Diapiric intrusions in foreset slope sediments, off Magdalena delta, Colombia. Am Assoc Petrol Geol Bull 32(11):2197–2207

Toto E, Kellogs J (1992) Structure of the Sinú San Jacinto fold belt: an active accretionary prism in northern Colombia. J South Am Earth Sci 5(2):211–222

Vernette G (1985) La plateforme Continentale Caraïbe de Colombie. Importance du diapirisme argileux sur la Morphologie et la Sédimentation 387 p Thèse de doctorat Université Bordeaux. France

Vernette G, Blanc G, Briceño L, Carvajal H, Faugeres C, Gayet J, Gonthier E, Griboulard R, Molina A (1988) Manifestaciones tectónicas en márgenes activas. Comparación entre dos sectores del Caribe – Margen Colombiana y Prisma de Barbados. Memorias VI Seminario de Ciencias y Tecnologías del Mar. pp 240–252. Bogotá. Colombia

Vernette G, Gayet J, Bobier C, Briceño L, Mauffret A, Molina A (1990) El frente de deformación sur – Caribe en la región de Cartagena. Posición y relación con la plataforma. Memorias del VII Seminario de Ciencias y Tecnologías del Mar. Comisión Colombiana de Oceanografía. pp 195–209. Cali

Vernette G, Mauffret A, Bobier C, Briceño L, Gayet J (1992) Mud diapirism, fan sedimentation and strike-slip faulting, Caribbean Colombian Margin. Tectonophysics 335–349

Vinnels J, Butler R, McCaffrey W, Patton D (2010) Depositional processes across the Sinú Accretionary Prism, offshore Colombia. Mar Pet Geol 27:794–809

The Arboletes-Punta Rey Littoral, Southern Caribbean Coast

4

Iván Darío Correa Arango and Juan Felipe Paniagua-Arroyave

Abstract

The Arboletes-Punta Rey littoral is a 5.5-km-long stretch of coast located at the southern Caribbean coast of Colombia, 80 km by car (paved road) to Montería. Geologically, it is located at terrains of the Sinú folded belt, a tectonically active sedimentary wedge evolving under the morphogenetic influence of numerous onshore and offshore manifestations of mud diapirism. It has a tropical climate. During the dry season (December–April), the zone is under the influences of the N–NE Trade winds that generate swells with wave periods between 6 and 9 s and significant wave heights up to 2 m. These waves are strongly modified by the serrated contours of the coastline and are rapidly eroding the beaches and littoral rocky formations of the area. During the wet season, the trade winds are replaced by lighter, 2–4 m/s, S to SW winds that generate seas with significant wave heights of up to 0.6 m. Net sand drift during the year in the area is toward the SW. The Arboletes-Punta Rey landscape is configured by an emerged marine terrace, a diapiric dome with active mud volcanoes, and by cliffs and their associated erosional features including caves, arches, stacks, and scarps of mass movements. These features are cut on sedimentary, highly weathered and densely fractured mudstones and shales, and in poorly consolidated diapiric muds. Besides its geomorphological interest, the Arboletes littoral is an interesting example of historical, kilometric-magnitude erosional coastline changes driven by the combination of natural- and man-induced causes including, in a short-term perspective, the poor geotechnical properties of rocks, bioerosion, absence of rainfall and waste waters management, strong wave action, beach sand mining, and inadequate coastal engineering practices.

Keywords

Coastal erosion • Mud diapirism • Caribbean coast

I.D. Correa Arango (✉) · J.F. Paniagua-Arroyave
Área de Ciencias del Mar, Departamento de Ciencias de la Tierra,
Universidad EAFIT, Medellín, Antioquia, Colombia
e-mail: icorrea@eafit.edu.co

J.F. Paniagua-Arroyave
Geomorphology Laboratory, Department of Geological Sciences,
University of Florida, Gainesville, Florida, United States
e-mail: jf.paniagua@ufl.edu

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_4

4.1 Introduction

The "sea of the seven colors" is a sentence used in the popular tradition and in tourism advertising campaigns to describe the beautiful seawaters of the southern Caribbean of Colombia. It was probably true for the Spanish conquerors of the sixteenth century, but the condition of crystalline waters, reflecting in many places of the colored coralline reefs and uncovered sedimentary rocks of sea bottom, has progressively deteriorated due to increasing human occupation that has led to multiplication of soil erosion rates of the Andes and the high sediment supplies to the sea by the southern Caribbean rivers. Consequently, oceanic turbidity values rose, and sea waters were further muddled by the ongoing erosion of the coastal relief as pre-existent protecting beaches have progressively disappeared in most of the Southern Caribbean.

Despite this undesirable evolution and condition, the southern Caribbean Coast of Colombia remains a mosaic of landscapes of outstanding interest, both because of its varied origins and combination of coastal features and the high rates of morphological changes. One of the most noticeable areas in this respect is the Arboletes-Punta Rey littoral (APR) located between the city of Arboletes (Lat 8° 51′ N, Long 76° 26′ W) and Punta Rey (also named as Punta Arboletes) (Lat 8° 53′ 29″ N; Long 76° 29′ 41″) (Fig. 4.1). This stretch of coast deserves particular interest for several reasons. First, it illustrates very well the typical landscapes of a tropical, microtidal, tectonic littoral characterized by emerged marine terraces, and sedimentary cliffs with their entire suite of associated erosional features, including notches, arches, caves, stacks, shore platforms, and several types of mass movements. Second, its historical evolution, traced back from the end of the eighteenth century to present, shows noticeable morphological changes resulting from strong erosional trends that caused shoreline displacement up to 1.5 km in the most critical area. Third, shoreline changes in the area have been driven by both natural and anthropic factors, in a context characterized by the practically total absence of a medium to long-term coastal management framework.

4.2 Physical Context of the Arboletes-Punta Rey Littoral

The climate of the southern Caribbean of Colombia depends on the annual displacements of the low-pressure Intertropical Convergence Zone (ITCZ) whose position controls the occurrence of rainfall and defines the dry and wet seasons within the equatorial latitudes (Andrade and Barton 2000; Andrade 2003). Mean annual temperature in the area is of 28 °C, with monthly deviations less than 2 °C. Humidity values vary between 80 and 90 %. Mean annual rainfalls for the southern Caribbean of Colombia are ca. 40 mm/month in the Arboletes area.

During the dry season, the Trade Winds from the N and NE predominate with velocities between 4 and 9 m/s. They generate long swells with wave periods of 6–9 s and mean significant wave heights of up to 2 m, which are scattered by the gentle platform and coastal projections to the sea of the serrated littoral of the southern Caribbean Coast. Breakers from the Trade Wind swells produce strong shore currents toward the SW that are evidenced by the displacement of the turbid sediment plumes in this direction and also by sand drift in the same direction, which seems to be the direction of the net sand drift during the year. During the rainy season (March–November), the Trade Winds are replaced by lighter, variable winds coming from the S and SW with mean velocities of 2 m/s and maximum velocities of 4 m/s (Molina et al. 1992; Andrade 2003).

The current Arboletes-Punta Rey coastline extends by 5.5 km with a general NE–N trend, from the city of Arboletes to the present Punta Rey area. Due to the emplacement

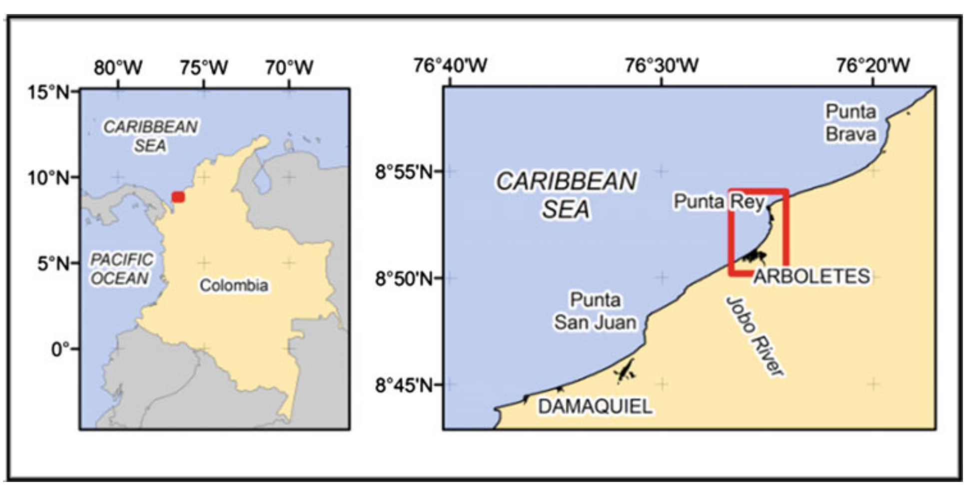


Fig. 4.1 Location of the Arboletes-Punta Rey littoral

of rocky material as a defense against shore erosion, this sector is currently a relatively resistant area that marks an abrupt coastline turn to the NEE in direction to Punta Brava, and the next hard rocky point located 14 km to the NE (Figs. 4.1 and 4.2). Before the generalized shore erosion trend started, until 1938, the coastline contour between Punta Rey and Arboletes was defined by wide beaches and its plain contour was that of a logarithmic spiral (Z-bay form) with its tale toward the southwest. This configuration is common along coastlines primarily influenced by the patterns of wave diffraction and refraction (Hsu et al. 1987). The gradual disappearance of the Punta Rey peninsula totally modified this initial condition by allowing waves to arrive directly to the shore, and hence smooth the initial Z-bay configuration to the NE–N alignment (Fig. 4.2).

The Arboletes-Punta Rey littoral zone is located on terrains of the Sinú fold belt, a sedimentary prism of Oligocene to Pliocene rocks accreted to northern South America under the tectonic interactions between the Nazca, Caribbean, and South American plates (Duque 1979, 1984; Toto and Kellogg 1992, see Carvajal, Chap. 3). Structurally, the Sinu belt is characterized by wide synclines and narrow anticlines associated with inverse faults, and also by numerous offshore and onshore diapiric structures evidenced on sea

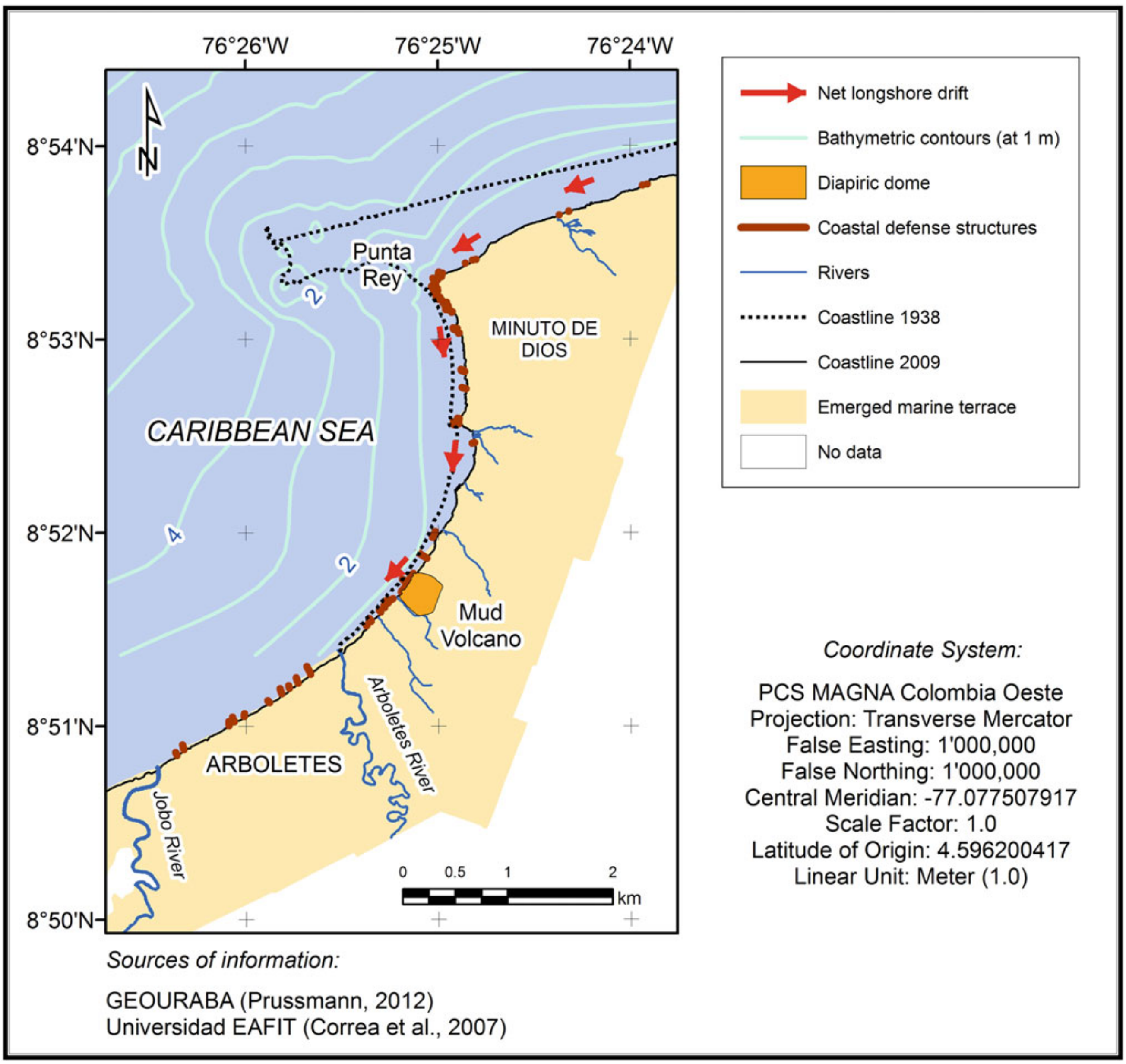


Fig. 4.2 Geomorphological sketch of the Arboletes-Punta Rey littoral

bottom and inland areas by kilometric to minor-size domes, often with extrusive mud volcanoes and mud flows related to faults and fracture zones (Ramírez 1976; Vernette 1985; Vernette et al. 1992). In the APR littoral fringe, the surface is covered by soils and the rocky basement crops out only along active sea cliffs and in some deep ravines draining toward the sea. Rocks in the area are typically consolidated, highly weathered, and fragmented mudstones and shales, with minor intercalations of conglomerates and conglomeratic sandstone lenses. The area has several mud volcanoes and extrusive mud centers well identified in geographical sketches dating from the beginnings of the twentieth century (Ramírez 1976).

The geomorphological framework is that of a gently sloping, NW–N tilted emerged terrace (the Arboletes terrace) that extends from the Jobo river mouth (3 km south of Arboletes) to Punta Rey, and for about 5.5 km to the E where it finds the hilly coastal relief and marks the position of an ancient coastline more than 20 m above the present sea level (Figs. 4.2 and 4.3). This terraced surface, 1 m high in Punta Rey and 8 m high in Arboletes, was cut by waves in the already mentioned basement rocks, and it is in some places covered by up to 1.5 m of Holocene shallow marine and fluvial sediments. The Arboletes terrace is one of the several emerged marine features (beach ridges, stacks, and corals), which attain maximum elevation of 36 m and are typical of the southern Caribbean Coast of Colombia, providing thereby evidence of active tectonic deformation of the area. Subtracting the elevations of these features to a hydro-isostatic factor of 3.5 m (as suggested by Clark and Bloom 1979), Page (1982) proposed a middle to late Holocene regional upwarping trend between the gulfs of Urabá and Morrosquillo, with associated tectonic uplift between 10 and 30 m, at a rate of 2–6 mm/yr.

Bathymetric profiles in front of the APR coastline show an erosional, gently sloping platform that reaches 4 m depth around 2.5 km offshore (Fig. 4.2). The northern zone near Punta Arboletes is a shallow, submarine E–W oriented salient, evidencing the submarine basement of the eroded Punta Rey Peninsula, with a shallower zone emerging at Isla Rey, a hard limestone erosional remnant. In the south of Punta Arboletes, shelf profiles show a more or less regular and concave configuration corresponding to an erosional shore platform capped by thin deposits of muds.

Because the strong erosional trend suffered by the Arboletes-Punta Rey littoral during the last decades, most of its beaches existing prior to 1938 are now absent and the current coastline is mainly marked by cliffs with minor sandy veneers exposed only during low tides. Present beaches in front of Arboletes and in some localized areas to the north are all fixed by groins that retain sand and wooden trunks in the upward sand drift direction.

Cliff profiles in the Arboletes-Punta Rey zone vary between vertical scarps of 1 and 6 m high in the more resistant or recently exposed zones to 35°–40° sloping irregular surfaces resulting from the occurrence of mud flows, debris flows, and rotational slumps from the medium and higher levels of the Arboletes terrace. Where sub-vertically dipping and more consolidated strata intercalate with less resistant strata, shore platforms, stacks, and arches are common. Along the zones subjected to stronger wave attack, cliff retreat concurs with the formation of long tunnels and caves (up to 10 m long) that penetrate the terrace basement and induce the collapse of its surface, resulting in the formation of semicircular small embayments rapidly widening by the collapse of its borders. The net result of these processes is the configuration of a highly irregular, crenulated coastline, later regularized in lapses of 3–4 years or even faster (Figs. 4.2 and 4.3).

Mass movements in the APR littoral and adjacent sectors of the southern Caribbean of Colombia often occur during the 5–20 transitional days between the dry and wet seasons. Rainfall waters percolate through the desiccated soils, and the densely fractured mudstone saturates the external borders of the terrace and promotes sliding by lubricating its fractured zones (González and Guarín 2003). This condition was promoted during the human occupation by several activities and/or omissions, including deforestation of the original forest (replacement with pasture for cattle or by palm crops) and the digging of water reservoirs and permeable drainage handmade channels and septic tanks. The regular transit of cattle along well-defined paths is also an important cause of soil cracking in the APR zone. Percolation of waters in soil and rocks is further facilitated in some places by bioturbation features and animal holes including crabs (Fig. 4.3).

The Arboletes mud volcano is the most important touristic attraction of the area, offering the daily way of life for numerous people of the region as employment in activities like transportation, restaurants, and even body massages, proverbially considered as very effective skin cleaners and beauty products (Figs. 4.2 and 4.4). The volcano is located on the top of a roughly circular diapiric dome with a basal diameter of about 350 m and a height above present sea level of approximately 25 m. Currently, the dome has five small craters of 2–3 m in diameter located in its southern flank, the main crater placed in its top, with 30 m height. This crater is a 30-m-wide circular depression that originally had a diameter no greater than 5 m according to the testimonies of inhabitants. Most of the time, 1- to 2-m-diameter gas bubbles are expelled around the center of the crater whose superior mud level is artificially controlled by drainage channels in the seaward direction.

Fig. 4.3 Geomorphological features of the Arboletes-Punta Rey terrace and coastline. **a** Aerial view of Punta Rey, view to the south; photo by Aeroestudios, 2009. **b** Punta Rey′s northern groin; up right Isla Rey. **c** Aerial view of El Minuto de Dios, view to the east; note the irregular, erosional coastline contours; photo by Aeroestudios, 2009. **d** Cliffed coastline and associated erosional features south of El Minuto de Dios; photo by I. D. Correa Arango, 2012. **e** Aerial view of Arboletes, view to the East; photo by Aeroestudios, 2009. **f** Erosional features of Arboletes urban shore; view to the north. Photo by I. D. Correa Arango, 2006

There are no reports dealing with explosive eruptions in the Arboletes's mud volcano or in the other minor nearby volcanoes. According to inhabitant's testimonies, the volcano had, in the last five decades, at least six episodes (2–4 days of duration) of continuous, "out of normal" volumes of mud extrusions that were also noted at sea by gas bubbles in the near offshore zone. These eruptions formed new minor craters and spread out important volumes of lukewarm mud in direction of the sea and on the Punta Rey-Arboletes road. The last of these episodes of activity occurred in August 5, 2008 (Fig. 4.4).

The conditions of slow, tranquil mud extrusion and spreading are not valid for some other mud volcanoes of the southern Caribbean coast of Colombia as evidenced by the Damaquiel and of "Cacahual" volcanoes. The Damaquiel mud volcano locates 25 km southwest of Arboletes and 200 m offshore the Damaquiel village; its present morphological expression is that of a shallow and low tide emerged platform remnant of 4–8-m-high cones formed during violent episodes of mud extrusion, the last in 2007. The "Cacahual" volcano, near the village of San Pedro de Urabá (Lat 8° 17″ N; Long 76° 23″ W), is probably the most violent eruption reported for the Caribbean of Colombia (Fig. 4.4). It was an explosive event occurred immediately after the earthquake on October 18, 1992 and extruded a mud volume estimated in 50,000 m^3 (Martinez 1994; Correa 2005). Seven persons were killed by this paroxysmal event.

4.3 The Historical APR Coastline Evolution

The historical evolution of the APR coastline can be traced back to the end of the eighteenth century when the first reliable cartography for the Caribbean of Colombia offers the start point for subsequent comparisons (Fig. 4.5). Brigadier Fidalgo's chart clearly maps the already mentioned Punta Rey peninsula, a low coastal salient of 1.5 km length and 200 m wide that continued the coastline contour to the west and had its distal point at Isla Rey, a resistant limestone outcrop 5 m diameter and 3 m height that remains visible today.

Fig. 4.4 Arboletes mud volcano. **a** Aerial view to the east; note the 30-m-wide main crater and the extrusion center to the south, coastline marked by mud slumps and mud flows. Photo by Aeroestudios, 2009. **b** Main crater, view to the west. Photo by I. D. Correa Arango, 2012. **c** Fluid mud been extruded just at the side of the showers for swimmers during the last eruption of the volcano. Photo by I. D. Correa Arango, 2008. **d** New cabins for tourist built up in 2009 on the southern flank of the dome, 30 m from the main crater. Photo by I. D. Correa Arango, 2008. **e** The Cacahual mud volcano after the explosive event of October 18, 1992; Courtesy of Andrés Velásquez. **f** Damaquiel shoal at the base of eroded mud volcano; low tide. Photo by R. A. Morton, 2002

Comparison of this chart with the Instituto Geográfico Agustín Codazzi—IGAC–aerial photographs taken in 1938 and 1953 evidences no appreciable changes in the area, but more recent photographs (1959,1962, 1974, 1984, 1994, and 2005) well illustrate the sequence of coastline retreat and associated land losses in the APR littoral (Fig. 4.5). This severe, 12 years process, reflects in part the westward advance of a natural shore retreat trend affecting the coastline southwest of Punta Brava, but it was also favored by sand and rock mining and, probably more important, by a cross channel cut by Punta Rey's fishermen in order to shorten the way to the "open waters" north of Punta Arboletes. (González and Guarín 2003; González 2007; Correa et al. 2007).

The erosion of Punta Rey peninsula was followed by the generalized losses of beaches to the south and the consequent practically total deprotection of the essentially non-eroding previous coastal slopes rarely hit by waves in the 1970s. Net result of this situation was the definition of the border of active cliffs all along the Arboletes terrace and volcano coastlines and, since 1975, the chaotic building up of more than 37 groins that for its most part did not retain enough sand for beach formation but instead accelerated greatly the natural erosion rates by conforming new, secondary Z-bay forms whose southward tales were configured in the terraces and mud volcano borders (Fig. 4.5). Given the poor geotechnical properties of the Arboletes mudstones and the adverse effects of the majority of the groins built up, coastal retreat proceeded at high rates and reaches magnitudes up to 60 m in the Arboletes urban sector, where the entire beaches and the first line of infrastructure of residential homes and restaurants were lost.

4.4 Concluding Remarks

Coast retreat along the APR littoral reflects in the very bottom generalized deficit of sands, also common in numerous sectors of the Southern Caribbean of Colombia. This deficit is at the origin of the drastic coastline changes and land loses that

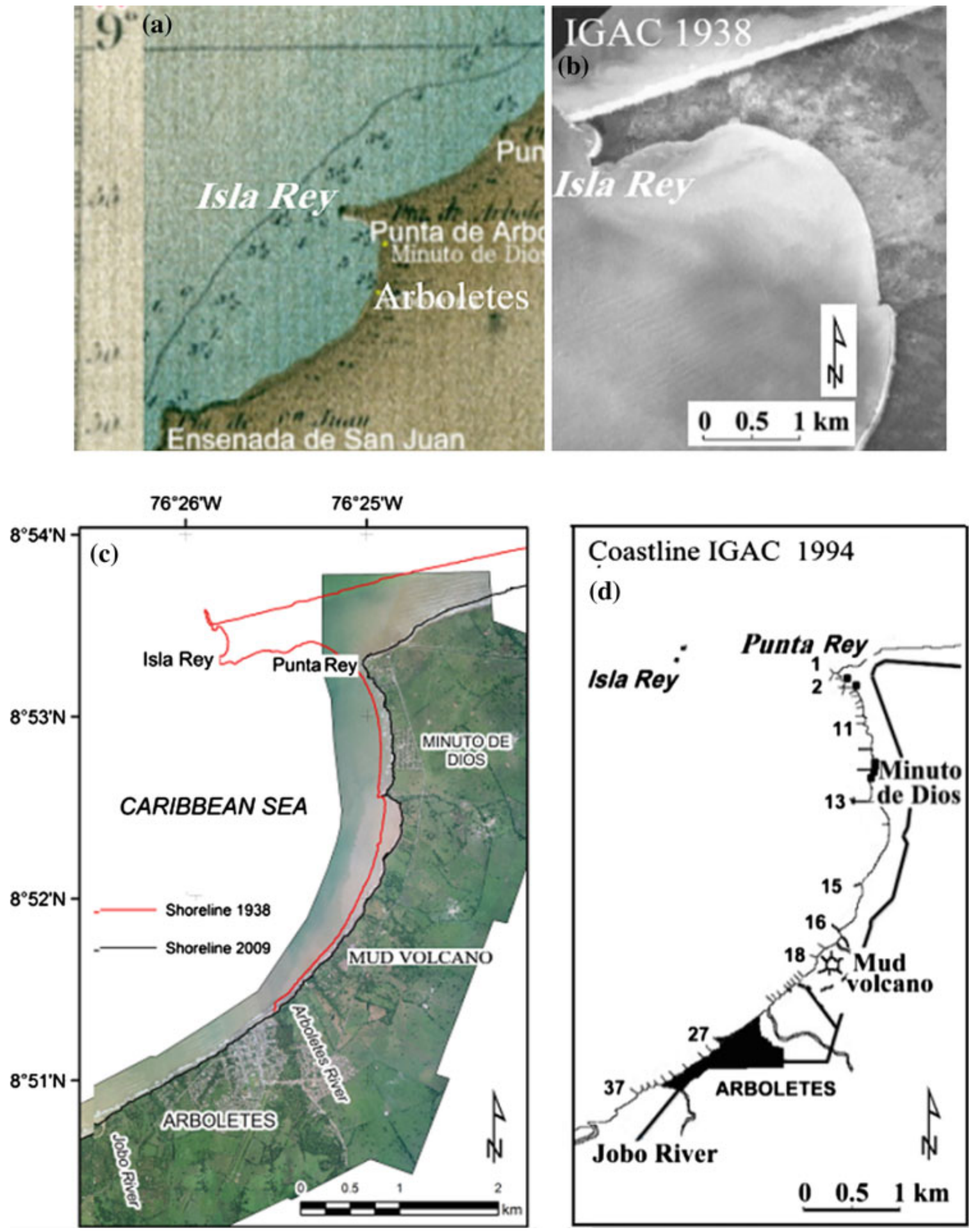


Fig. 4.5 Historical evolution of the Arboletes-Punta Rey littoral. **a** Spanish chart by Brigadier Fidalgo showing the Punta Rey peninsula and the position of Isla Rey, beginnings of nineteenth century. From Atlas de Mapas Antiguos de Colombia. **b** The Isla Rey peninsula, aerial photography by Instituto Geográfico Agustín Codazzi (IGAC), 1938. **c** Coastline changes in the Arboletes-Punta Rey littoral between 1938 and 2009; note the total disappearance of Punta Rey peninsula and the strong erosional trend affecting the northeast of the area, to Punta Brava, 12 km to the northeast – see Fig. 4.1 for location of this place. **d** The Arboletes-Punta Rey coastline in 1994 and location of up to 37 groins built to date. Note the deep erosional embayment caused by groin no. 13; groin no. 27 greatly accelerated beach and cliff erosion to the south of Arboletes (see Fig. 4.3f). From Correa and Vernette, 2004

in historical times have affected severely the physical infrastructure of practically all the villages and small cities of the Southern Caribbean of Colombia, Arboletes being just one of numerous cases meriting detailed and integral studies. In order to get coastal management criteria, some preliminary exercises have been made to predict the future coastline positions in the area, considering the predicted sea level rise scenarios associated to Global Change and supposing that no new engineering defenses will be constructed for facing shore retreat in the area. One of these exercises used the SCAPE simplified equation of Walkden and Dickson (2008) based on the historical coastline retreat rates for the period of 1938–2009. For a more probable global sea level rise rate variation from 2.32 to 8.33 mm/year, results predict that the active erosional trend will continue and would cause a cliff line retreat up to 155 m for the year 2059, associated retreat rates being of ~3.10 m/year (Fig. 4.6) (Paniagua-Arroyave 2013). Results show also some other interesting points to the future, for example, ~20,000 m^3 of muddy sediments would be released to the sea from the forecasted cliff erosion, further contributing to its already turbid nature and diminishing the landscape quality, one of the conditions most appreciated in the standards for global tourism activities (Rangel et al. 2013). Mudstones erosion will not provide sands and gravels

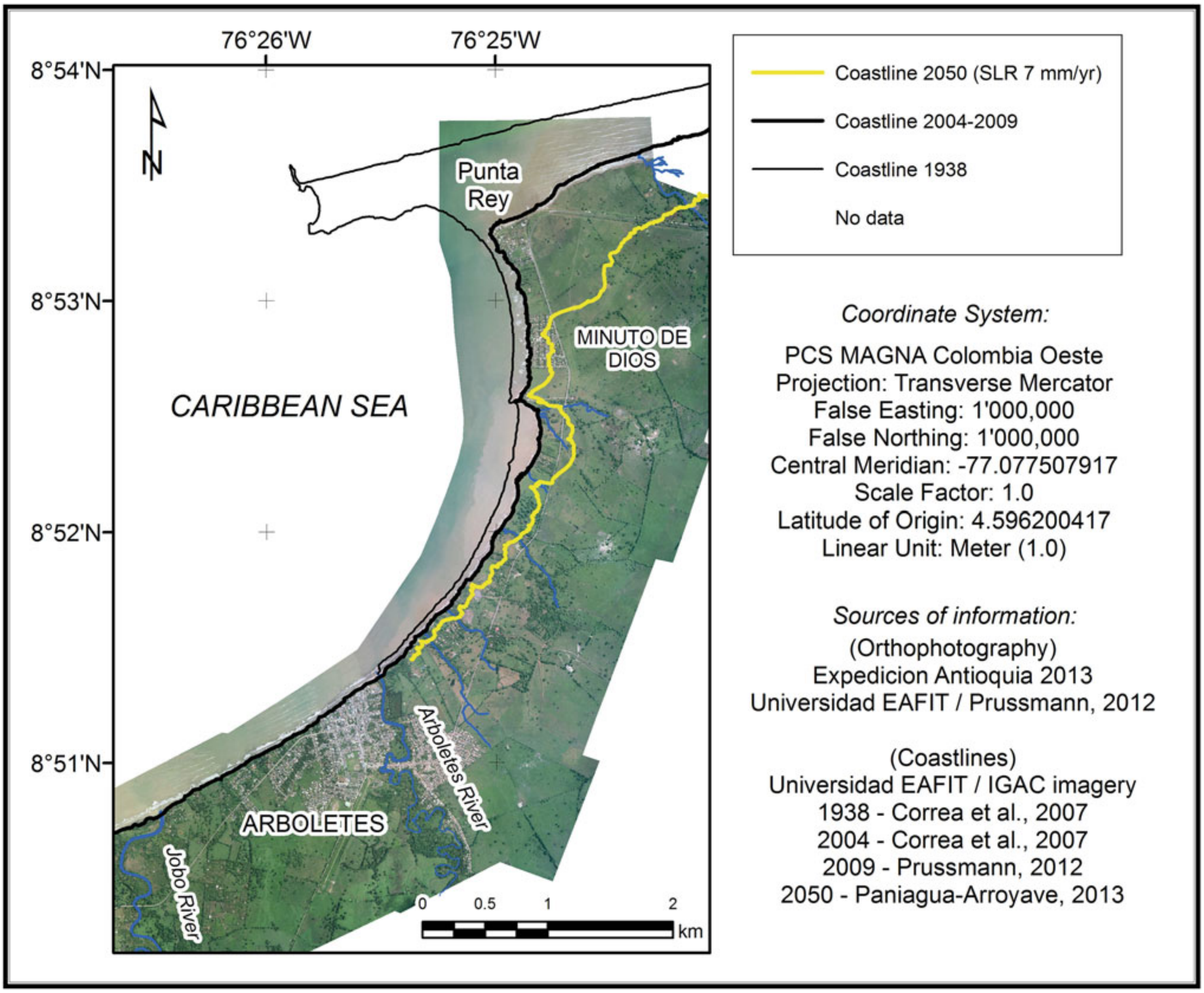


Fig. 4.6 Projected position for the Arboletes-Punta Rey coastline to the year 2050 using the SCAPE equation. From Paniagua-Arroyave 2013

to the APR littoral, so these future supplies of sediments would not be a significant source for beach material.

The APR littoral is only one of several zones that had been historically affected by strong erosional trends, beaches, and cliffs lines, recession been the rule along the most length of the southern Caribbean Coast of Colombia where there is a net deficit of sandy sediments. Detailed assessing of risks associated to mud diapirism is still absent in this and the other affected areas of the Caribbean of Colombia. In such unstable geological and geomorphological frameworks, it is obvious that major future coastal morphological changes will occur and that a complete panorama of coastal management options should be considered in order to preserve the qualities and development opportunities offered by its landscapes.

References

Andrade CA (2003) Análisis del nivel del mar en la zona costera colombiana. In: Invemar (Santa Marta, Colombia) Definición de la vulnerabilidad de los sistemas biogeofísicos y socioeconómicos debido a un cambio en el nivel del mar en la zona costera colombiana (Caribe, Insular y Pacífico) y medidas para su adaptación. Informe técnico No. 4, 125p

Andrade CA, Barton EC (2000) Eddy development and motion in the Caribbean Sea. J Geophys Res 15(11):26191–26201

Atlas de Mapas Antiguos de Colombia (1992) Siglos XVI a XIX (segunda edición). Editorial Arco, Bogota 187p

Carvajal JH, Geomorphological features of Mud Diapirism. The Central Caribbean Coast, Chapter 3. p 1–23

Correa ID (2006) El litoral antioqueño. In: Hermelin M (ed) Geografía de Antioquia. Fondo Editorial Universidad Eafit, Academia Colombiana de Ciencias Exactas, Físicas y Naturales—capítulo de Antioquia, pp 137–150

Correa ID, Vernette G (2004) Introducción al Problema de la Erosión Litoral en Urabá (Sector Arboletes—Turbo) Costa Caribe Colombiana. Bolet Invest Mar Cost Invemar 33:5–26

Correa ID, Alcántara–Carrió J, González RD (2005) Historial and recent shore erosion along Colombian Caribbean coast. Journal of Coastal Research In: Proceedings of the 2nd Meeting in Marine Science, Valencia, Spain, P 52–57

Correa ID, Acosta S, Bedoya G (2007) Análisis de las causas y monitoreo de la erosión litoral en el Departamento de Córdoba. Convenio de Transferencia Horizontal de Ciencia y Tecnología No. 30 Corporación Autónoma de los Valles del Sinú y San Jorge—CVS–Universidad Eafit, Departamento de Geología (Área de Ciencias del Mar. Fondo Editorial Universidad Eafit, 128 p

Clark JA, Bloom AL (1979) Hydroisostasy and Holocene emergence of South America. In: Suguio K, Fairchild TR, Martin L, Flexor JM (eds) Proceedings of the international symposium on coastal evolution in the quaternary, The Brazilian National Working Group for the IGCP Project 61, pp 41–60

Duque H (1979) Major structural elements and evolution of Northwestern Colombia. In: Watkins JS, Montadert L, Dickerson PW (eds) Geological and geophysical investigations of continental margins. Am Assoc Petr Geol Mem 29:329–351

Duque H (1984) Structural style, diapirism and accretionary episodes of the Sinú—San Jacinto terrane. Southwestern Caribbean borderland. In: Bonini WE, Hargraves R B, Sagham R (eds) The South American—Caribbean plate boundary and regional tectonic. Geol Soc Amer Mem 162:303—316 (Version en español en Boletín Geológico INGEOMINAS Vol. 27 No. 2. Bogota. p. 1–29)

González DA (2007) Erosión litoral en el Sur del Departamento de Córdoba (Minuto de Dios—Santander de la Cruz): magnitudes, factores y estrategias de control y mitigación. MSc thesis in Ciencias de la Tierra, Departamento de Geología Universidad Eafit Medellin. 87 p

González DA, Guarín T, Johan F (2003) Evolución geomorfológica de los acantilados entre Arboletes (Antioquia) y la desembocadura del Río Córdoba (Córdoba). Geology Thesis, Departamento de Geología Universidad Eafit, Medellín. 998 p

Hsu JRC, Silvester R, Xia YM (1987) New characteristics of equilibrium shaped bays. Proceedings of the 8th International Conference on Coastal Engineering, ASCE, p 140–144

Martínez JM (1994) Los sismos del Atrato medio 17 y 18 de octubre de 1992 Noroccidente de Colombia. Rev Ingeominas 4:35–70

Molina A, Chevillot Ph (1992) La percepción remota aplicada para determinar la circulación de las aguas superficiales del Golfo de Urabá y las variaciones de su línea de costa. Boletín Científico CIOH 11:43–58

Page WD (1982) Holocene deformation of the Caribbean Coast Northwestern Colombia. Woodward and Clyde Consultants, San Francisco 25 p

Paniagua-Arroyave JF (2013) Migración histórica actualizada y predicción de la posición de la línea de costa en sectores acantilados críticos del litoral antioqueño considerando escenarios de ascenso del nivel del mar. MSc thesis in Ciencias de la Tierra, Departamento de Geología, Universidad Eafit, Medellín. 88 p

Prussmann J (2012) Nuevos elementos para el Manejo Integrado de la Región de Urabá, Costa caribe Colombiana. Base de datos espacial geomorfológica de la Franja Litoral de los Departamentos de Antioquia y Chocó. MSc Tesis in Ciencias de la Tierra, Departamento de Geología, Universidad Eafit, Medellín. 91p

Ramírez JE (1976) Los diapiros del Mar Caribe colombiano. Memorias Primer Congreso Colombiano de Geología, Separata 39 pp

Rangel BN, Correa ID, Anfuso G, Ergin A, Williams AT (2013) Assessing and managing scenery of the Caribbean Coast of Colombia. Tour Manag 35:41–58

Thomas YF, García VC, Cesaraccio M, Rojas X (2007) El Paisaje en el Golfo. In: Garcia-Valencia C (ed) Atlas del Golfo de Urabá, una mirada al Caribe de Antioquia y Choco. Instituto de Investigaciones Marinas y Costeras Invemar y Gobernación de Antioquia, Santa Marta, Colombia, pp 75–127

Toto E, Kellogs J (1992) Structure of the Sinú San Jacinto fold belt—An active acretionary prism in northern Colombia. J S Am Earth Sci 5(2):211–222

Vernette G (1985) La plateforme Continentale Caraïbe de Colombie. Importance du diapirisme argeliaux Sur la Morphologie et la Sedimentation. These de doctorat Université Bordeaux. Francia. 387

Vernette G, Mauffret A, Bobier C, Briceño L and Gayet J (1992) Mud diapirism, fan sedimentation and strike- slip faulting, Caribbean Colombian Margin. Tectonophysics. p 335–349

Walkden M, Dickson M (2008) Equilibrium erosion of soft rock shores with a shallow or absent beach under increased sea leve rise. Mar Geol 251:75–84

La Playa Badlands and Their Earth Pillars

5

Michel Hermelin

Abstract

A badland terrain cut in the landscape near the town of La Playa has been known since the Spanish conquest and has inspired many Colombian poets. It consists of earth pillars of unknown age cut in arkosic coarse-grained sand containing cobbles which may reach heights of 30 m. The sediments originate from weathered metamorphic rocks belonging to the Silgara Formation and igneous Jurassic rocks, which were eroded and deposited as a broad valley fill, making the Algodonal Formation. The present climate is probably too humid to permit such erosional landforms to develop, and the present badland development is probably arrested. It would be important to monitor the evolution of the “estoraques” in order to design the best management for their preservation. This Unique Natural Area is protected by the National Park Administration and it can be easily reached by car from the city of Ocaña, Norte de Santander.

Keywords

Surface erosion • Earth pillars

5.1 Introduction

Situated in the northern Eastern Cordillera, some 20 km from the historical city of Ocaña, the *Estoraques* Unique Natural Area displays a spectacular badland landscape, which attracts many tourists. It can be reached in 20 min by car from Ocaña or from Cúcuta (5 h); these two cities are connected to the country by air and paved roads (Fig. 5.1). The village of La Playa, from which the Estoraques Area can be reached in a 10-min walk, is located in the western slope of the northernmost part of the Eastern Cordillera. It is drained by the Algodonal River, a tributary of the Catatumbo river which flows northward and ends in the Maracaibo Lake, in Venezuela.

Estoraque in Spanish is the name of a tree (storax: *Liquidambar orientalis*, commonly called oriental sweetgum or Turkish sweetgum), which may have inspired the regional designation for earth pillars in eastern Colombia. The term badlands is used although these types of landforms are generally associated with a much drier kind of climate: the fact that they are covered by vegetation indicates that they are probably formed under climatic conditions much harsher than the present one, as human influence must be discarded.

5.2 Historical Background

The first Europeans to reach the region in 1531 were Spanish soldiers belonging to the Alfinger expedition, which started in Coro (Venezuela) and disappeared after the burial of the

M. Hermelin (✉)
Grupo de Geología Ambiental y de Ingeniería Sísmica,
Universidad EAFIT, Medellín, Colombia
e-mail: hermelin@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_5

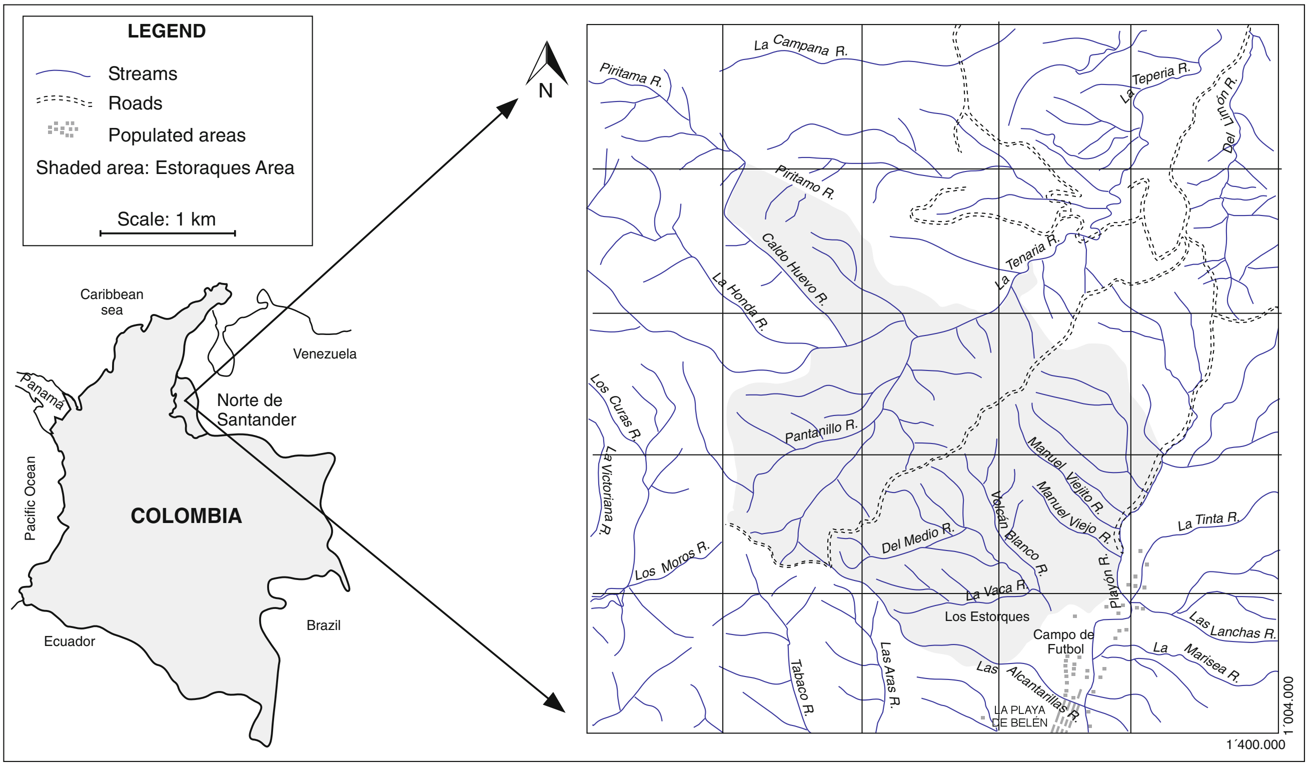


Fig. 5.1 Location of the Estoraques area

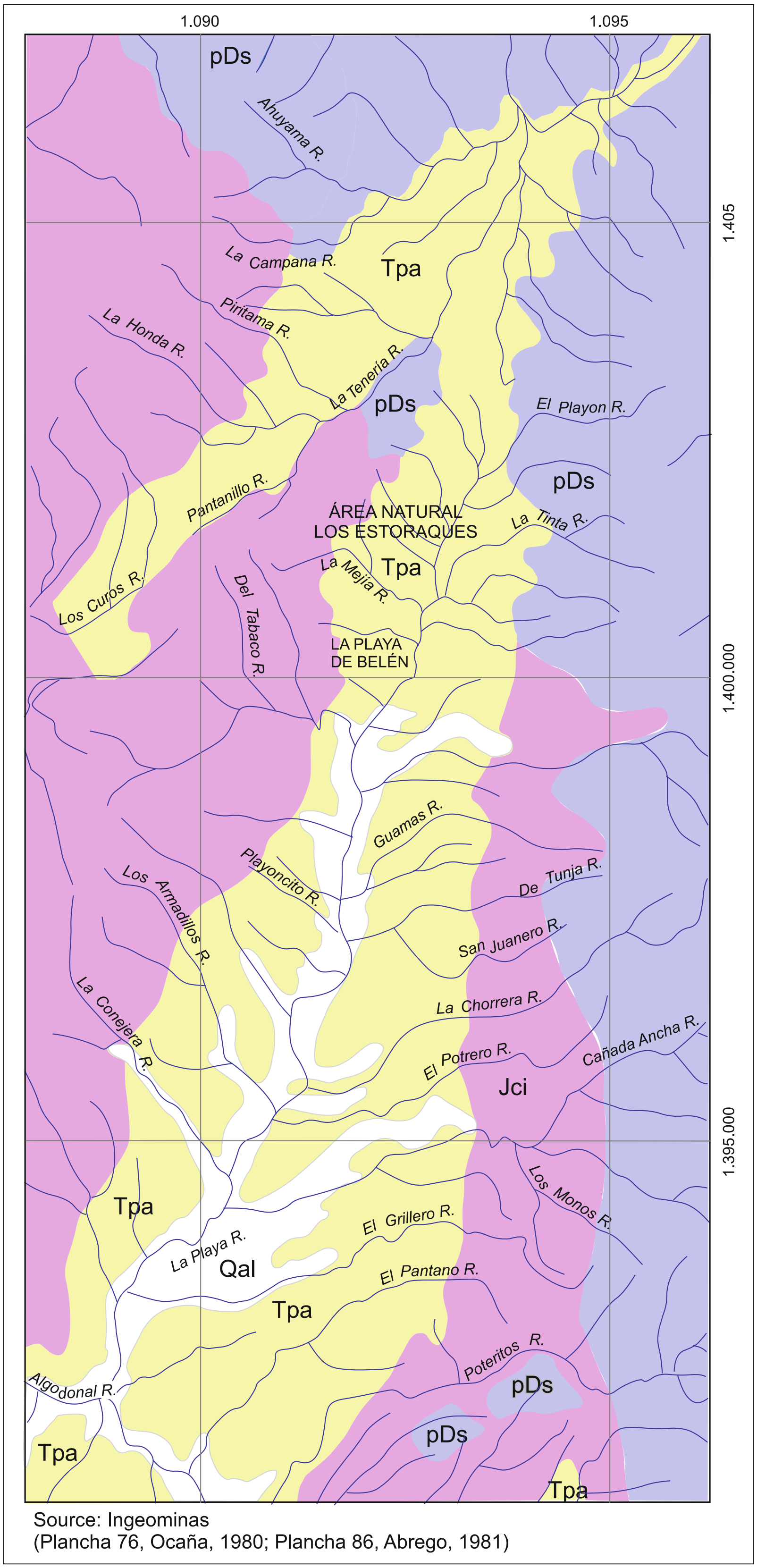
treasure they had stolen from the Indians. In his travel diary written in 1851 during his participation in the Chorographic Commission, the first Colombian intent to map the entire country, Ancízar (1984) mentions “hills and small denudation valleys dissected by ruinous ravines which are cut every time rain waters hurl through these unstable trenches” in the area.

The nearby village of La Playa de Belén was founded in 1857 and its population increase made it a municipality in 1930. The first registered visit to the area by geologists was in 1946 (Botero and Sarmiento 1947). They described the deposits in which the *estoraques* (earth pillars) were carved as continental sediments (Algodonal Formation), which were given a Pliocene age after a dubious identification of vegetal remnants made by Royo and Gómez (1947).

El Espectador, a Bogotá newspaper, was published in its Sunday Magazine (1959), a colorful description of the *Estoraques*. Their unusual shape also inspired a well-known regional writer, Lamus (1963), who published a collection of poems entitled “Los Estoraques,” which contributed to the dissemination of the word in Colombia.

In 1976, *INDERENA*, at that time the national environmental authority before the creation of the Ministry, hired Phyllis Louise Reed, an American forestry engineer, in order to prepare a preliminary plan for the “Unique Natural Area Los Estoraques.” Ms. Reed is still remembered by the oldest people of the region, where she remained for about three years. Meanwhile, *INGEOMINAS* (the National Geological Survey) carried out mapping projects and published several reports and maps about regional geology (Arias and Vargas 1978; Daconte and Salinas 1980; Ingeominas 1980; Guzman 1981), from the School of Engineering of the Universidad Francisco de Santander, Cúcuta, and produced a report on the physical properties of the materials from which *estoraques* are derived. *INDERENA* (1985) prepared a diagnostic for the declaration of the area as a natural park, which was approved by the Ministry of Agriculture (1988) and covers an area of 6.4 km^2.

Aparicio and Rojas (2002) made a detailed study of the area from the geomorphological standpoint including different units and classifications based on their susceptibility to erosion. They proposed that the area should be classified as a unique protected area for its geomorphologic interest. The operating plan of the area by Suarez et al. (2009) is the most recent document available at the National Park Library in Bogotá.



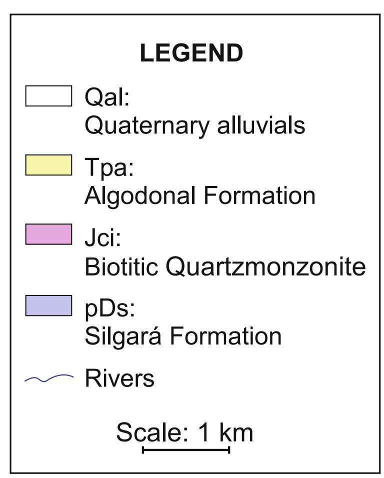


Fig. 5.2 Geological map of the area

Fig. 5.3 The dissected Algodonal Formation with slightly inclined slopes toward the axis of the Quebrada El Playón. Hills in the horizon are built of pre-Devonian metamorphic rocks of the Silgara Formation. *Photography* Michel Hermelin

5.3 Geology

The village of La Playa de Belen, located in a narrow alluvial plain, can be reached from Ocaña or Cúcuta, following the Algodonal River until reaching the locality of Chapinero-Guayabal and then its tributary *Quebrada El Playón* for 4 km. Altitudes of the region are from 1450 to 1700 m a.s.l., which mean a pleasant temperature all year round (about 20 °C); annual rainfall is about 900 mm with a maximum humidity in April–May and October–November. The Playón River has four small tributaries, in which one of them was intermittent (Reed 1976). The area was originally covered by premontane dry forest, following Holdridge's life-zone classification. It has been replaced, in relatively flat areas, by crops, particularly onions, and most of the area has been deprived of its original vegetation.

The area consists basically of an alluviated valley cut in older fluvial deposits surrounded by convex hillslopes which reach about 1700 m.a.s.l. (Fig. 5.2). The oldest component of local geology is the Silgara Formation (PDS), which is a sequence of metamorphic rocks derived from clastic protolith, containing slates, phyllites, impure metalimonites, metagraywackes, and cobbly metagraywackes with less quantities of calcareous slates and phyllites (Aparicio and Rojas 2003). Stratification is typically thin and cyclic. In this area, this geologic formation is mainly represented by phyllites and schists, with intercalations of metarenites, quartzites, and metalimonites. Its age is considered as pre-Middle Devonian, and it has been correlated with the Güejar and Quetame Groups in the Oriental Cordillera and the Perijá Series in the Sierra de Perijá (Aparicio and Rojas 2002).

Mesozoic is represented by igneous rocks (Jci). In this area, quartz-monzonitic intrusive phases and a series of rocks produced by ryolithic volcanism are predominant. A separation of different igneous rocks proved to be unfeasible, due to their close relations. The intrusive rocks present a great textural variation, and their composition varies between granite and quartz monzonite, containing white, pink, and greenish feldspars, quartz, and some biotite and chlorite. The rock is crossed by siliceous to mafic dykes, irregularly distributed, and of variable thickness. Rhyolites show different colors and have a low mica content. Mafic

Fig. 5.4 Estoraques (*Earth pillars*). Lichen (*lower right*) and tree growth may indicate that the erosion process has stopped. *Photography* Michel Hermelin

dykes, diabases, and basalts have also been described in the area (Aparicio and Rojas 2003). K/Ar age determinations carried out in the neighboring Rio Negro Batholith gave ages of 172 ± 6 and 177 ± 6 Ma, which correspond to the Jurassic.

The much younger Algodonal Formation (Tpa) stretches on both sides of Quebrada El Playón. It is composed of unconsolidated conglomerates, with clay intercalations. Its age is still uncertain, from late Neogene to early Quaternary. Its measured thickness is 554 m, and it was emplaced mainly as alluvial cones and torrential deposits, although some lacustrine deposits have been signaled. Descriptions made in the area (Aparicio and Rojas 2002) include the following levels: (1) the basal (Member One) conglomeratic beds intercalated with clay and sand beds; (2) Intermediate level (Member Two), with a predominance of thick sand beds, with some conglomeratic layers; and (3) Member Three, in the upper part of the deposit, formed by conglomeratic layers intercalated with thick clay levels containing sandy layers and gravel lenses. The *estoraques* were carved in the Algodonales Formation (Fig. 5.3). Finally, the alluvial deposits (Qa1) are found along the main rivers draining the area.

5.4 The Estoraques

The pillars may reach heights of 30–40 m and several preliminary observations can be made regarding their origin. They were carved in the unconsolidated sediments of the Algodonal Formation by surface erosion processes, whereas the preservation of the pillars was due to the presence of more cemented layers at the surface, probably caused by some pedogenic process, such as iron accumulation and hardening (Reed 1976) (Figs. 5.4, 5.5 and 5.6). The existence of several layers of hardened material also explains the occurrence of truncated pillars of different sizes. The smooth dipping of the sediment layers toward the present axis of the valley indicates that the paleotopography of the area, when they were emplaced, was not very different from that of the present (Fig. 5.7). The sediments do not appear to have suffered from any type of chemical weathering since their emplacement, accomplished mainly by fluvial and torrential processes.

Besides pillars, some meseta like and small tunnels formed by the coalescence of gullies can be observed. Gully floors are covered by sediments with the same mineralogical

Fig. 5.5 Harder layers protecting the tops of the pillars. *Photography* Michel Hermelin

composition that the pillars, but compacted by rain drops and trekking. No collapsed pillars were observed.

The influence of mechanical weathering, as well as thermoclastic fragmentation and salt crystallization mentioned by several authors (Reed 1976; Guzmán 1981; Gamboa 1998), does not seem to have any basis as the corresponding evidence is lacking. However, the presence of swelling clays, signaled by Guzmán (1981), may have some importance but has to be proven by X-ray diffraction. On the other hand, the role given by the author to the presence of limestone is totally unfounded. An aeolian influence, insinuated in the Cote Lamus poems (1963) and mentioned by other authors, apparently belongs to imagination, at least under the present climate. However, this legend is faithfully transmitted by local guides to the tourists.

Human influence on the formation of the *estoraques* is difficult to ascertain. Changes in land use, which occurred after the Spanish conquest, probably influenced erosion rates. The present evolution of the area is not known, excluding scarce reports of pillar falls. No systematic monitoring has been yet established.

Fig. 5.6 Strong local differences in resistance to weathering processes generate intricate forms such as rock windows and arches. *Photography* Michel Hermelin

Fig. 5.7 Textural aspects and dip of the Algodonal Formation. *Photography* Michel Hermelin

5.5 Conclusions

The *Estoraques* Unique Area certainly deserves a visit by people interested in the evolution of tropical landscapes. However, many questions still remain unanswered on the origin of this magnificent sample of badlands in a relatively dry Andean forest ecosystem. These include the following:

– What is the real age of the Algodonal Formation? This may, perhaps, be answered using Optically Stimulated Luminescence (OSL) on quartz grains included in the deposit. A judicious sampling could eventually give precise dating of the accumulation processes of these sediments and permit useful deductions on their erosion rates.
– What is the present erosion rate of the badlands? The answer could arise from a systematic study of a series of aerial photos and satellite images of the area. Furthermore, systematic annual surveys, based on photos and direct topographic measurements, are fundamental in order to determine the relationship between changes in land use and the erosion and the preservation of pillars.
– A meteorological station should be set up in the park to adopt the necessary measures in order to obtain a precise register of temperatures and rainfalls all year round.
– A permanent survey of the sediments produced in the area would be very useful to establish their variation as a function of rainfall.
– On a more detailed scale, some pins could be discreetly planted in the pillars in order to survey their morphological changes through time.
– The mineralogy and petrography of the Algodonales Formation should be studied, particularly in order to determine the presence of arkoses and swelling clays.
– Finally, detailed topographic and geomorphologic maps (1:5000) of the area should be prepared.

References

Ancízar M (1984) Peregrinación de Alpha, Tomo I y II, Viajes Biblioteca Banco Popular N. 7 y 9, Bogotá
Sunday Magazine (1959) (Magazin Dominical), Los estoraques como árboles de piedra, El Espectador Bogotá
Aparicio MF, Rojas TA (2002) Estudio geológico y morfodinámico e inventario geoambiental del Área Natural Única los Estoraques. Geology thesis, Universidad Industrial de Santander, 97 p
Arias A, Vargas R (1978) (Informe 1759 Ingeominas) Geología de las Planchas 86 Abrego, Departamento de N. de Santander Boletín Geológico vol. 23 No 2, INGEOMINAS, Bogotá
Botero RG, Sarmiento AA (1947) Reconocimiento geológico de la carretera Ocaña-Abrego-Sardinata, Departamento de Norte de Santander Servicio Geológico Nacional, Bogotá, 82 p
Cote Lamus E (1963) Los Estoraques. Imprenta Nacional, Edición del Ministerio de Educación, Bogotá
Daconte R, Salinas R (1980) Geología de las Planchas 66 (Miraflores) y 76 (Ocaña) Informe 1844, INGEOMINAS, Bogotá
Gamboa AG (1998) Informe Servicio Guardaparques Voluntarios. Unidad Administrativa Especial, Sistema de Parques Nacionales 8 p
Guzmán G (1981) Primer estudio físico de Los Estoraques en el municipio de La Playa. Universidad Francisco De Santander, Cúcuta
INDERENA (1985) Diagnóstico para la declaratoria del Área Natural Única –"Los Estoraques"- como integrante del sistema de parques nacionales y lineamientos de manejo, Municipio de La Playa, Norte de Santander (incluye dentro de los linderos el área de reserva forestal protectora de la cuenca de la quebrada Tenería, declarada por Acuerdo No 22 de mayo de 1984), ms, 32 p
INGEOMINAS (1980) Mapa geológico.Plancha 76 Ocaña. Escala 1:100000
Reed PL (1976) Plan Preliminar para el Área Natural Única "Los Estoraques" INDERENA, Bucaramanga, 120 p
Ministerio de Agricultura (1988) República de Colombia Resolución Ejecutiva No 135 del 24 de Mayo de 1988
Royo, Gómez J (1947) Estudio de varias muestras recogidas por los geólogos G, Botero R y A Sarmiento A. en Norte de Santander Servicio Geológico Nacional, Bogotá, 8 p
Suárez FL, Barajas ROL, Bayona TE, Vargas AJ (2009) Plan de Manejo Área Natural Única Los Estoraques. Área Natural Única Los Estoraque, Parques Nacionales 239 p

6 The Chicamocha River Canyon

Georgina Guzmán

Abstract

In the Bucaramanga region, the Oriental Cordillera shows a very peculiar relief consisting of mesas separated by deep and abrupt canyons cut in sedimentary and crystalline rocks. These landscapes are underlined by the sub-arid climate which characterizes these steep valleys, often lacking vegetation cover. These contrasted life zones and geomorphological evolution experienced by the region make it an interesting place both for earth scientists and tourists. The recent installation of a cable car which crosses the canyon contributes to its attractiveness as a scenic place.

Keywords

River canyons • Mesetas • Semi-arid geomorphology

6.1 Introduction

The Chicamocha River source is situated near Tunja, the capital of the Department of Boyacá. After a meandering tract in the highlands, which rise to 2500 m a.s.l, the valley becomes a canyon near Paz de Río. The river flows in the bottom of a gorge until it merges with the Suarez River in the Department of Santander to become the Sogamoso River, which finally discharges its waters in the Magdalena River (Fig. 6.1). The best expression of the canyon is found around the city of Bucaramanga; it can be appreciated from the roads from San Gil to Bucaramanga and from this city to Zapatoca. The canyon can also be seen from the air by taking the cable car which, since 2009, crosses the valley from the Chicamocha National Park, in the road from San San Gil to Bucaramanga, to the Santos Mesa. This park is located 54 km from Bucaramanga, a car ride of about 1 h.

Julivert (1958) described the canyon area as a Mesozoic block, which he called the "Mesetas region," and interpreted it as an extensive tabular relief which stretches from Bucaramanga to the surroundings of Velez. It is characterized by the presence of horizontal strata cut by two important faults: the Santa Marta-Bucaramanga and the Suarez Faults. The latter, trending north to south, divides the meseta relief in two structural zones: the western one, where the town of Zapatoca is located and the eastern one, where lie the Mesa de los Santos (Gomez and Cuervo 2012) and Barichara (Fig. 6.2).

6.2 Climate

The climate of the area is strongly affected by topography. The expected temperature decrease with altitude is accompanied by relief controlled precipitation, which results in permanently dry and warm canyons and related slopes and much more humid conditions in the mesetas and higher slopes developed in the Santander Massif and other surrounding mountains (IGAC 2007). Following Holdridge classification, average annual rainfall for very dry forest is 500–100 mm and 1000–2000 mm for dry forest. In both cases, average temperatures are higher then 24 °C. For mesetas, average annual rainfall is from 1000

G. Guzmán (✉)
Universidad Industrial de Santander, Bucaramanga, Colombia
e-mail: gguzmano@yahoo.es

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_6

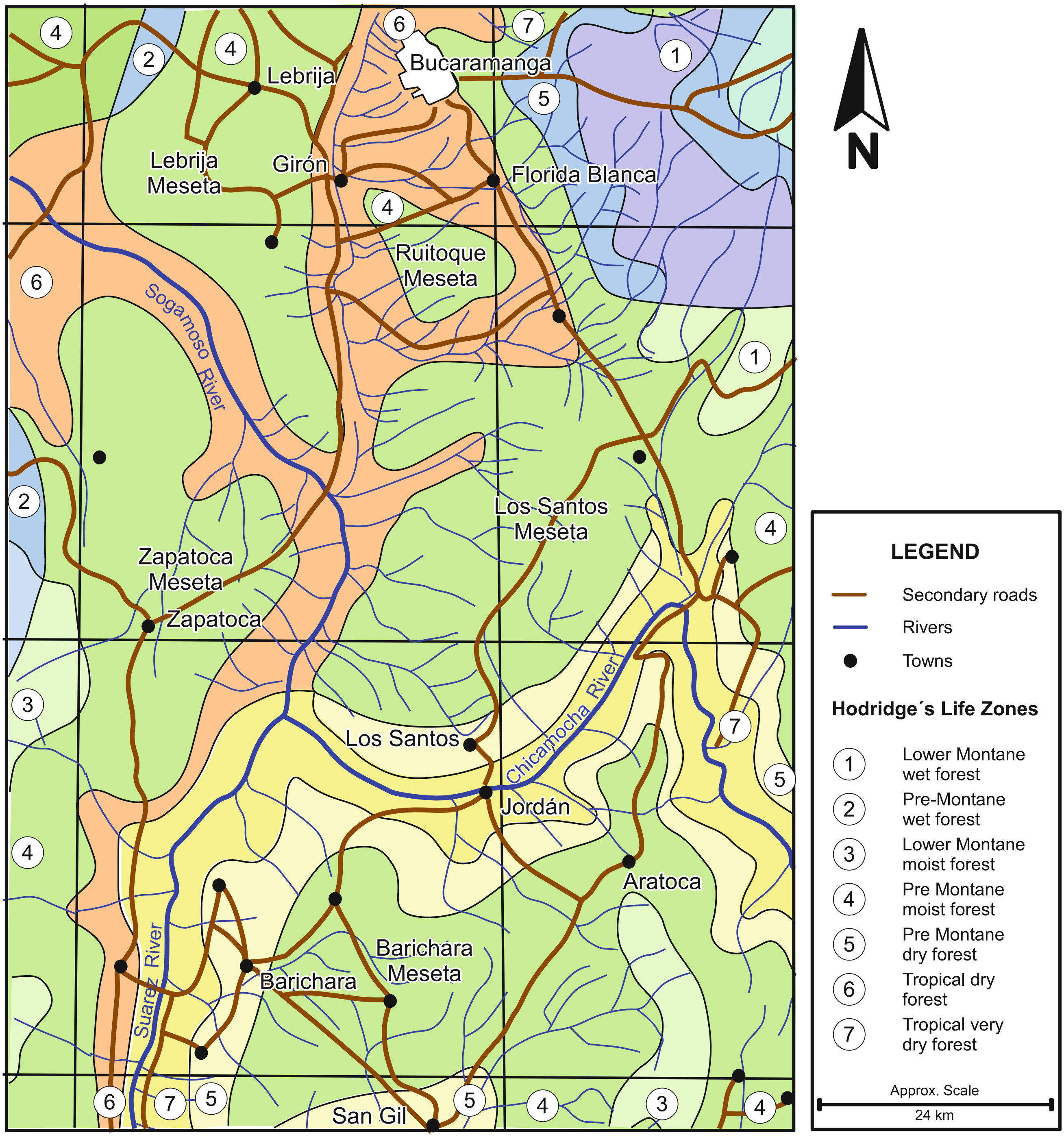


Fig. 6.1 Localization and vegetation zones. Drier ecosystems are located in the *bottom* of the canyons (numbers *6* and *7* in the map). Pre-Montane humid forest in the mesetas. Adapted from Espinal (1977)

to 2000 mm but evapotranspiration is lower as temperature average is from 20 to 24 °C. (Espinal 1977) Rainfall distribution corresponds roughly to the convergence zone localization: March and April and October–November are more humid than the rest the year.

Natural vegetation is adapted to climate: dry canyons are covered by sub-desertic, xerophytic tropical dry to very dry forest, characterized by cactus and brushes with very small leaves to prevent evapotranspiration (Fig. 6.3).

Soil are poorly developed in the canyon slopes. Human intervention consisted certainly in the burning of the original vegetation and the introduction of grazing cattle as goat and sheep; these animals proved to be the only species able to survive in such areas, although their impact in some was

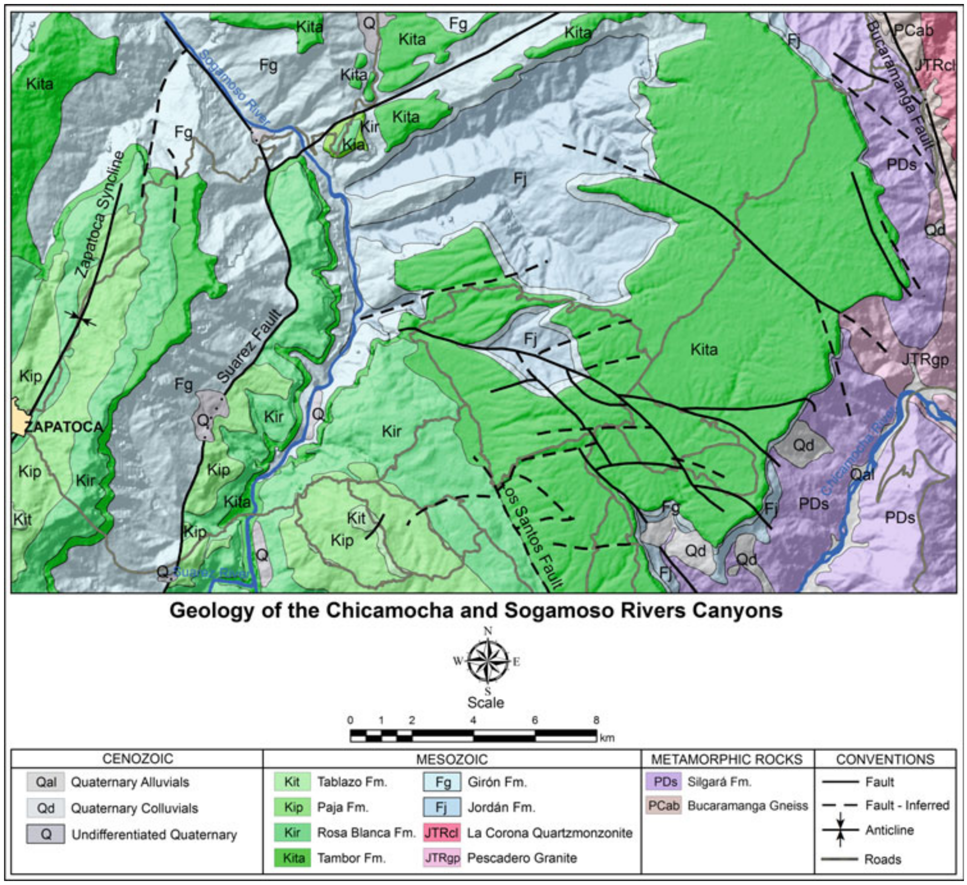


Fig. 6.2 Geology. The major Bucaramanga Fault separates Jurassic and Paleozoic igneous and metamorphic rocks on the east, Jurassic and Cretaceous sedimentary strata on the west, forming the mesetas. Adapted from Ingeominas (1977) and Ward et al. (1969)

particularly drastic, as for instance in lopes developed on igneous and metamorphic rocks (Fig. 6.4), giving rise to practically irreversible erosion phenomena.

6.3 Geological Aspects

The Santander Massif (Macizo de Santander) is one of the several old massifs found in the Eastern Cordillera.

It is an igneous–metamorphic complex and its older rocks are Precambrian gneisses, schists, quartzites, orthogneisses, and migmatites. Lower grade metamorphic rocks including phyllites, marbles, and metasiltstones, apparently of Ordovician–Silurian age, are also present, as are the Upper Paleozoic (Middle Devonian–Permian) sedimentary rocks, which present evidence of metamorphism too. During Triassic–Jurassic, igneous activity resulted in the intrusion of several batholiths and other plutons as stocks, which are part of the Santander Plutonic Group (INGEOMINAS 1993) (Fig. 6.2).

The main lithostratigraphic units that have been recognized in the Chicamocha Canyon are as follows:

Silgara Formation A low grade metamorphic rock unit of sedimentary origin, composed of micaceous schists, intruded by leucocratic granite, aplites, pegmatites, and dacitic porphyry dykes. It has been assigned a Cambrian–Ordovician age (Ward et al. 1973; Restrepo 1982).

Pescadero Granite. It was first described by Ward et al. (1973). Its radiometric age is 193.6 Ma and it constitutes the igneous basement of the mesetas. In the Chicamocha Canyon, it has been described as an igneous rock with textures from porphyritic to phaneritic, which intruded the Silgara Formation to form coarse-grained, pegmatite-like bodies and also as very fine-grained rhyolites, composed of potassic feldspars, quartz, and biotite; pegmatites contain large muscovite plates.

Jordan Formation It is formed by greenish-gray, coarse-grained to slightly conglomeratic sandstones, with cross-stratification, intercalated by greenish-gray claystones

Fig. 6.3 Semiarid intervened vegetation in the Chicamocha Canyon (tropical dry forest); photo was taken after a rain period; during dry season the almost complete loss of the leaves gives to the landscape a more arid aspect (Photo Michel Hermelin)

levels. In the upper part, red-brownish to red-grayish siltstones and medium sized layers of fine-grained sandstones are present. Two thin layers of felsic-welded tuffs have also been described. It was deposited in a volcano-clastic continental environment. The thickness of this formation varies between 300 and 660 m (Ward et al. 1973). It is discordantly overlain by the Giron Formation. On the basis of its stratigraphic relations, the Jordan Formation is considered of Lower to Middle Jurassic age.

Giron Formation The Giron Formation can be observed both on the eastern and the western side of the Santander Massif. In both cases, it becomes progressively thinner until it disappears completely (Julivert 1963a, b). In the west, where its outcrops are better preserved, it has been described as a clastic siliceous succession with a characteristic red to purple red color discordantly overlying the Jordan Formation (Cediel 1968).

Tambor Formation Its type locality was defined by Cediel (1968) who described this unit as the assemblage of three levels: the lower one, composed of sandstones, mainly arkosic, with frequent reddish color; the middle one, clayey with sandstone intercalations, also of reddish to pink color; and the upper one, made of white sandstone with a stratification better defined than that present in the lower level. This formation was renamed Santos by (Etayo-Serna 1982). The total thickness is of more than 200 m along the western edge of the Santos Meseta and 120 m in the eastern edge. This formation is concordantly overlain by Rosablanca Formation and its contact with Giron Formation is transitional (Fig. 6.5).

Rosablanca Formation The Rosablanca Formation stratigraphy was studied in detail in a 318-in-thick succession located in the Sogamoso River Canyon, west of the Santos Meseta, by Zamarreño de Julivert (1963). Its lower

Fig. 6.4 Surface erosion and rill and gully development on the Silgara Formation in the Pescadero Area. Crystalline rocks appear to be much more susceptible to surface erosion than surrounding sedimentary rocks (Photo Michel Hermelin)

part is composed of limestone and gypsum layers containing oolites, ostracods, and dolomites. The lower part presents evaporite deposits as gypsum and polyhalite, which indicate hypersalinity and quiet sedimentary conditions. Gypsum is presently mined in horizontal tunnels along the Sogamoso River (Fig. 6.7). The rest of the sequence was deposited in a shallow marine neritic environment. Strata show a tabular geometry and are strongly fractured and weathered. The thick limestone layers look bluish gray when fresh, while weathering gives them pale yellow tone. Dark gray tabular layers of calcareous mudstones with diffuse plane lamination and calcareous nodules can be observed in the bottom of the formation, together with dark gray limestones in thick to very thick layers with tabular shape. This formation is concordant with both the underlying Los Santos Formation and the overlying Paja Formation; its age is Jurassic and comprised between Valangian and Lower Hauterivian (Etayo-Serna 1968; Etayo and Rodriguez 1985) (Figs. 6.5, 6.6 and 6.7).

Paja Formation It consists of shale layers, slightly fossiliferous, containing septaria and calcite veins (Julivert 1958). It was described by Julivert et al. (1964) as lutites with gypsum and calcareous nodules. Its thickness varies between 125 and 625 m. In some of the mesetas, red fissile mudstone can be observed to occur in thick layers with notorious plane parallel lamination and gypsum plates filling fractures parallel to stratification, intercalated with tabular layers of black marl.

Tablazo Formation The sequence of this unit consists of gray to black, fossil-bearing limestones, locally containing glauconite and black clays. These are intercalated with horizons of gray to bluish gray, fossiliferous claystones in medium to large layers with subordinate gray, fine to medium grained sandstones, and slightly calcareous clays in thin

Fig. 6.5 South eastern flank of Los Santos Meseta. Vertical scarp corresponds to the Tambor-Los Santos Formation sandstones underlain by a thin layer of Giron Formation. The lower slope is Silgara Formation and slope deposits (Photo Michel Hermelin)

layers (Wheeler, in Morales 1958). The sedimentary environment seems to correspond to shallow, neritic conditions. The total thickness varies between 150 and 325 m. The Tablazo Formation shows a concordant contact with the underlying Paja Formation.

Quaternary deposits They are found mainly on the Jordan and Los Santos Formation and along the main river banks. Alluvial deposits form terraces containing pebbles and blocks of different compositions and sizes along the Chicamocha and Sogamoso Rivers. Colluvial deposits were emplaced by mass movements mainly along the Chicamocha and Sogamoso River canyons and deposited principally on the Jordan and Los Santos Formations (Carrillo et al. 2003) (Fig. 6.8).

From the structural standpoint, the Chicamocha River canyon affects the part of the Los Santos and Barichara Mesa relief, which expresses the recent structural evolution of the Andean system, showing several types of deformation styles (Julivert 1958). The Mesetas region is limited by two important features: the Santa Marta-Bucaramanga Fault System, which uplifted the Bucaramanga Massif and the Suarez fault, with a N–S orientation parallel to the Suarez River and partially to be Sogamoso River. This fault divides the Mesetas region in two second-order structural units: the western one formed by the Lebrija Meseta and Zapatoca Massif and the eastern one which includes Bucaramanga, the Ruitoque and Los Santos Mesetas and the Barichara-Curití-San Gil area.

6.4 Geomorphological Evolution

The Chicamocha River Canyon is the result of fluvial erosion favored by the presence of faults that weakened the rock and permitted the excavation of deep valleys with steep slopes. Julivert (1958) signaled that the region's most notorious morphologic characteristics is the platform aspect

Fig. 6.6 The lower, vertical slope was cut in the Tambor-Los Santos Formation (from river to **a**). The inclined, stratified part corresponds to the Rosablanca Formation (**a**, **b**). The *upper part* belongs to the Paja Formation (Photo Michel Hermelin)

of all the units: these remnants are nothing else than fragments of an older continuous plain (Fig. 6.9a). Formed probably since Early Cenozoic in the graben comprised between Suarez and Bucaramanga Faults which was later excavated by the ancestors of the present rivers: Chicamoca, Suarez and Sogamoso (Fig. 6.9b). Los Santos and Barichara Mesas form structural surfaces. Each one of the mesetas has developed a complex hydrographic network which is the beginning to excavate its drainage consisting in meandering streams with longitudinal profiles showing a relatively advanced evolution. All these streams have falls of 800–100 m to reach the Chicamocha and Suarez Rivers (Julivert 1958). According to this author, the canyons are gorges broadened by the long fluvial erosional activity.

The capture of Chicamocha river, which originally flew along the Bucaramanga fault, by an affluent of the Suarez-Sogamoso River part and that of the Sogamoso by an affluent of the Magdalena River flowing toward the North West complete the evolution (Fig. 6.9c). With respect to the chronology, Julivert (1958) considers that the movements which created the depressed areas between Bucramanga Suarez Faults began in late Cenozoic. The area remained relatively flat until the Pliocene cordillera uplift which reactivated the river excavation to produce the canyons.

Within the Chicamocha Canyon, areas with homogeneous relief can be recognized as product of the interaction of meteorological, geological, hydrological, and biological factors. In general, crystalline rocks give rise to moderate slopes (Fig. 6.5, lower part). Jurassic Giron clastic sediments and Cretaceous Rosablanca stratified limestones produce intermediate slopes (Figs. 6.10, 6.6a–b section). Steeper, vertical slope develops on Cretaceous Tambor. Los Santos Formation sandsstones. The main landforms identified in the canyon are as follows:

- slopes, remnant hills, scarps, and torrential fans which are generally associated with both erosional processes and structural influences.
- terraces and floodplains related to fluvial processes

Fig. 6.7 Cretaceous Rosablanca Formation with tunnels for gypsum exploitation. Most of the mines are in production (Photo Michel Hermelin)

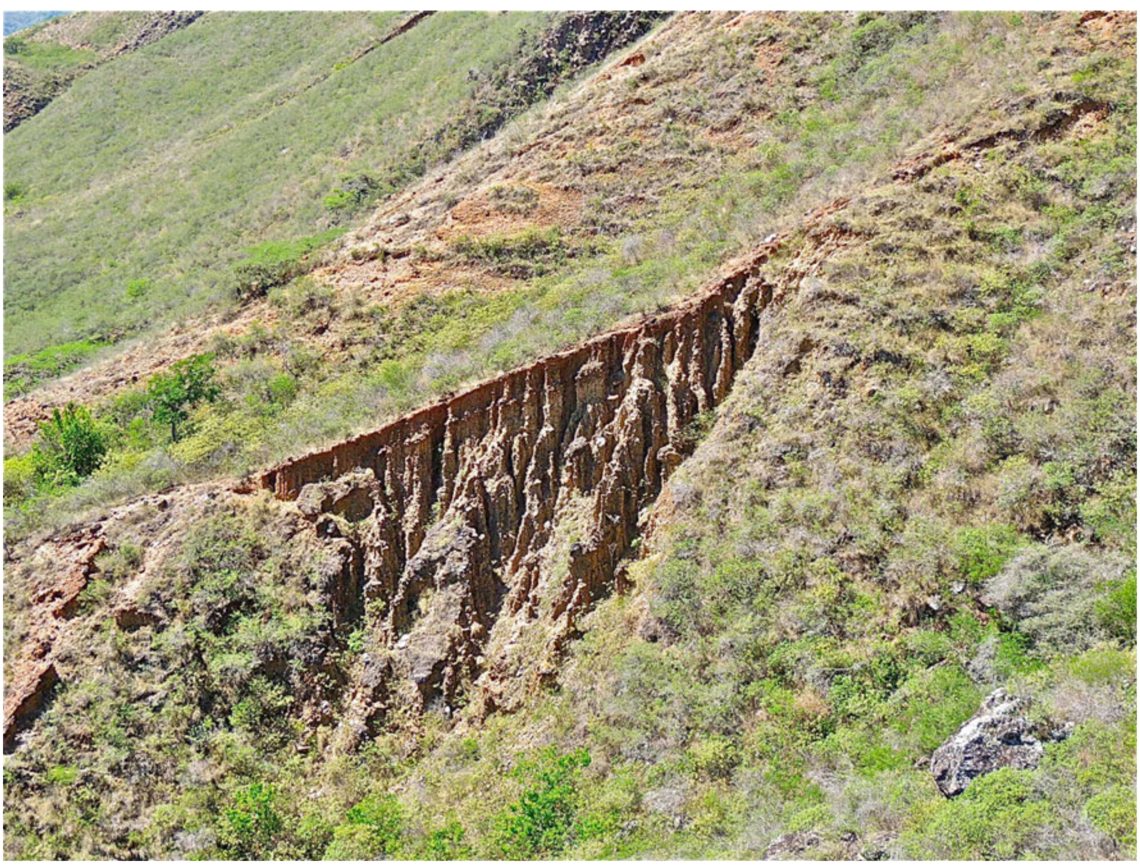


Fig. 6.8 Poorly cemented and locally heavily eroded Quaternary deposits, Chicamocha Canyon (Photo Michel Hermelin)

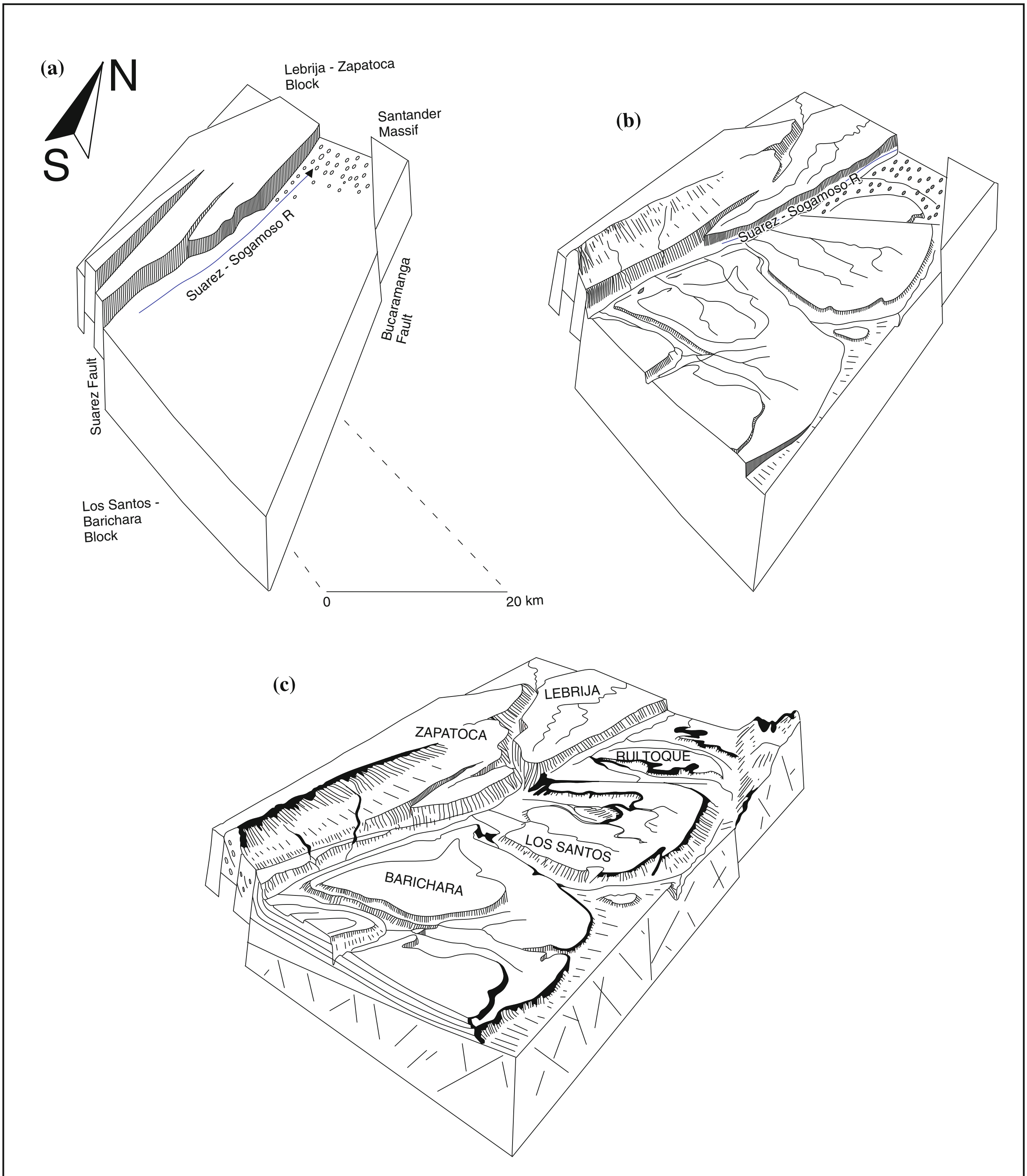


Fig. 6.9 Geomorphological evolution of the mesetas region. Adapted from Julivert (1958) (see text for comments)

Fig. 6.10 Sogamoso River Canyon carved on Jurassic Giron Formation. A slope deposit is visible on the *left*. On the *right*, stratification is also masked by slope deposits. *Red color* is typical of Giron Formation sediments (Photo Michel Hermelin)

References

Carrillo E, Castro E, Ibañez D, Vargas G (2003) Metodología para la zonificación de la susceptibilidad a movimientos en masa, escala 1:100.000, en la zona central de la Cuenca del río Chicamocha, Santander – Colombia. INGEOMINAS. 37 p

Cediel F (1968) El Grupo Girón una molasa Mesozoica de la Cordillera Oriental: Bol. Geol., Derv. Geol. Nal, Bogotá 16 (1–3):5–96

Espinal LS (1977) Zonas de vida o formaciones vegetales de Colombia. Mapa ecológico. Memoria Explicativa. Bogotá IGAC

Etayo-Serna F (1968) El sistema Cretáceo en la región de Villa de Leyva y zonas próximas. Geol Colomb 5:5–74

Etayo Serna F (1982) Análisis facial del inicio del avance marino del Cretácico en la región del Macizo de Santander. Excursión pre congreso Colombiano de Geología No 2

Etayo-Serena F, Rodriguez G (1985) Edad de la Formación Los Santos en Proyecto Cretácico, Publicación Especial de INGEOPMINAS No. 16, Cap. 26, p. 1–6, Bogotá

Gómez JD, Cuervo RG (2012) Estudio geológico enfocado a la caracterización paisajística de la Mesa de los Santos, Santander, Colombia. Proyecto de Grado. Trabajo de Investigación. Escuela de Geología. UIS. Bucaramanga. p 164

INGEOMINAS (1977) Mapa Geológico Plancha 120, Bucaramanga 1:100 000

INGEOMINAS (1993) Subdirección de geología regional nororiente. IV Simposio de Geología Regional. Contribución al conocimiento de la geología de los Santanderes: Guía de excursiones Geológicas, Sección geológica: Bucaramanga-Berlín-Vetas- Pamplona. Junio 13 al 19 de 1993. Bucaramanga

IGAC (2007) Los Cañones Colombianos: una síntesis geográfica. IGAC, Bogotá; 243 p

Julivert M (1958) La morfoestructura de la zona de mesas al SW de Bucaramanga (Colombia S.A.) Boletín de Geología Nº 1 de la UIS Facultad de Petróleos, Departamento de geología. Bucaramanga. pp 9–41

Julivert M (1963a) Estratigrafía y sedimentología de la parte inferior de la Formación Guaduas al sur de la Sabana de Bogotá (Cordilera Oriental). Bol Geol UIS 12:85–99

Julivert M (1963b) Nuevas observaciones sobre la estratigrafía y tectónica del Cuaternario de los alrededores de Bucaramanga Boletin de Geología Universidad Industrial de Santander, Bucaramanga Nº15 pp 5–34

Julivert M (1970) Cover and basement tectonic in the Cordillera Oriental of Colombia, South America, and a comparison with some other folded Chains. Geol Soc Am Bull 81:3623–3646

Julivert M, Barrero D, Navas J (1964) Geología de la Mesa de Los Santos. Bol Geol UIS 18:5–11

Morales LG (1958) COLOMBIAN PETROLEUM INDUSTRY. General geology and oil occurence in the middle Magdalena Valley, Colombia - Habitat of oil. Symposium AAPG, p 641–695

Restrepo JJ (1982) Compilación de edades radiométricas de Colombia. Departamentos Andinos hasta 1982. Boletin de Ciencias de la Tierra, Medellín 7–8, pp 201–247

Ward DE, Goldsmith R, Jimeno VA, Cruz BJ, Gomez R (1969) Mapa geológico del cuadrángulo H-12 "Bucaramanga". Colombia. Inst. Nal. Inv. Geol. Min. Bogotá

Ward DE, Goldsmith R, Cruz BJ (1973) Geología de los cuadrángulos H-12 "Bucaramanga". Y H-13 "Pamplona". Departamento de Santander, Boletin Geologico, vol 21, no. 1–3, pp 1–133

Zamarreño I de Julivert (1963) Estudio petrográfico de las calizas de la Formación Rosablanca de la Región de la Mesa de los Santos (Cordillera Oriental Colombia). Boletín de Geología Nº 15 de la UIS Facultad de Petróleos, Departamento de geología. Bucaramanga. pp 5–34

7 The El Cocuy Snowy Range

Domingo Mendivelso

Abstract

The El Cocuy Snowy Sierra located in the Colombian Eastern Cordillera axis was formed on a thick, folded sequence of Cretaceous marine sedimentary rocks. It is capped by retreating glaciers, which left glacial, fluvioglacial and fluvio–lacustrine Quaternary deposits and landforms: moraines, cirques, and lakes distributed in the upper watersheds of rivers draining both to the Eastern Plains and the Magdalena River. The surrounding landscapes are considered among the most spectacular in the country.

Keywords

Tropical glacial geomorphology • Ice recession

7.1 Introduction

The El Cocuy Snowy Sierra (herein ECSS, also called Chita or Güicán) is considered one of the seven wonders of the Department of Boyacá; it is indeed one of the most beautiful landscapes in Colombia. It reaches 5493 m a.s.l., the highest point of Eastern Cordillera. It is located near the inflection point of the Eastern Cordillera, north of the Department of Boyacá (Fig. 7.1).

From the geological standpoint, it consists of Cretaceous claystones and marine calcareous rock sequences, and of younger, Cenozoic sandstones unconformably deposited in a continental environment. These rocks lie on PreCambrian Guyana Shield rocks. Glacial and fluvioglacial processes carved the mountain tops and left numerous glacial deposits and landforms. Due to relief asymmetry and higher precipitation on the eastern side, glaciers are better preserved on the eastern slope.

ECSS lies in a national park (*Parque Nacional Natural El Cocuy*), which covers 3060 km^2 and includes 23 snow-covered summits surrounded by *páramos* and Andean forest on the lower slopes. Animals, such as tapirs, brown bears, Andean condors, eagles, and *páramo* deers, can still be observed. Sierra can be reached by trails from the villages of El Cocuy or Güicán. It is recommended that visitors are accompanied by a local guide. The best time to visit Sierra is during the drier seasons, July–August or December–February, the latter being the most favorable. The ideal time to spend there is one week; but shorter itineraries can be arranged. The landscapes conserve the pristine beauty of the high Andes: snowy peaks, cascades, cirques, and lakes surrounded by the *páramo* green vegetation (Fig. 7.2).

7.2 Previous Studies

The first scientific excursion to the ECSS was made by Manuel Ancízar in 1851 (in Codazzi 1851) while carrying on the first official geographical survey of the country, the “Comision Corográfica.” He correctly identified and describes “morenas,” from the French word “moraines,” stating that he used this ready-made translation because he found no equivalent term in Spanish dictionaries. He

D. Mendivelso (✉)
Instituto Geográfico Agustín Codazzi (IGAC), Bogotá, Colombia
e-mail: domelo11@hotmail.com

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_7

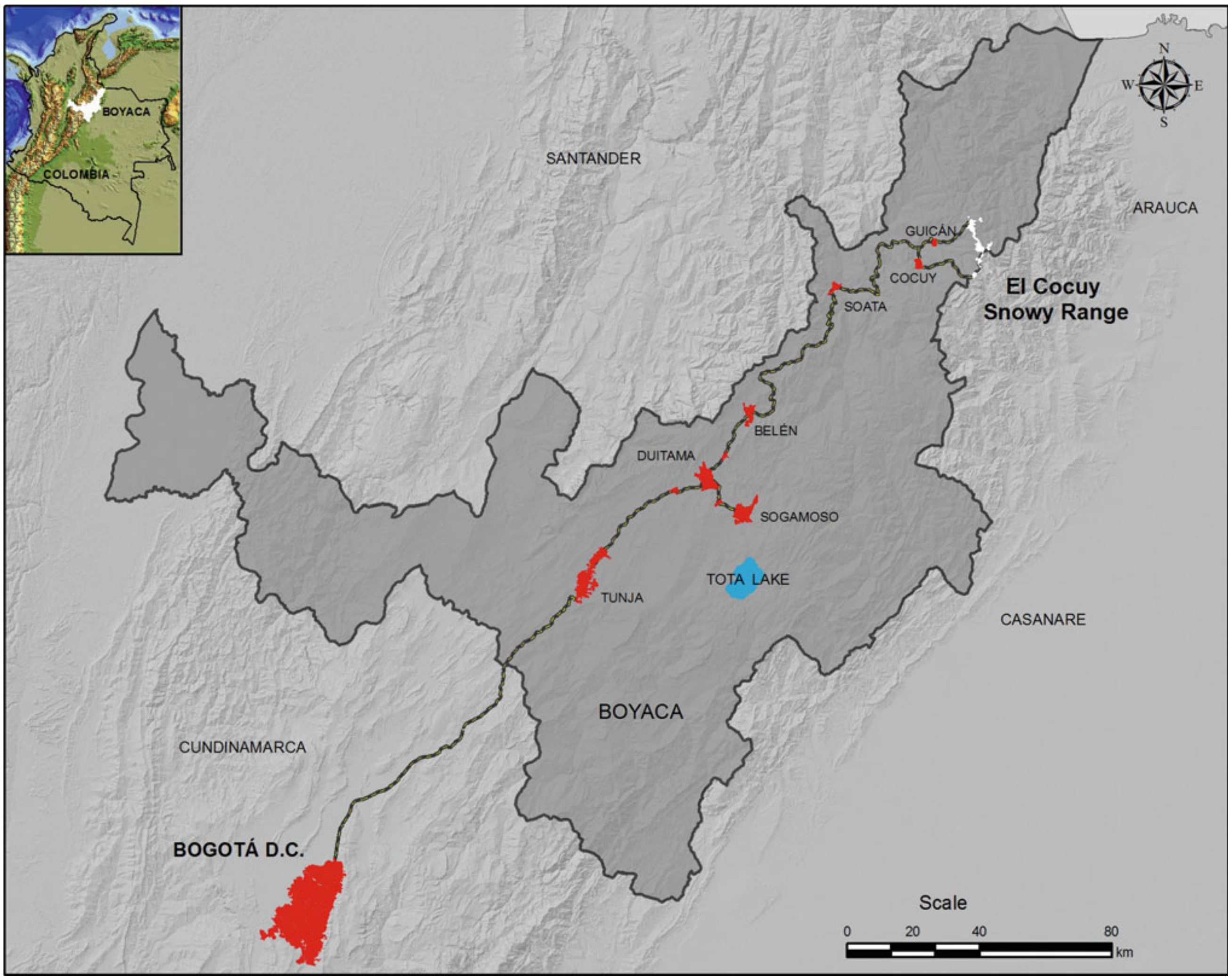


Fig. 7.1 Regional map showing the access to El Cocuy Snowy Range from Bogotá

measured an altitude of 4150 m a.s.l. for the ice lower limit (Fig. 7.3).

Hettner, the well-known German geographer, spent several days in the ECSS in 1884 and left a good description of his itineraries (Hettner, 1976). He found that the lower ice limit was at 4560 m a.s.l., and identified remnants from moraines at much lower altitudes. He left open the question about the cause of the ice cap retreat, considering a decrease in rainfall or increase in temperature. He was well aware of the previous descriptions made by Ancízar two decades before.

One of the first explorations of Sierra during the twentieth century was carried out by Krauss (1938) and Oppenheim (1941). Later, González et al. (1965) established the glacial chronology of the area using pollen and radiocarbon dating. Brűnnschweiler (1981) published morphographic and morphogenetic maps of the southern flank of ECSS. Van der Hammen et al. (1981) published a detailed study on glacial deposits and deglaciation chronology. Further studies were carried by Florez (2003) and Ceballos et al. (2006). Present monitoring is made by IDEAM (1997, 2013).

7.3 Geology

One of the first modern geological studies on the area was published by Fabre (1981); the area is presently covered by 1:100,000 geological map numbers 137 and 153 (*Servicio Geológico Colombiano*, 1982) (Fig. 7.4). A short description

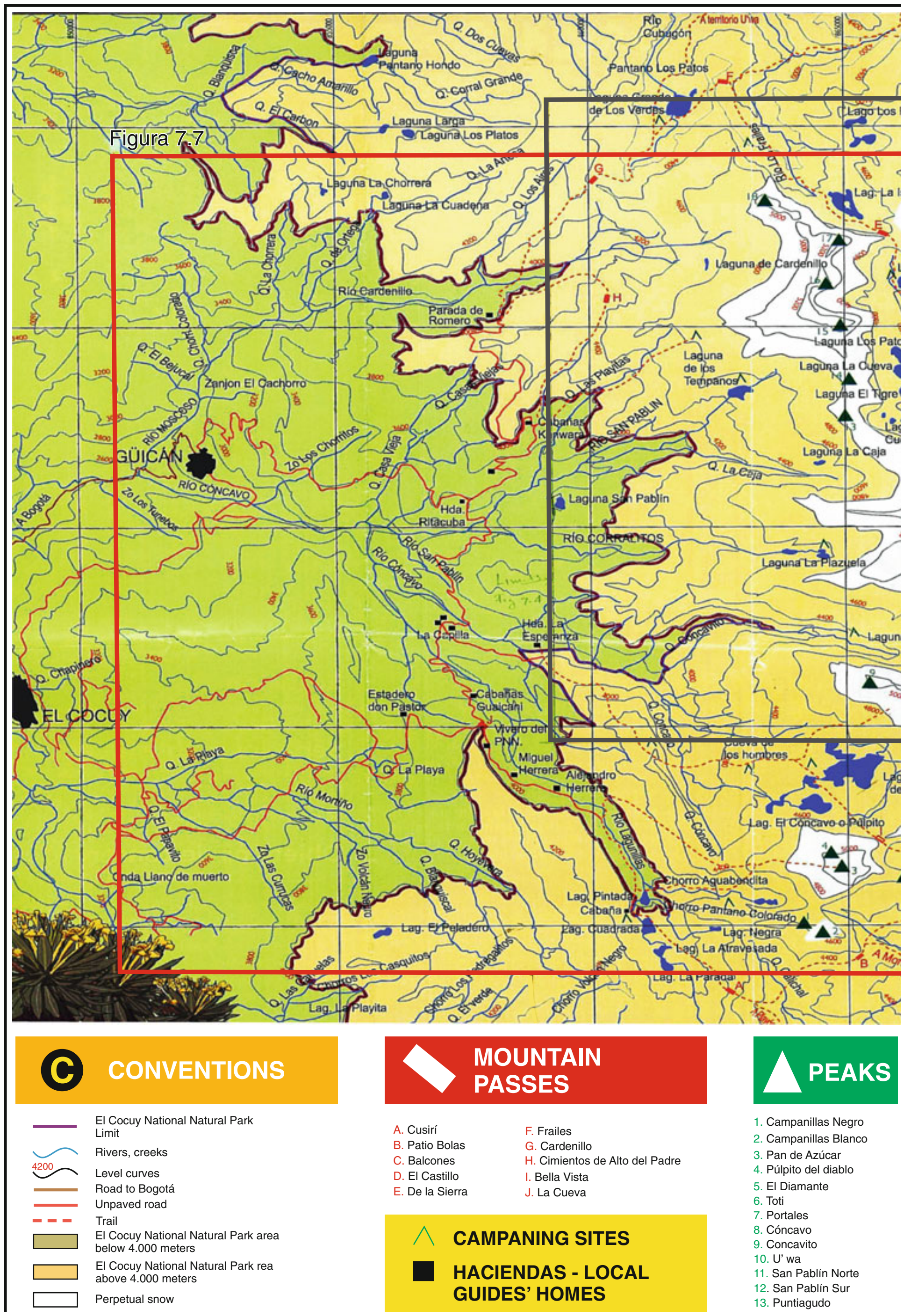


Fig. 7.2 Map of the National Natural El Cocuy Park (Parques Nacionales 2014)

of the stratigraphy is as follows, beginning with the older rocks:

- Río Negro Formation (Kim) (Aptian) is composed of white, quartzic, fine- to medium-grained sandstones, with siliceous cement and quartz pebbles with diameters up to one cm; they form thick beds with cross-bedding, intercalated with carbonaceous mudstones containing plant remnants and with dark gray, fined-grained sandstones, with some calcareous levels containing fossil bivalves.
- Tibú Mercedes Formation (Kitm) is composed of siltstones deposited in a coastal marine environment in a subsiding basin (Aptian) (Fabre 1981).

Fig. 7.3 **a** Water painting (painted in 1851) of the Black Ritacuba Glacier (Codazzi 1851). **b** *Photo* taken at the same place by Jorge Ceballos, IDEAM, in March 2010

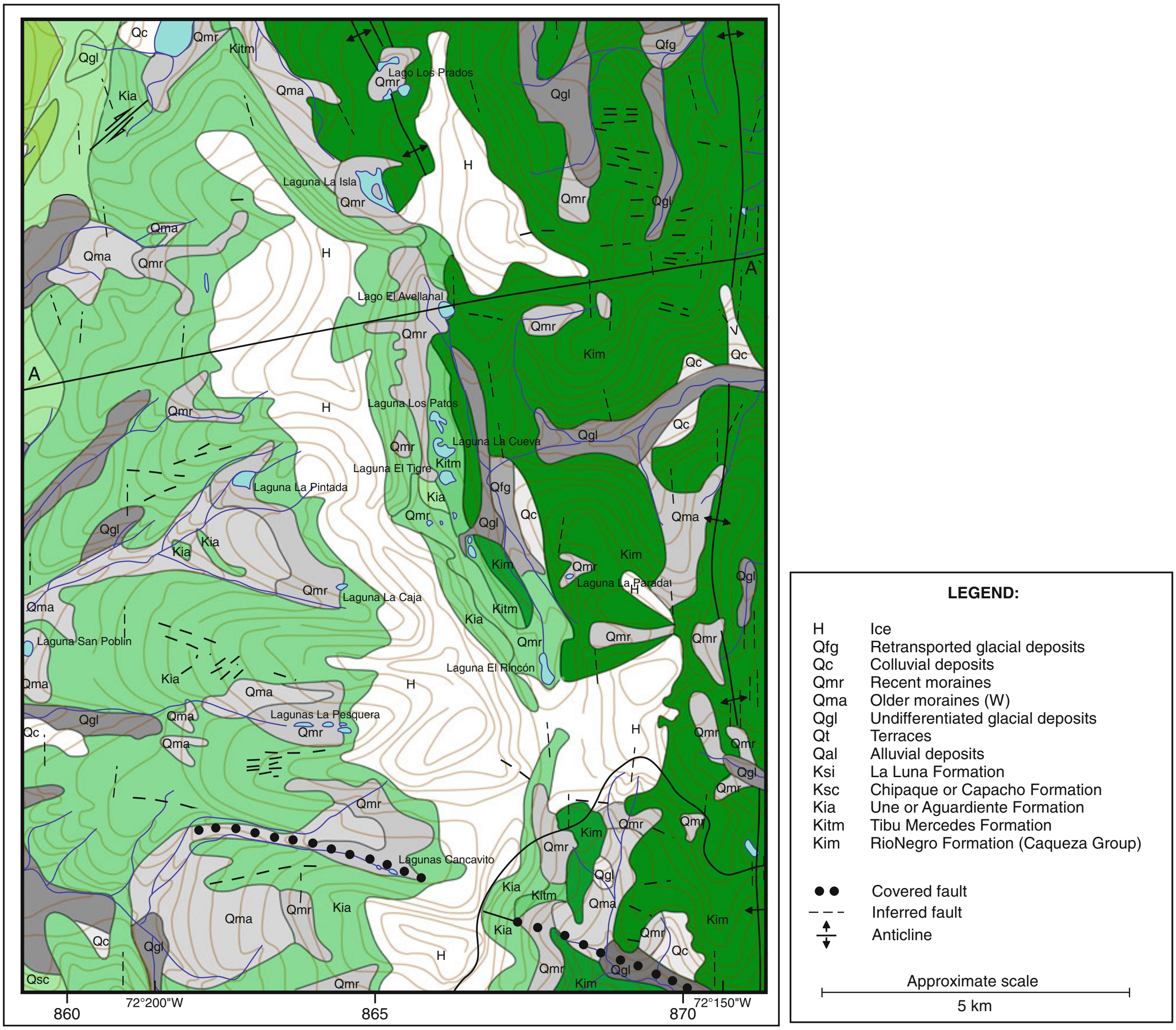


Fig. 7.4 Geological map, from Ingeominas (1985). The limits of this map are shown in black in Fig. 7.2

On the western slope two main formations are as follows:

- *Aguardiente* Formation (Kia) (Aptian), which is a thick sequence of white, quartzic, fine- to coarse-grained and even conglomeratic sandstones with cross-bedding, intercalated with dark-gray to black very fine-grained sandstones with undulated or lenticular bedding; toward the base of the formation, black carbonaceous mudstones are present and contain plant remnants.
- *Capacho* Formation (Ksc) (Cenomanian), composed of siltstones and mudstones, intercalated with orthochemical and biochemical rocks, mainly limestones and marls.

All the previously described rocks are deeply folded and faulted.

- Quaternary deposits: thick glacial (Qm), fluvioglacial (Qfg), fluvio–lacustrine (Qal), and alluvial deposits (Qa) were formed during colder Quaternary stages.

Major structures are the Sinsiga Anticline and the Blanquiscal Syncline which are located on the eastern flank. On the western flank, a thick Cretaceous rock sequence forms a homocline, followed by a series of anticline- and syncline-type structures, amongst which the Guicán Anticline and the Las Mercedes Syncline can be distinguished. Most of these structures have their axes oriented from N30° W to N–S, which indicates that predominant compression was ENE–WSW. Among the fault systems, the El Ratoncillo—Campo Hermoso Fault separates two major structures located in the higher eastern part of the Sierra known as the

Fig. 7.5 Syncline, La Esperanza farm, La Cueva site, Güican municipality. *Photography* Domingo Mendivelso

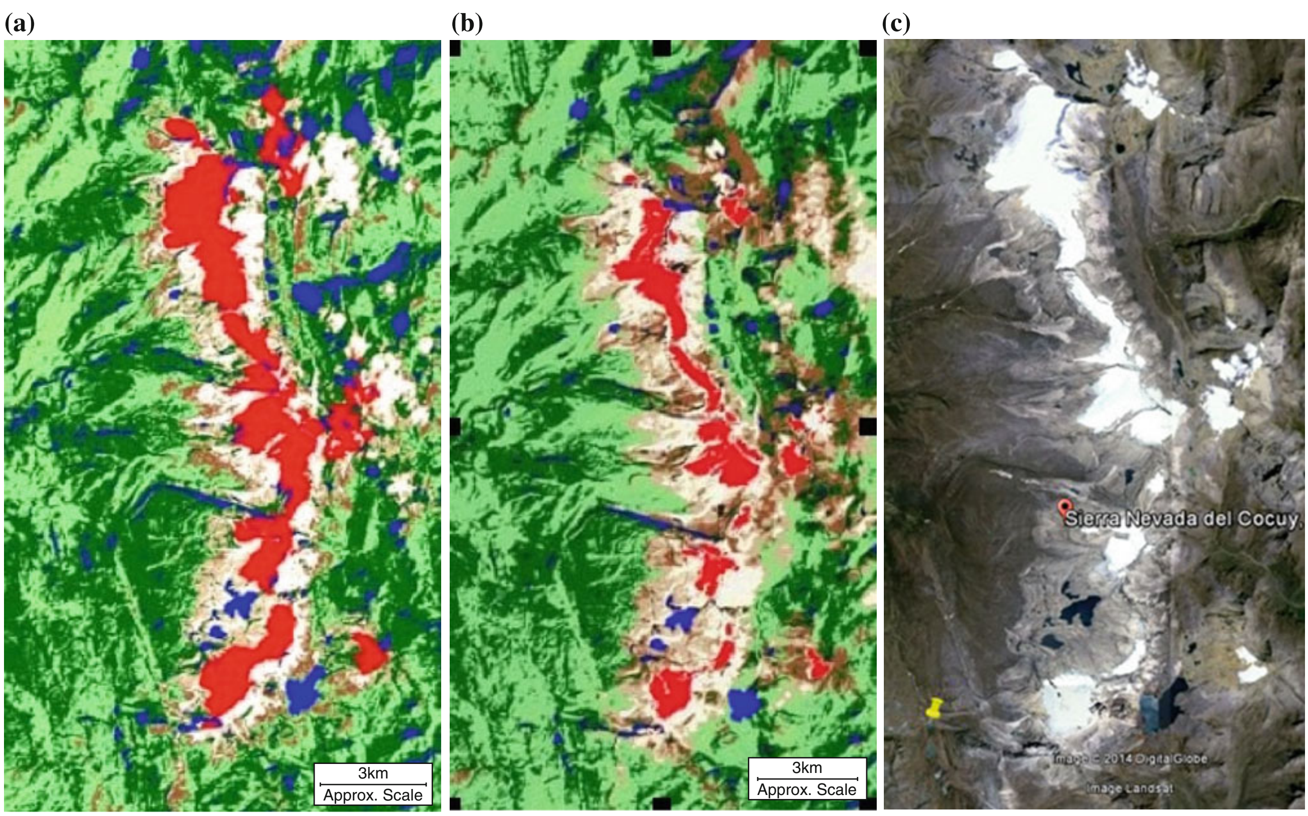


Fig. 7.6 **a** (1986) three satellite images showing rapid ice retreat during the last 3 decades. In the Landsat images, ice is represented in *red* color and lakes in *blue*; in the Google Earth image, ice is *white* and lakes are *black*. **b** (2003). **c** (2014)

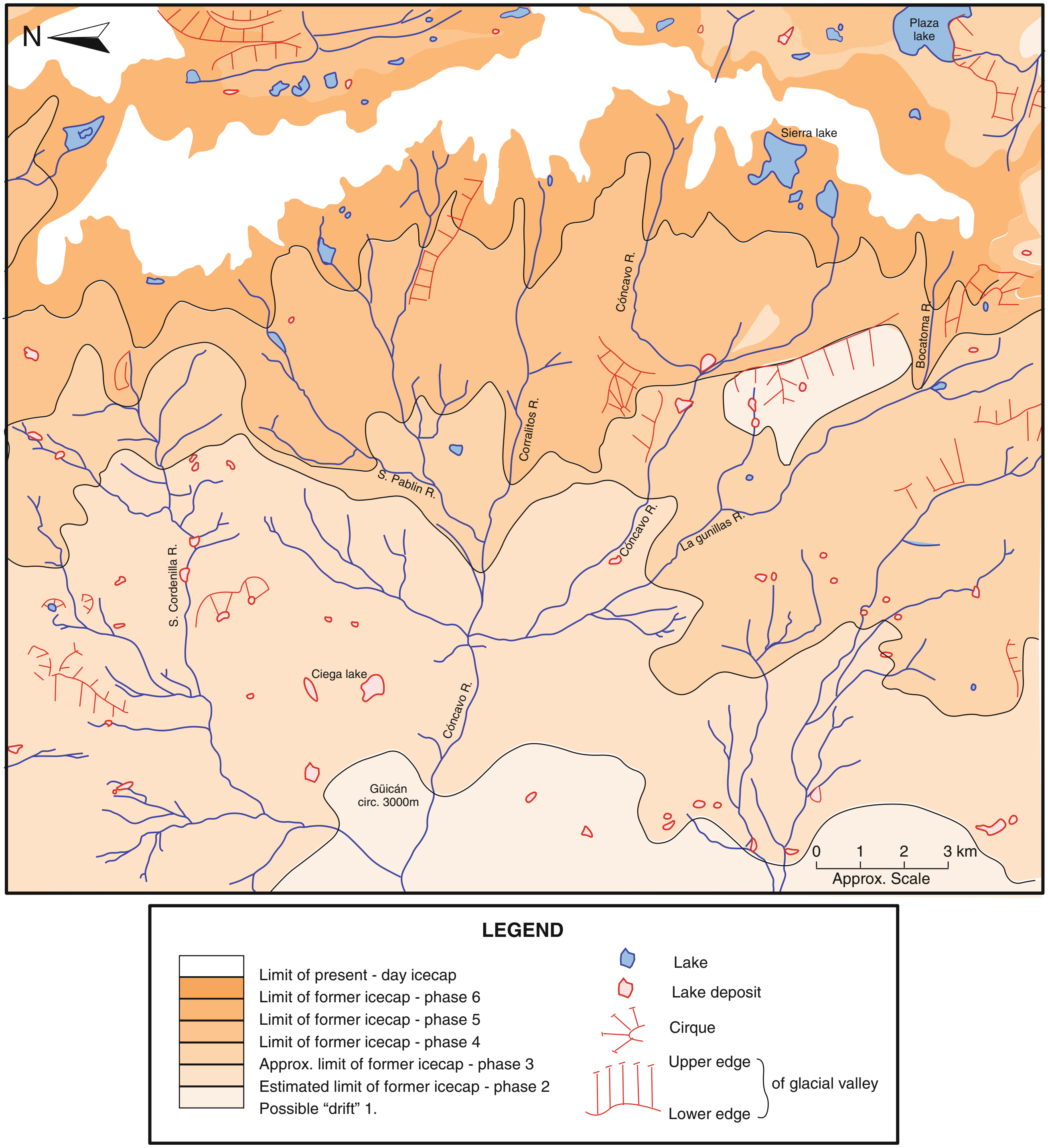


Fig. 7.7 Morphological map showing successive ice retreats and landforms of glacial origin (Adapted from van der Hammen et al. 1981) Map limits are shown in *red* in Fig. 7.2

Blanquiscal Anticline in the east and a homoclinal sequence in the west.

Coarse-grained, clastic sedimentary rocks are densely fractured in several directions, due to tectonic movements that occurred during the Andean Orogeny, at the end of Cenozoic. Additionally, these rocks were affected by ice fracturation.

Sierra is located on folded and faulted structures that conform a major anticline oriented N–S, which occupy the eastern slope of the ice-covered area. Westward from the glaciers, a series of anticline- and syncline-type minor folds

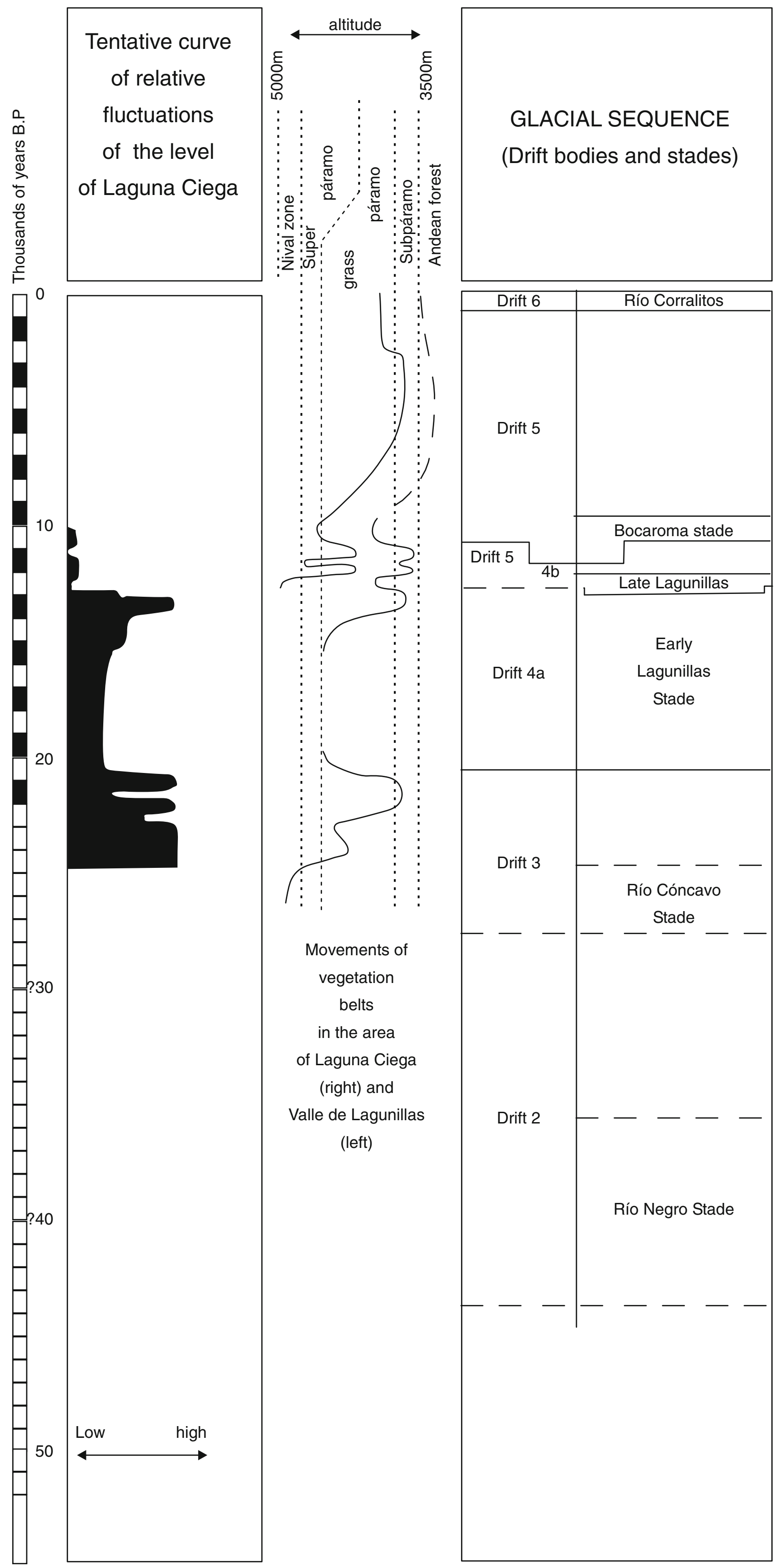


Fig. 7.8 Diagram showing the chronology of climatic fluctuations during the last 45,000 years BP and their influence of Ciega Lake sediments, vegetation belts and glacial deposits sequence. Adapted from Van der Hammen et al. 1981

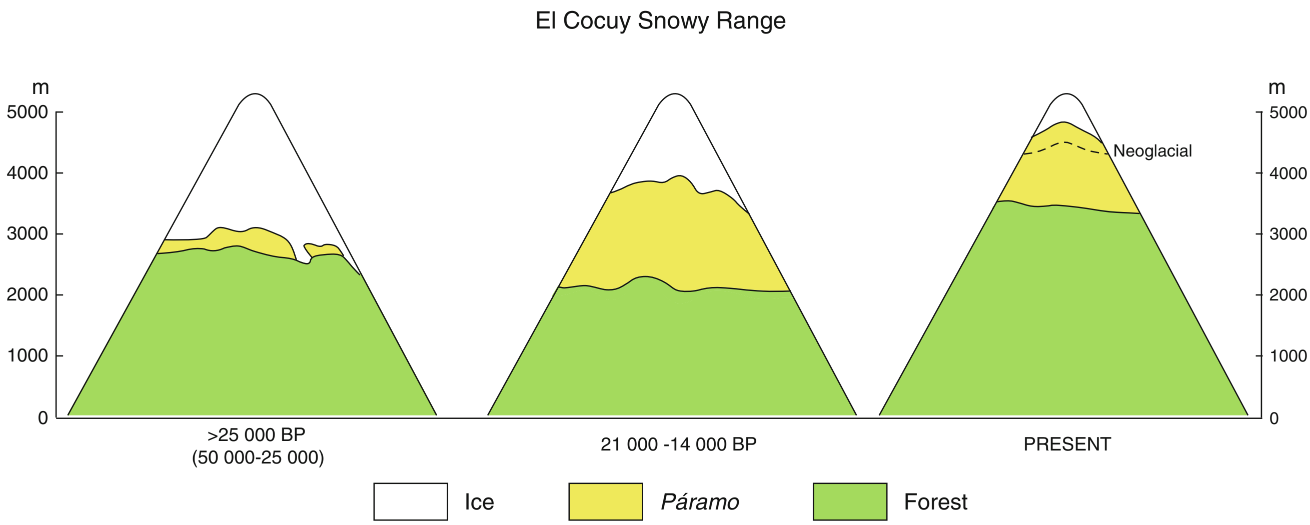


Fig. 7.9 Simplified diagram showing altitudinal changes of vegetation belts since the Last Glacial Maximum. (Adapted from Van del Hammen 1992)

Fig. 7.10 El Concavo, la Cueva site. In the foreground, the *curve*-shaped terminal moraines deposited by the glacier which occupied the Concavito River Valley. *Photography* Domingo Mendivelso

Fig. 7.11 Black Ritacuba glacier. Notice the numerous cracks probably related to fast ice fusion, the vertical scarps, and the debris-covered slopes. *Photography* Michel Hermelin

Fig. 7.12 Structural slope developed on sandstones from the Aguardiente Formation, polished by ice of the retreating white Ritacuba Glacier. *Photography* Michel Hermelin

Fig. 7.13 Front view of lateral moraines left by White Campanilla Glacier (in the background) during its retreat. *Photography* Domingo Mendivelso

can be observed (Fig. 7.5). On the western side of Sierra lies a large homoclinal-type structure; on its crest, well-stratified rocks from the Aguardiente Formation form a scarp on which lie the present glacial relicts.

7.4 Ice Retreat

The lowest altitude (about 4400 m a.s.l.) was reached by glaciers at the end of Little Ice Age around 1850, a date which coincides with that of the watercolor painted in 1851 during the "Comision Corográfica" (see Fig. 7.3a). Glaciers were larger on the western slopes due to the gentle inclination produced by tilted sandstone beds and shorter on the steeper eastern slopes. However, more abundant rainfall in the west permitted the glaciers to reach 4200 m a.s.l., where relief was not too steep.

The ice cap is receding very rapidly, as show in the photo of Fig. 7.3b, taken at the same place where the painting was made 150 years before. What was probably a single mass of ice at the middle of nineteenth century became a series of isolated glaciers which cover an area of about 16 km^2 which are receding at a rate of about 1 km^2/year. This process is clearly evidenced by satellite images taken in 1986, 2003, and 2014 (Fig. 7.6a–c, respectively) where ice retreat is perfectly visible for the last three decades.

Van der Hammen and collaborators carried out detailed studies on the landscape evolution during Upper Pleistocene and Holocene (Gonzalez et al. 1965; Van der Hammen et al. 1981) using photo interpretation, field observation, palynological analysis of lake sediments, and radiocarbon dating. They obtained a complete description of the climate variations and ice cover changes for the last 40,000 years for the eastern slope of the ECSS (Fig. 7.7 and 7.8), where they identified six different glacial drifts and stades. The variation of vegetation belts in the ECSS during the last 40 000 years is summarized in Fig. 7.9 (Van der Hammen 1992).

More recently, Jomelli et al. (2014), using ^{10}Be and ^{3}He isotopes accumulation by cosmic rays in the Ritacuba Negro moraines (Fig. 7.14), were able to determine the influence of the Antartic Cold Reversal (14,500–12,900 years ago) and of the Younger Dryas (12,800–11,500 years ago) on the rate of glacial retreat in the Northern Andes.

Fig. 7.14 Ritacuba moraines along the Cardenillo River. In the background folded sandstone strata polished by ice. *Photography* Michel Hermelin

Fig. 7.15 Cirque-type glacier developed on tthe dip slope of slightly inclined sandstone bed, near Ritacuba Blanco. *Photo* Domingo Mendivelso

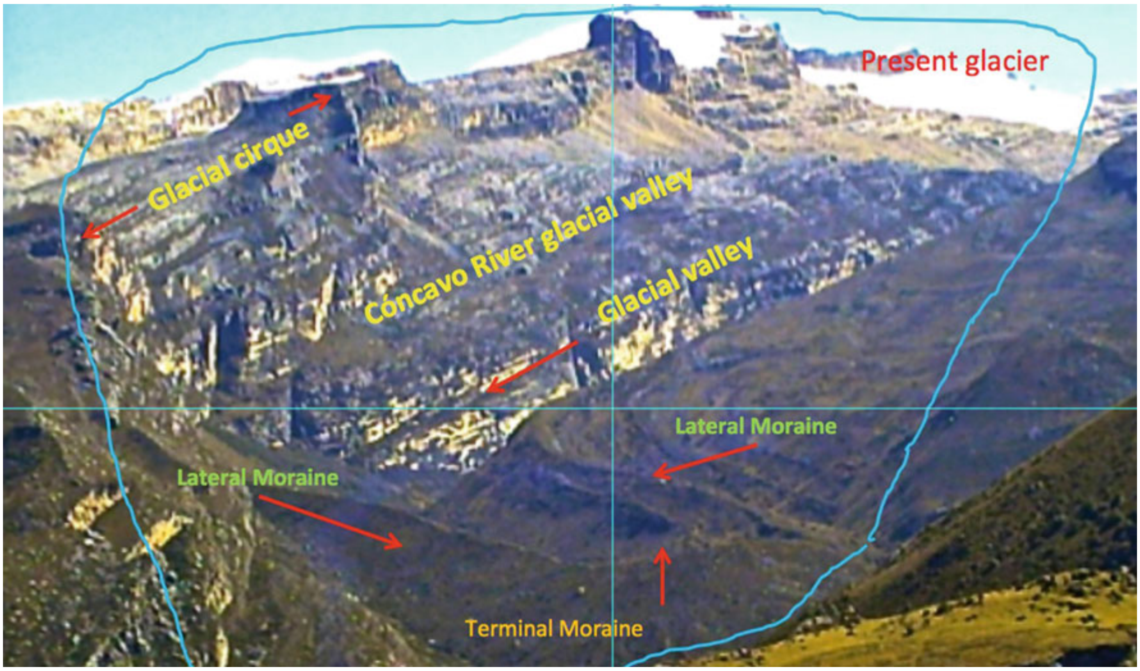
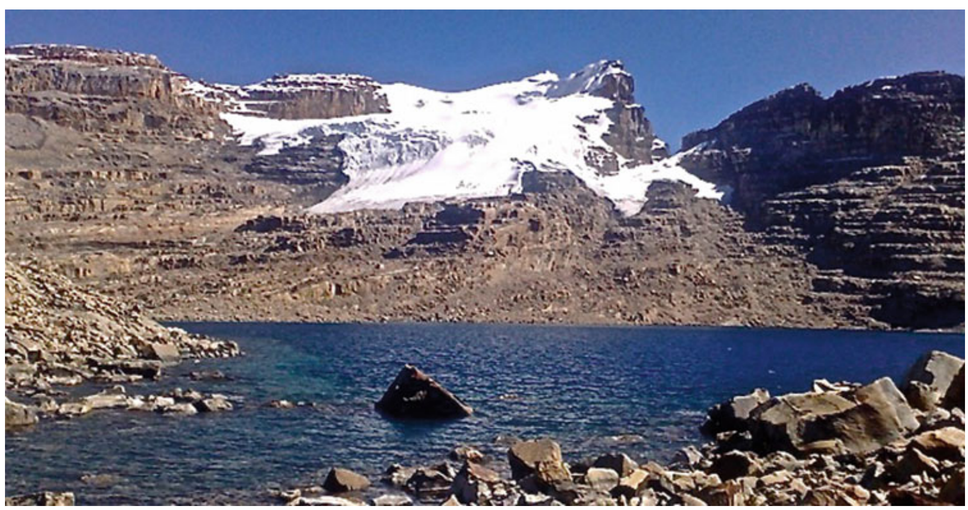


Fig. 7.16 The Río Cóncavo River ancient glacial valley showing several cirques. *Photography* Domingo Mendivelso

Fig. 7.17 Laguna Grande de la Sierra (Sierra Big Lake), La Cueva site, Güicán; the second largest in the ECSN. *Photography* Domingo Mendivelso



7.5 Geomorphology

Land forms are associated with ice activity and were modified by fluvial and slope processes after ice melting. The preservation of ice-formed features is inversely proportional to their age, thus directly related to their altitude on the other hand; the effectiveness of geomorphic processes acting in tropical periglacial environments is still a subject of discussion (Khobzi 1981). Ice formation and thawing operate only on a day–night basis, thus reducing the capacity cryoclastic processes. Khobzi (1981) attributes the relatively compact aspect of moraines to this phenomenon. Relatively, scares occurrence of solifluxion is also noticeable.

Important landforms which can be observed in the ECSS include the following:

- Ice caps deposited on slightly inclined slopes, generally developed on sandstone beds (El Cóncavo Fig. 7.10) or on steeper topography (Ritacuba Blanco) forming cirque-like accumulations (Fig. 7.11).
- U-shaped valleys excavated by glaciers (Fig. 7.16) and polished rock surfaces (Fig. 7.12),

- Moraines, which reach a width of 300 m and 80-100 m height. Front and particularly when ice movements were parallel to bedding in resistant rocks lateral moraines are the best preserved deposits. They form elongated bodies that end forming frontal arcs. Recessional moraines generally follow contour lines (Figs. 7.7, 7.13, 7.14, and 7.16).
- Cirques which develop on dip slope of tilted sedimentary strata (Fig. 7.15) or on steeper slopes or scarps (Figs. 7.10, 7.11, and 7.16). In the lower part of the Concavo Glacier (Fig. 7.10), the concave part of the rocky scarp was excavated by the glacier which also generates a cirque located on the dip surface of the tilted sandstone beds (defined by shadows on the ice). Debris accumulation on the foot of the vertical cliff are re-transported glacial materials, with probably little influence of cryoclastic processes (Khobzi 1981)
- Colluvial deposits on the foot of scarps mainly composed of blocks (Fig. 7.10).
- Lakes are numerous and may be related to old cirques or to valley dammed by moraine deposits (Fig. 7.17). Most of the lower lakes are now filled with sediments produced by surrounding surface erosion (Fig. 7.7).

7.6 Access and Recommendations

The best access from Bogotá is to follow the Northern Highway to Tunja, Paipa, and Duitama; then secondary roads to Santa Rosa de Viterbo, Cerinza, Belén, Susacón, Soata, Boavita, El Uvito, San Mateo, and Guacamayas, where it is possible to reach El Cocuy or Güicán. From both villages at least four different trails lead to the glaciers. Comfortable lodging can be found in both places (Fig. 7.1, 7.2).

References

Brűnnschweiler D (1981) Glacial and periglacial form systems of the Colombian Quaternary. Revista CIAF 6(1–3):53–76 (Bogotá)

Ceballos JL (2006) Monitoreo de los Glaciares de la Sierra Nevada de El Cocuy

Codazzi A (1851) Descripción del Cantón de Sogamoso, Provincia de Tundama in Geografía Física y Política de La Confederación Granadina Vol. III, Estado de Boyacá, Tomo III: Antiguas Provincias de Tunja y Tundama y de los cantones de Chiquinquirá y Moniquirá, Work directed by General Agustín Codazzi. Edition, Analysis and Commentaries by Domínguez CA, Barona G, Figueroa A y Gómez AJ, Universidad Nacional, UPTC y del Cauca, 2003

Fabre A (1981) Estratigrafía de la Sierra Nevada del Cocuy. Revista Norandina, Boyacá y Arauca, Cordillera Oriental (Colombia)

Flórez A (2003) Colombia: Evolución de sus relieves y modelados. National University of Colombia, Bogotá 240 p

González E, van der Hammen Th, Flint RT (1965) Late Quaternary glacial and vegetacional sequence in Valle de Lagunillas. Sierra Nevada del Cocuy. Colombia. Leidse Geologische Mededelingen 32:157–182

Hettner A (1976) Viaje por los Andes Colombianos (1882–1884) Translation by H. Henk, Banco de la República, Bogotá 415 p

IDEAM (1997) Los Glaciares Colombianos, Expresión del cambio climático. Available at www.ideam.gov.co

IDEAM (2013) Glaciares de Colombia: más que montañas con hielo

Jomelli V, Favier V; Vuille M, Braucher R, Martin L, Blard PH, Colose C, Brunstein D, He F, Khodri M, Bourlés D, Leanni L, Rinterknecht V, Grancher D, Francou B, Ceballos JL, Fonseca F, Liu Z, Otto- Bliesnes B (2014) A major advance of tropical Andean glaciers during the Antartic cold reversal doi:10.1038/Nature13546

Khobzi J (1981) Aspectos de geomorfología periglacial, glaciar y fluvioglaciar en las montañas tropicales húmedas norandinas. Geología Norandina 3:37–43

Kraus E (1938) Excursión al Nevado del Cocuy (Revista PAN, Bogotá). Reproducido en Revista Campo Abierto, No. 2, División de Montañismo, p. 7–9

Oppenheim V (1941) Pleistocene glaciations in Colombia, SA Revista Academia Colombiana de Ciencias Exactas, Físicas y Naturales 5 (17):76–83

Parques Nacionales (2014) Manual para Caminantes, Parque Nacional Natural El Cocuy, Ministerio de Ambiente y Desarrollo Sostenible, Bogotá

Servicio Geológico Colombiano (formerly INGEOMINAS); Geología de la Plancha No. 137, El Cocuy, Scale 1:100 000, from 1982, published in 1985

Servicio Geologico Colombiano (formerly INGEOMINAS); Geología de la Plancha No. 153, Chita, Scale 1:100 000, from 1982, published in 1985

Van der Hammen Th (1992) Historia, Ecología y Vegetación Bogotá: Fondo FEN Colombia. Corporación Colombiana para la Amazonia Araracuara, Fondo de Promoción de la Cultura 411 p

Van der Hammen Th, Bareld J, de Jong H, de Veers AA (1981) Glacial sequence and environmental history in the Sierra Nevada del Cocuy (Colombia). Paleogeography, Paleoclimatology, Paleoecology v 8 p

Tota Lake

8

Héctor Fonseca and Ítalo Reyes

Abstract

Tota Lake, the largest in Colombia, is a high mountain depression located at 3000 m a.s.l. Its origin is due to geologic and geomorphic processes, which occurred since the beginning of the Eastern Cordillera uplift and the formation of an elongated closed basin associated to folding and inverse faulting with the SW–NE direction and a preferential vergence to the SE. The final process was the emplacement of large fluvioglacial deposits during the last deglaciation of the surrounding mountains, which reach altitudes of 3800 m a.s.l. The lake drains toward the Oriental plains and is one of the Upía River sources. A concrete dam was built to control the lake level. Due to the quality of its landscape and its ecological, environmental and social function, as well as the present impacts produced by human activities that may have negative consequences on its sustainability, Tota has been included in the list of Ramsar International Convention of important wetlands in Colombia.

Keyword

High altitude lake

8.1 Introduction

Tota Lake is a depression in the high Andes, located in the Department (State) of Boyacá, in the eastern part of the Eastern Cordillera, precisely on the water divide between the Orinoco River and the Magdalena River basins. It occupies part of the municipalities of Aquitania (aka *Pueblo Viejo*), Tota, and Cuítiva. It covers 55.94 km^2 and contains 2023 × 10^6 m^3 of water when it reaches the altitude of 3015.03 m a.s.l. Its perimeter measures 47 km (approximately 7 × 12 km). Its maximum depth is 67 m and the average depth is 34 m (Pérez 2013). Surrounding fluvial basins are covered by "*páramo*" biomes; they reach 3800 m a.s.l. and cover 224 km^2, including the lake and the Olarte River basin (Fig. 8.1). The lake has fostered the development of activities in the lake itself, in its basin, and in the surrounding region (water supply for several municipalities and factories). Its landscape and its ecological, environmental, and social function, together with the impacts arising from activities that may endanger its sustainability, enabled its inclusion in the Ramsar International Convention on Wetlands, in order to encourage conservation and rational use of the lake and its surroundings through local, regional, and national activities complemented by international cooperation.

According to M. Ancízar (in Codazzi 1851–2003), Juan de San Martín was the first Spaniard to reach Tota Lake in 1537, guided by Indians from the village of Iza. The same author states that more than a century after the conquest,

H. Fonseca (✉) · Í. Reyes
UPTC Universidad Pedagógica y Tecnológica de Colombia, Escuela de Ingeniería Geológica, Sogamoso, Colombia
e-mail: hector.fonseca@uptc.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_8

Fig. 8.1 Panoramic view of Tota Lake. Playa Blanca (White Beach) can be seen in the foreground; Punta Larga (Long Cape) on the *left*; San Pedro and Cerrochico Islands in the *right background*. *Photography* Hector Fonseca

legends about "a gigantic black fish with a bull head and the size of a whale," called "the devil" by the Indians, prohibited people from accessing the lake and its islands. The report of the *Comisión Corográfica* (the first Colombian Geographical Survey in 1851) describes several well-established villages around the lake (Codazzi 1851–2003). Hettner, a famous nineteenth century German geomorphologist, left a good description of Tota, which he visited the area in 1883/1884 (Hettner 1976).

Several geological and geomorphological aspects of the lake and its immediate surroundings are presented here. The lake can be visited following the road system that surrounds it and may be easily reached in a 45 min car ride from the city of Sogamoso by following the paved road toward Cusiana or Iza (Fig. 8.2).

8.2 Geology

Tota Lake is the result of geological processes related to the Colombian Eastern Cordillera uplift and deformations of the Upper-Cretaceous to Lower-Cenozoic sedimentary sequence, which predominates in the Sogamoso–Paz de Río sedimentary basin (Ulloa et al. 1998). Its present extension and storage capacity were strongly influenced by siltation due to the growth of alluvial fans located in northern, eastern, and southern areas. These sedimentation processes are still active, as evidenced by lake and recent slope deposits.

The Tota Lake basin was formed on Upper Cretaceous to Paleogene sedimentary rocks corresponding to the following units (Fig. 8.3):

- The Chipaque Formation. Outcrops are located in the anticline nuclei and along inverse faults with large displacements (Reyes 1982). On the western side, between the towns of Cuítiva and Tota, the upper part of the formation consists of black slaty claystones with local intercalations of thin sandstone beds. The same stratigraphic level can be observed in Llano de Alarcón, on the northern shore; in the Saguatá Cove, between Susacá Peninsula and the Los Pozos River, and in the Desaguadero Cove.
- The Ermitaño Formation. It is well exposed on the northeast shore along the road between Aquitania and the Susacá Peninsula. The lower part has a thickness of about 200 m and consists of black slaty claystones intercalated with thick sandstone beds. The lower sandstone, about 10 m thick, is a characteristic stratigraphic level well-known in the region. The medium part, with a thickness of about 450 m, is formed by cherts and sandstone beds alternating with thick claystone beds, which signal contact with the overlying Guaduas Formation. These sandstones lie on a group of cherts, alternating with claystones and two marker beds consisting of lumachelle limestone.
- The Guaduas Formation can be observed in the northern area of the fluvial basin. It consists of 190 m of black slaty claystone with scarce sandy levels in its lower part; the upper part is formed by alternate beds of sandstones, claystones, and coal seams.
- The Socha Sandstone Formation is present on the southwestern shore of the lake, in the western flank of the syncline that surrounds the Playa Blanca Cove. It is

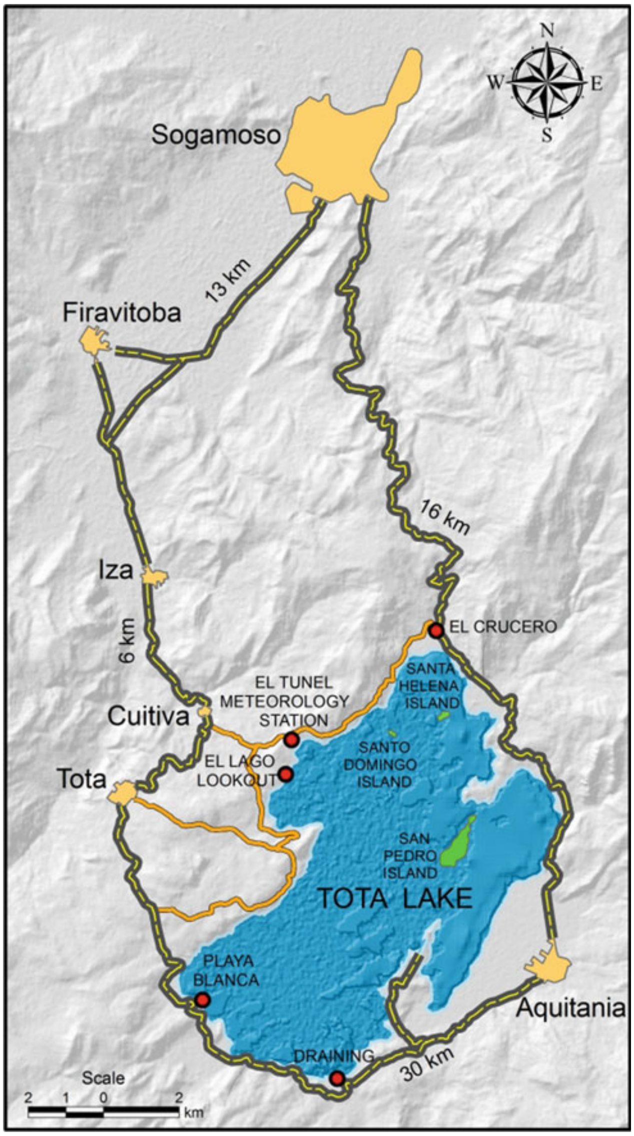


Fig. 8.2 Road access to Tota Lake from Sogamosos

formed by thick red sandstone beds in the lower part, with soft clay zones in the upper part (Reyes 1982).

- The Picacho Formation consists of thick beds of white, friable, and coarse-grained sandstones that are used locally as building material. It has been described in the syncline that forms the Playa Blanca Cove.
- Quaternary deposits, which partially cover the rocks surrounding Tota Lake, consist of large alluvial cones, lacustrine deposits, slope deposits, and recent deposits located in the stream beds, beaches, bottom of the lake, and deltas. Well-exposed alluvial cones can be observed in the Tobal and Los Pozos Rivers, east of the lake, where the town of Aquitania has been built; and in the Olarte River in the south, in the sector comprised between the outlet and the Upía gap.

From the tectonic standpoint, the area is arranged in the SW–NE folds associated with large longitudinal faults with a thrust component that dips generally toward the SE. Strike faults cross the tectonic train and displace the fold axes, creating a complex structure. The main folds are (Fig. 8.3):

- The Los Pozos Anticline, an asymmetric fold whose axis stretches on the NW shore of the bay, formed between the Tobal River and the Susacá Peninsula.
- The Alarcón Anticline, a symmetric fold whose flanks lose their inclination toward SW; its axis crosses the Llano de Alarcón Bay and the Santa Helena Island. The syncline that was initially formed between these two structures was affected by the La Puerta Fault and lost its structural individuality (Reyes 1982).
- The Pueblo Viejo Syncline is an asymmetrical structure with a more inclined eastern flank; it can be observed in north of Aquitania, with numerous dislocations caused by transversal faults; its western flank gives its shape to the El Potrero Peninsula.
- The Balcones Syncline is an asymmetrical fold with slightly inclined flanks dislocated by transverse faults; it plunges toward SW, as observed in the Cuítiva tunnel west of the lake.
- The Cuítiva Anticline is asymmetrical; it is associated with a longitudinal fault that affected its western flank.

The structural difference between the NE and SW part of Tota Lake is notorious due to the presence of a large transverse dislocation, the Aquitania Fault, which stretches between the villages of Aquitania and Cuítiva, displacing the structure axes. Other dislocations that affect the lake basin are La Puerta Fault, which divides the lake longitudinally in two almost symmetrical parts, and Pueblo Viejo Fault, which uplifts the S–E–NE area and permits the outcropping of Middle Cretaceous rocks. And this transforms the lake basin in a small dislocated syncline.

8.3 Geomorphology of the Lake Basin

Tota Lake occupies a high mountain depression. Its maximum water level is controlled by a man-made structure built where surplus waters cut a 2-m-deep channel in sediments from the Olarte River alluvial cone. This place coincides with one of the sources of the Upía River, which drains into the Meta River. This level is located at an altitude of 3015 m a. s. l.

The lake is elongated in SW–NE direction, with a maximum length of 12 km. On the eastern shore, the El Potrero (south) and the Susacá (north) Peninsulas, together with the San Pedro and Cerro Chico Islands, form a continuous

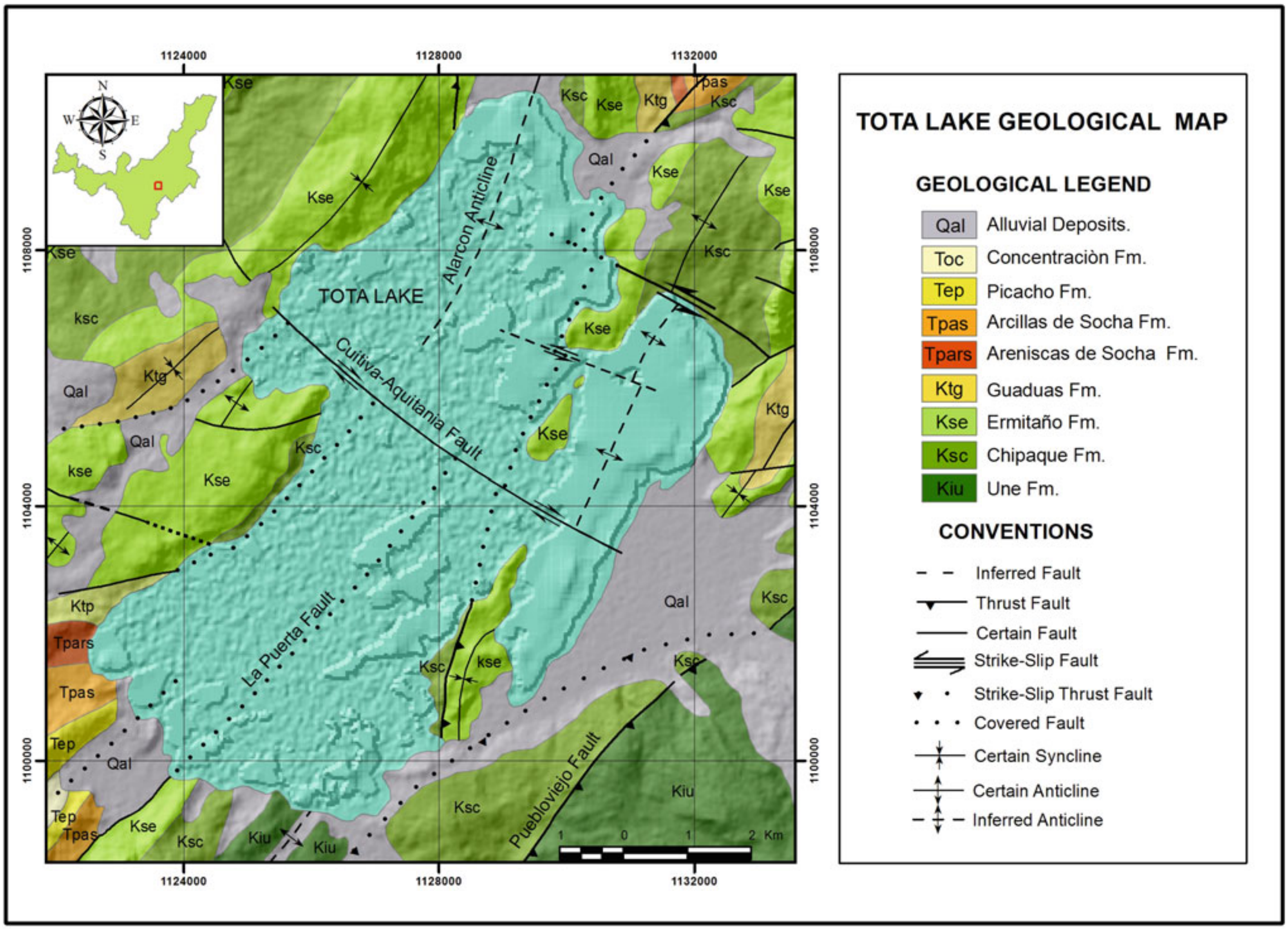


Fig. 8.3 Geological map (Reyes 1982)

longitudinal ridge consisting of hard rocks that enclose a secondary basin, entirely filled by sediments deposited by the Tobal and the Los Pozos Rivers. On the western edge, the lakeshore is rocky and forms the Punta Larga Peninsula and two small islands: Santo Domingo and Santa Helena (Fig. 8.4).

Tota Lake was formed under the influence of endogenous geological processes, lithological conditions, and regional structural evolution (Reyes 1982). Its extension and capacity were highly influenced by alluvial cones filling in the east and south sectors. Structural influence on the shape of the lake is notorious and its longitudinal extent is parallel to the regional tectonic direction. Peninsulas and islands coincide with the main anticlines, Alarcón and Los Pozos (Reyes 1982).

The coastal system has morphological features that are further related to lithology. The largest bays are located in areas underlain by clayey formation, such as the Alarcón, Los Pozos, Saguatá, and DesaguaderoBays, which are related to the Chipaque Formation. The Boquerón de Cuítiva Bay corresponds to claystones from the Ermitaño Formation; the Donsiquirá and La Puerta Bays coincide with the Guaduas Formation outcrops.

On the other hand, islands and peninsulas correspond to outcrops of harder rocks, such as the El Potrero, Susacá, and Punta Larga Peninsulas and the San Pedro Island, with rocky slopes underlain by sandstones and cherts from the Ermitaño Formation. Playa Blanca Bay and beach are located on the axis of a narrow syncline that plunges toward the center of the lake; the two capes that limit them are formed by thick sandstone strata. The Chipaqué Formation (correlated with the Conejo and Churuvita Formations) is in the axis of the Alarcón and Los Pozos Anticlines and their SW prolongations and the bays are the expression of these structures.

Sediment supply also plays an important role in shaping the morphology of the lake basin. Alluvial cones are present at the mouths of the Donsiquirá, El Salitre, Los Ricos (Llanos de Alarcón), Los Pozos, Tobal, Olarte, La Puerta, and Buenos Aires rivers. Most of the them, and in particular those located in the north and east, form deltas, while the western shore shows a tendency to host extensive beaches, as observed in the Donsiquirá, Playa Blanca, La Puerta, Saguatá, and

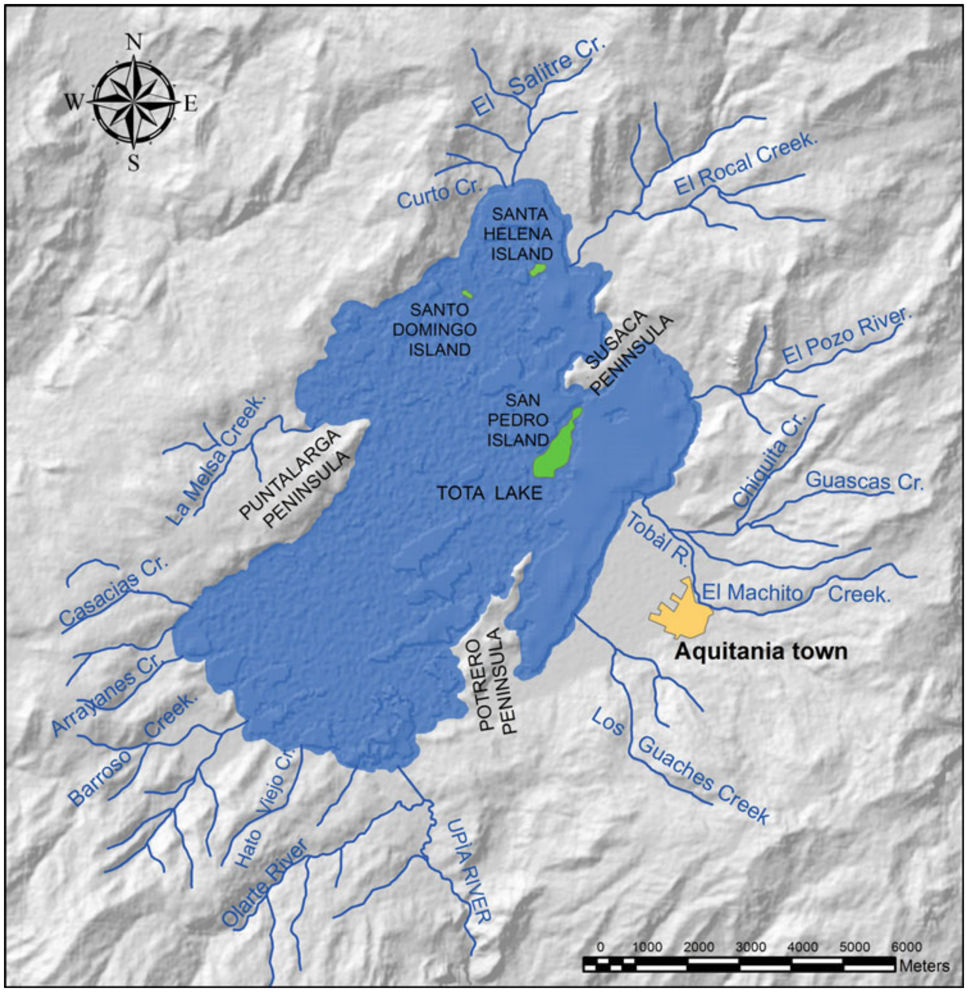


Fig. 8.4 Coastal system and main tributaries

Boquerón de Cuítiva Bays. Streams bringing more sediments show a higher hydrological development. The Hato Laguna and Tobal Rivers, the latter with the highest sedimentation rate, as expressed by a 450 ha area, fill the Aquitania Plain, where onions are the main crop (Reyes 1982).

8.4 Origin of the Lake

Grosse (1928) considered that Tota Lake was a natural reservoir dammed by a rocky bar in the Boquerón de Upía site. The present water level was induced by erosion in the outlet. It is very difficult to demonstrate that the rocky bar was formed by the reactivation of tectonic movements after the filling of the lake (Reyes 1982).

Damming of the lake was probably the result of growth of the Olarte River alluvial cone. Flooding of a closed basin, due to glacial and fluvioglacial activity, is perhaps the most acceptable explanation for the origin of the lake (Reyes 1982). During the cordillera uplift, when erosion began, clayey formations were rapidly excavated, giving rise to valleys parallel to the structural strike; these valleys drained through deep gorges cut in areas of large transversal faults (Reyes 1982).

The lake was constantly exposed to changes. From the observation of their large alluvial cones, it can be inferred that the Hato Laguna, Tobal, and Olarte rivers were the largest tributaries; on the basis of the highest fluvial terrace level that exists in the area and of the presence of chaotic cobble deposits at Boquerón de Cuítiva, which indicate a turbulent input, evidence exists that the lake level reached an altitude 50 m higher than its present altitude (Reyes 1982). Regressive cutting by the Upía River incised the sandstone bar, where the lake drain currently lies. The Olarte River was captured by the Upía River and became its tributary, instead of flowing directly into the lake, as evidenced by a series of abandoned meanders. Currently, before engineering works started at Desaguadero, the Olarte and Upía rivers can be identified as a single stream with an individual thalweg followed by numerous meanders (Reyes 1982).

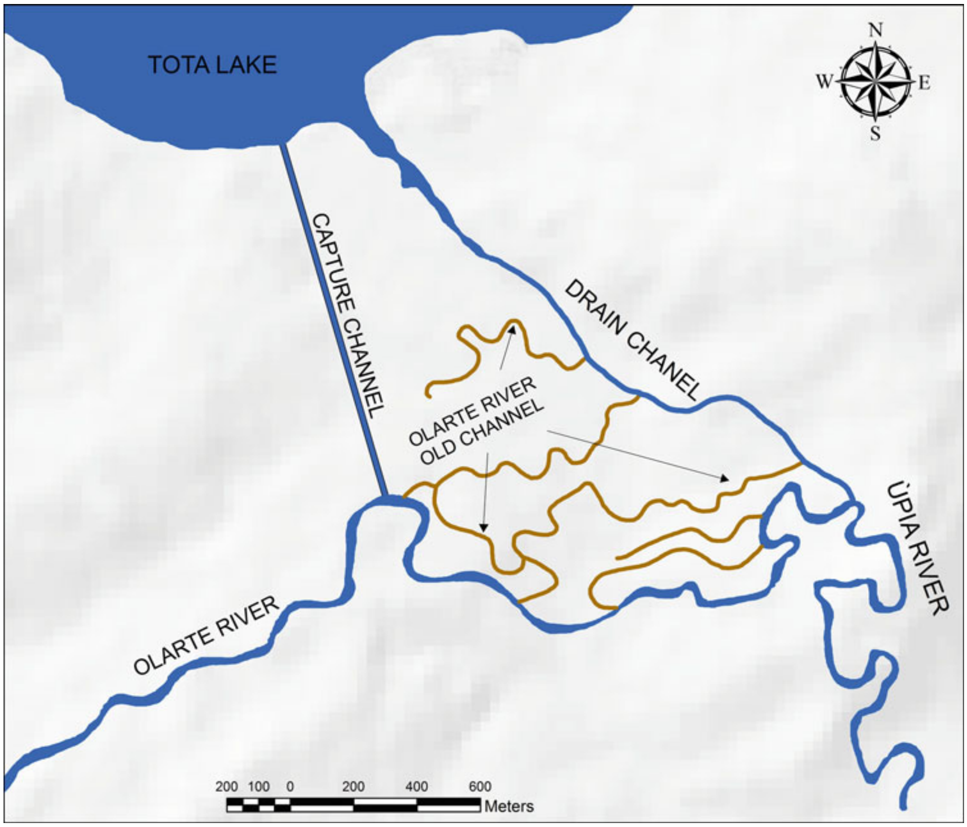


Fig. 8.5 Tota Lake drain to Upia River. (Italo Reyes)

Fig. 8.6 Sediment accumulation now used for agriculture (onion crops). *Photography* Michel Hermelin

Fig. 8.7 The Tota Lake from El Crucero. *Photography* Michel Hermelin

Except for man-made tunnels, the only river draining the lake is the Upía–Olarte river (Fig. 8.5) checked by an overflow structure at an altitude of the 3015 m a.s.l.

Extensive alluvial cones of the larger tributaries, the Tobal, and Hato Laguna Rivers, whose sources are at 3800 m a.s.l. (Fig. 8.6), evidence the importance of deglaciation in the lake formation. The Cusiana River source is also located at a similar altitude and shows abundant filled lakes (Toquilla); in both cases, large water and sediment supply can probably be correlated with morphogenic crises (Fig. 8.7).

8.5 Hydrological Aspects

Rain patterns in the lake area are unimodal, with an average annual precipitation of 1000 mm in the eastern part of the lake and 730 mm in the western part, with a maximum toward June–July and a minimum in January–February. Medium multi-annual relative humidity is near 82 %, but may reach 90 % during the rainy season and descend to 70 % during the dry period. On an annual basis, 54 % of the rain falling into the basin is converted into runoff. The remnant goes into evapotranspiration or is infiltrated in the underlying rocks. Residence time of the lake waters was estimated at 30 years by isotopic analysis (Cañón and Rodríguez 2002). The maximum level was measured in 1971 (3015.65 m a.s.l.) and the minimum level (1975) was 3013.79 m a.s.l. The latter was probably more due to evaporation rather than to water extraction. Isotopic balance suggests that losses due to infiltration are not significant (Cañón and Rodríguez 2002).

Hydric exploitation of the lake began in 1928, when the first tunnel (called *Cuítiva*) was built in order to irrigate the La Compañía Hacienda, in the Firavitoba–Iza Valley. In 1952, the Paz de Rio steelwork company bought the tunnel and improved its efficiency with siphons. In the same year, this company constructed the outflow at El Desaguadero, in order to raise the lake level and to increase the usable discharges. In 1990, 1800 l/s were extracted from the lake to supply water to several towns (Sogamoso, Tota, Cuítiva, Iza, and Nobsa) for industrial and domestic use. Toward the end of the 1990s, the outlet discharge was greatly reduced; today, it is estimated at 2000 l/s.

8.6 Lake Sediment Filling

With a supposed annual sediment supply of 20 000 m^3, 100 my would be necessary to fill the lake, taking into account a total volume of 1942 Mm^3. Another estimate from Hidroestudios (1978) gives an annual supply of 90,000 m^3. A more recent study (Cañón and Rodríguez 2002) estimates that annual sediment supply is 2.27 Mm^3; in this case, only 890 years would be necessary to fill the lake.

It is difficult to accept these values, since changes in land use of the surrounding slopes may have increased the erosion rate, but cannot be compared with sediment supply during morphogenic crises or during avulsion processes, which gave rise to the emplacement of the large alluvial cones by the Hato Laguna, Tobal, and Olarte rivers, during a lapse of time which was indeed much longer than the one estimated by the authors for the complete filling of the lake. On the other hand, the disappearance of the lake due to the erosion of its drain is out of the question as long as it is under human control.

Acknowledgments This paper was written in collaboration with Domingo Mendivelso López, Luis David Mesa, Camilo Neita Talero, Holman Ávila, and Edison Ángel.

References

Cañón J, Rodríguez C (2002) Balance Hídrico del lago Tota y estudio preliminar del comportamiento hidráulico en lagos. Masters thesis in Water Resources, Faculty of Engineering, National University of Colombia, Bogotá

Codazzi A (1851) Descripción del Cantón de Sogamoso, Provincia de Tundama in Geografía Física y Política de La Confederación Granadina Vol. III, Estado de Boyacá, Tomo III: Antiguas Provincias de Tunja y Tundama y de los cantones de Chiquinquirrá y Moniquirá, Work directed by General Agustín Codazzi. In: Domínguez CA, Barona G, Figueroa y A, Gómez AJ, Universidad Nacional, UPTC y del Cauca, 2003

Grosse E (1928) Informe geológico sobre la hoya hidrográfica de La laguna de Tota, Departamento de Boyacá. Compilación de Estudios Geológicos Oficiales Colombia. (1953). Tomo III, p. 233–243. Servicio Geológico Colombiano, Bogotá

Hettner A (1976) Viaje por los Andes Colombianos (1882–1884). (trans: Henk H). Banco de la República, Bogotá, 415 p

HIDROESTUDIOS Ltda. (1978) Estudio de conservación y manejo del lago de Tota y su cuenca. Corporación Autónoma Regional CAR. FONADE, Bogotá

Pérez A (2013) El Lago de Tota: un ejemplo de lo que no debe hacer en materia ambiental. In: Colombia, ed. Kimpress Ltda, Bogotá

Reyes Í (1982) Geología del lago de Tota. Universidad Pedagógica y Tecnológica de Colombia, UPTC

Ulloa C, Rodríguez E, Escobar R (1998) Geología de la Plancha 192, Laguna de Tota, INGEOMINAS

9 Guatavita Lake

Orlando Navas

Abstract

The original dwellers of the Bogotá highlands considered lakes as sacred places, and Guatavita was one of the most important lakes, as it was where gold offering to the gods took place. It is located at a 2 h car ride north of Bogota, at an altitude of 3050 m a.s.l. and its curious rounded shape fostered the development of several hypotheses on its origin: meteoritic, salt diapir dissolution, volcanic, and tectonic. A detailed study carried out on Cretaceous sedimentary rocks which underlie it and their structural components did not offer a better solution and the origin of the lake is still a matter of discussion. Several attempts to empty the lake, the last one from the beginning of twentieth century, left a large scar in one of the steep slopes which surround the lake basin.

Keyword

High altitude lake

9.1 Introduction

Guatavita was an important place for religious ceremonies held by the Chibchas, the former inhabitants of the Bogotá plateau (before the Spanish conquest). Besides its tradition and legends, it remains a place worth to be visited for the beauty and uniqueness of its landscape, located at an altitude of 3050 m a.s.l. The lake is located in a crater-like depression covered by bush vegetation and its origin has aroused many discussions amongst earth scientists.

Guatavita Lake is located approximately 55 km to the north-east from Bogotá. It can be reached by road, with the initial 50 km on a highway, then a secondary road to Sesquile and finally a 5 km paved road to the lake (Fig. 9.1a, b). The lake can be visited under the guidance provided by the regional environment corporation (CAR); visitors are received in a reconstructed indigenous building and follow a walking itinerary around the eastern flank of the lake.

Guatavita Lake is situated at the north-eastern end of the Peña Blanca ridge, which reaches the altitude of 3250 m a.s.l. This ridge is the eastern boundary of one of the prolongations of the northern part of the "Sabana" de Bogotá, near its northern limit. The area belongs to the low montane humid forest, (following Holdridge's classification), which receives an average rainfall of 1000–2000 mm/year and presents temperatures between 12 and 18 °C (IGAC 1977). It is presently covered by protected secondary forest, but was exposed to periglacial influence during the last glacial maximum, about 20,000 years ago. The vegetation at that time was "*páramo*," as defined in Chap. 1. The almost perfect circular shape of the slopes surrounding the lake has always attracted the attention of visitors and therefore the hollow has often been named a "crater." Several attempts to drain the lake were made during nineteenth century in order to recover the Chibcha gold objects which, following the tradition, were thrown every year in the lake during a religious ceremony. These works left an outlet which has been modified by erosion processes (Figs. 9.2 and 9.3). The

O. Navas (✉)
Consejo Profesional de Geología, Bogotá, Colombia
e-mail: onavas2011@gmail.com

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_9

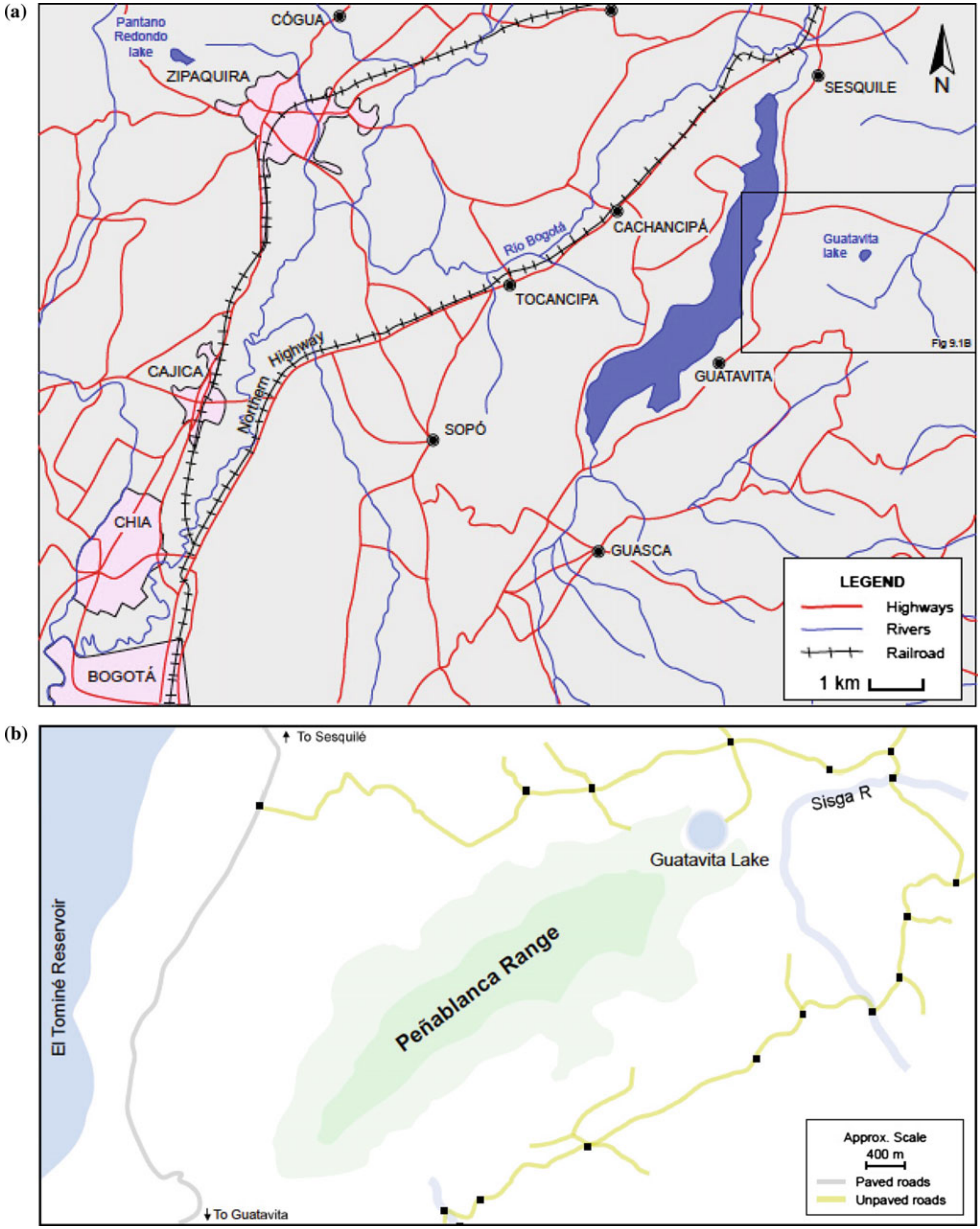


Fig. 9.1 **a** Road map from Bogotá to Guatavita. **b** Detailed map of the Guatavita Lake area

Fig. 9.2 Partial view of Guatavita Lake. The artificial outlet is on the left of the photography. Secondary forest covers most of the adjacent slopes. *Photography* Michel Hermelin

circular shape of the lake is slightly modified in the NW part, apparently due to the influence of landslides which were probably related to the desiccation episodes. The crater itself has a diameter of 400 m, its rims are at 3050 m a.s.l. and the water surface lies 100 m below (Fig. 9.4).

9.2 Regional Geology

The area is underlain by Upper Cretaceous and Cenozoic rocks and Quaternary deposits,

A summary of the regional stratigraphy is as follows:

- Upper Cretaceous
  - Upper Guadalupe Group (marine)

    Arenisca Dura (Hard Sandstone) composed of quartzitic, gray to white yellowish, fine-grained sandstones in thick strata, intercalated with siliceous sandstones. They form the cornice located at the south of the lake.

    Chert and Plaeners Formations, composed of siltstone and chert layers

    Labor and Tierna Formations. Labor consists of mudstones. Tierna (Arenisca Tierna, soft sandstone) is a clayey sandstone.
- Cenozoic
  - Guaduas Formation (continental) the upper part is formed by gray-laminated mudstone. The lower parts are purple, mottled sandstones with coal seams, and very thin sandstone intercalations.
  - Cacho Formation: friable, ferruginous, medium- to coarse-grained sandstones, occasionally conglomeratic.
  - Bogotá Formation: colluvial sequence of purple mudstones
  - Quaternary: unconsolidated deposits of silts one angular fragment covered by a thick, black soil.

The Guaduas Formation is considered to have been deposited during the Cretaceous–Cenozoic transition. A detailed lithologic description for Upper Guadalupe and Lower Guaduas is given in Fig. 9.5.

Fig. 9.3 Artificial drain cut in nineteenth century in the NW part of the lake. Gullying due to later surface erosion. *Photography* Michel Hermelin

Several folds and faults are present in the area, associated with the main structure called the Guatavita Anticline. The anticline main axis strikes SW–NE and disappears towards the NE under layers of the Guaduas Formation. Its periclinal closing forced the Liditas or Plaeners Formation layers into a vertical and semi-circular position, producing the closing of the lake. There are two main faults, normal to the Guatavita Anticline axis and one of them cuts the lake (Fig. 9.6).

9.3 Hypotheses on the Origin of the Lake

Four different hypotheses have been proposed to explain the unusual position and shape of the lake. According to various authors, the lake origin may be related to meteorite impact, collapse of a salt dome, long-term denudation and erosion, or volcanic processes.

Raasveldt (1954) favored the origin of the lake due to impact of an extraterrestrial object, on the basis of the crater-like landform. He suggested that the inversion of chert layers at the perimeter of the lake was produced as consequence of the impact. However, chert layer inversions and complex folding frequently occur in the region; the inversion observed in the vicinity of the lake can be explained by narrowing of the Guatavita Anticline in its periclinal closing. The opening seems to have been excavated by the Aguablanca Creek, which has been the natural drainage outlet (Fig. 9.4). Search for evidence of meteoritic impact (metamorphism, metallic fragments, fracture cones, etc.) gave no results. Therefore, Dietz and McHone (1972) doubted if the impact hypothesis is applicable to the Guatavita Lake.

Several researchers favored salt dome collapse as the most probable origin of the lake basin. Campbell and Buergl (1965) mentioned that salt diapirism which intruded Cretaceous sediments occurred in the region. The salt deposits have been associated with the Lower Cretaceous Chipaque Formation. It may thus be supposed that these diapirs might have crossed the Upper Cretaceous layers which form the Guatavita Anticline where the lake is located. This hypothesis received further support from Beattie and Lowman (1965) and Dietz and McHone (1972), who supposed that

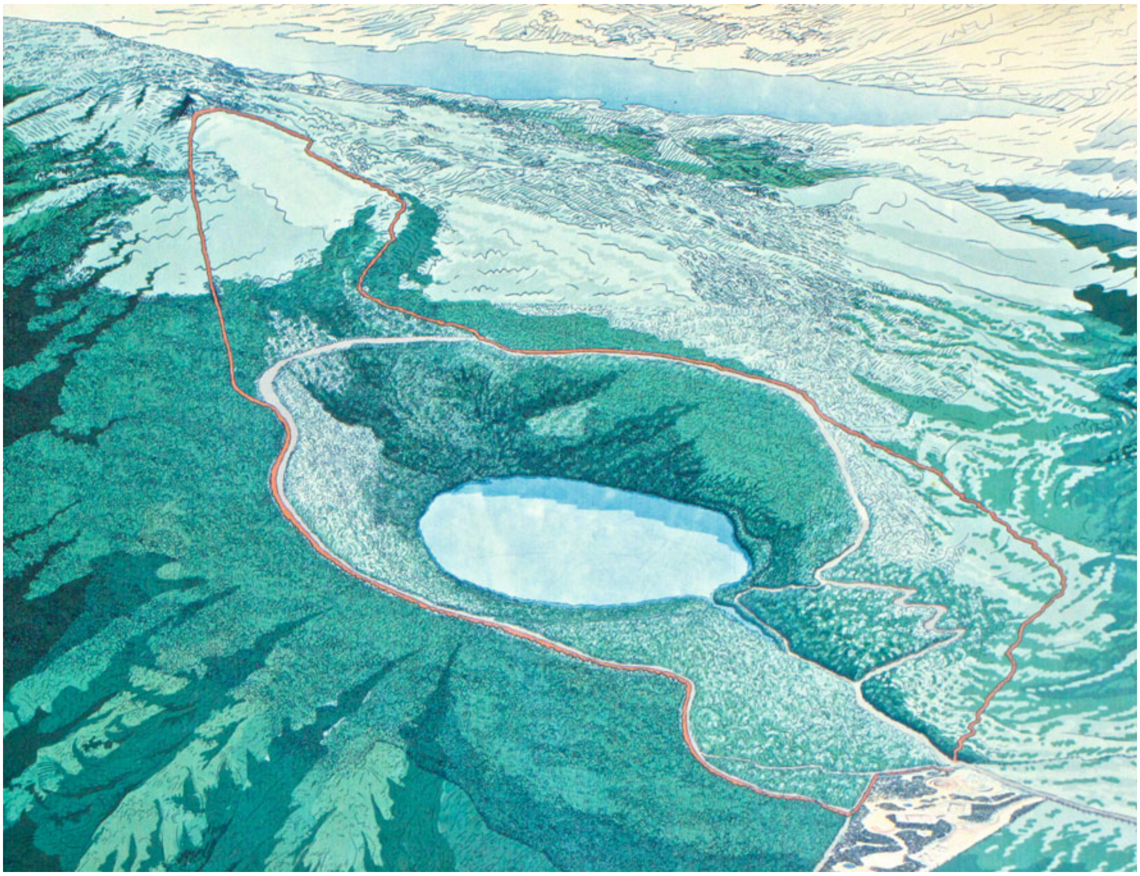


Fig. 9.4 Drawing of the Guatavita Lake surroundings. In the background, the Tomuné Reservoir (Drawing from CAR, Corporación Regional de Cundinamarca, Parque Natural de Guatavita)

the crater originated through the dissolution of a salt diapir. The latter authors, however, expressed doubt with respect to the shape of the crater, which would be unique. Ujueta (1969) concluded that the salt layers are concordant, a fact that indicates that they are in their original position or very near it. McLaughlin (1972) studied in detail the salt deposits of the region and stated that they were deposited in the Lower Cretaceous Chipaque Formation, far below the Guadalupe Group which crops out next to the lake.

Another possible origin was presented by Rosas and Navas (1989), who carried out revision of the existing geologic maps, an interpretation of air photos, and a detailed field survey, including the description of the stratigraphic column. They postulated a fluvial origin for the lake basin, in which major controls are structural, lithological, and geomorphic. The lake is located on the crest of the Guatavita Anticline, in the periclinal closing or nose, where sedimentary layers are vertical and form a circle (Fig. 9.6). The lake is cut by a transverse fault with the uplifted block located northeast of the lake. The downthrown block is formed by competent sandstone layers which were placed in contact with the footwall block along a fault, conformed by a more erodible group of clayey and chert beds with a higher disaggregation capacity; thin stratification and high degree of fracturing of clay and cherty layers favored the beginning of a differential erosion that could have proceeded along the creek bed, which followed the crest of the anticline in E–W direction. However, suppositions on which this hypothesis is based are unacceptable from the structural and geomorphological standpoints.

These authors observed evidence of a small glacier advancing along a short but broad U valley which descends in NE direction toward the lake; no deposits have been signaled, due to the intensive weathering and the presence of soil. The valley was probably formed by successive fluvial erosion followed by glacial abrasion in the stretch located

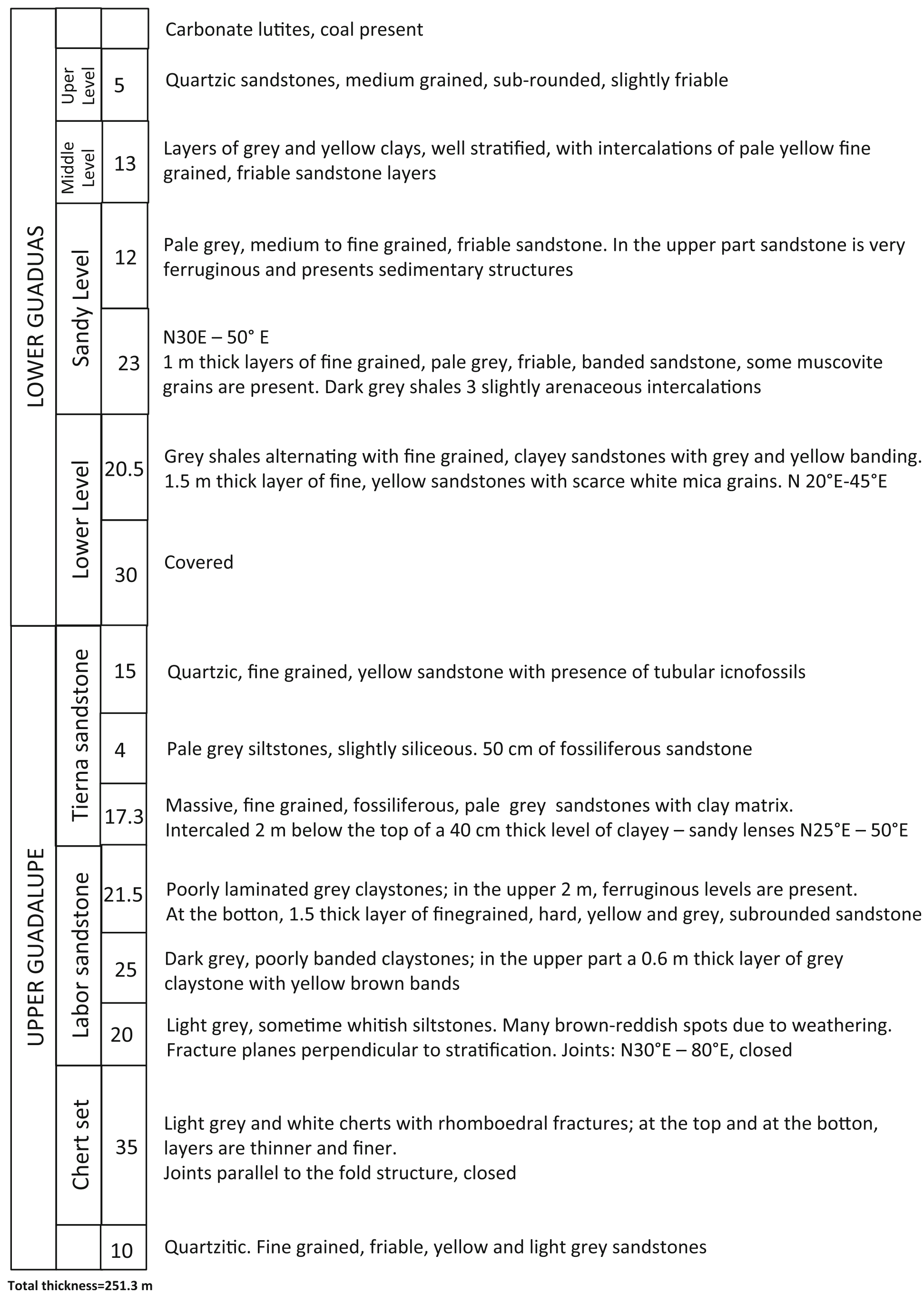


Fig. 9.5 Stratigraphic column intheGuatavitaarea.Section: roadfromCarbonerastoChaleche (Rosas and Navas 1989)

100 m above the lake level and further fluvial processes. Ice melting produced an increase in the discharge and enhanced erosional capacity of the stream. The present source for lake water is underground.

Volcanic origin is another possibility for the lake. However, although newly discovered evidences indicate the existence of Late Cenozoic or Quaternary volcanism in this part of the Eastern Cordillera, they were not found in the Guatavita lake surroundings (Galvis et al. 2004).

As evidenced in the previous discussion, the origin of the Guatavita Lake is still a matter of discussion. This does not mean that it is not worthwhile to visit this magnificent and strange landscape, which truly deserves to be admired.

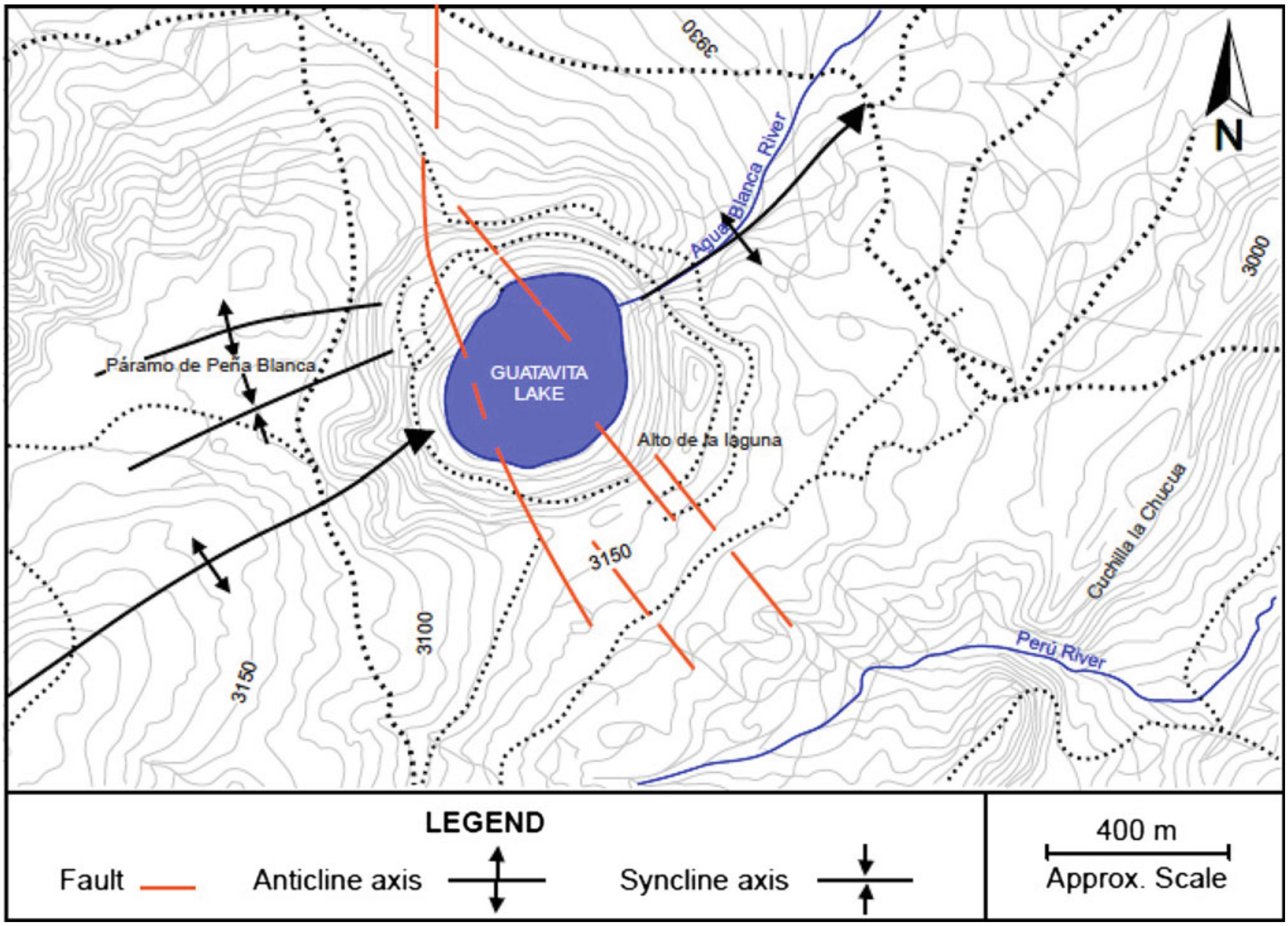


Fig. 9.6 Geological structures near the Guatavita Lake (Rosas and Navas 1989)

9.4 Archeological Significance

Chibcha people, who lived in the Bogotá high plain when the Spanish invasion occurred, had five worship places associated with lakes, located in different places. The most important one was the Guatavita Lake, where kings were elected and crowned, following historical tradition (Rodriguez-Freyle 2006).

In a decorated raft made of reeds, four incense burning braziers honored the new king, surrounded by four older “caciques”; he was undressed, covered with clay, powered with gold dust, and adorned with gold jewels (Fig. 9.7). Around the lake, in middle of bonfires, Indians covered with feathers and gold crowns played several instruments and sang until the raft reached the middle of the lake; then silence was made and the king and its companions threw their gold presents and plunged into the lake, after what songs and dances started again.

The first attempt to dry the lake was intended in 1586 by Spaniards; they obtained more that 12,000 pesos in gold. They were able to lower the water level by about 30 m (Rodriguez-Freyle 2006). Several unsuccessful drainage attempts were carried out later. The last one was in 1919, when a British company was able to desiccate the whole lake

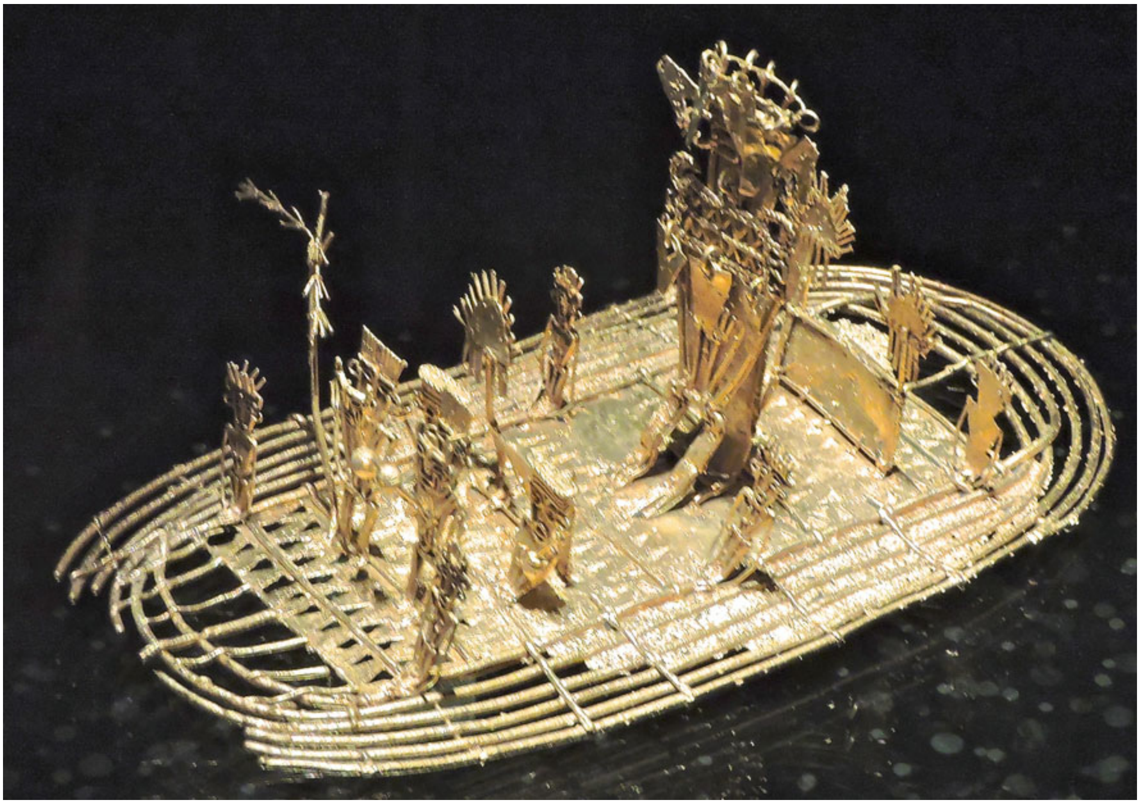


Fig. 9.7 Chibcha gold raft figure, Museo del Oro, Bogotá. *Photography* Michel Hermelin

and obtained a gold bounty which summed up 500 pounds and emeralds evaluated in 70 pounds. The El Dorado legend is still an attraction for researchers, explorers, and visitors all world over.

References

Beattie D, Lowman P (1955) Origin of the Laguna de Guatavita, Colombia. Gel. Soc. Am. Meeting Program, p. 10 (Abstract)

Campbell C, Bürgl H (1965) Section through the Eastern Cordillera of Colombia. Geol Soc America Bull 76(5):567–590

Dietz S, McHone J (1972) Laguna de Guatavita, not meteoric, probable salt collapse crater. Manuscrito Meteorics Soc, Instituto Geofísico de los Andes, Bogotá

Galvis J, de la Espriella R, Cortez R (2004) Vulcanismo en la Sabana de Bogotá, Guía salida de campo sin editar, Bogotá, 13 páginas

IGAC (Instituto Geográfico A. Codazzi) (1977) Mapa Ecológico Escala: 1: 500 000. Bogotá

INGEOMINAS (1975) Mapa geológico del cuadrángulo K-11. Zipaquirá, Escala 1:100 000

McLaughlin DH (1972) Evaporite deposits of Bogotá area, Eastern Cordillera, Colombia. AAPG Bull 56:2240–2259

Raasveldt H (1954) Los enigmas de la Laguna de Guatavita. Inst Geol Nacional, Bogotá, Colombia

Ramírez JE (1972) El Lago de Oro, Instituto Geofísico de los Andes Colombianos, serie C, No. 15, Bogotá, Colombia

Ramírez JE (1975) La Laguna de Guatavita Sociedad Geográfica de Colombia, Academia De Ciencias Geográficas, 12p. (www.sogeocol.co)

Rodríguez-Freyle J (2006) El Carnero, 6ª Edición, (First Edition 1638) Editorial Panamericana, Colombia, 305 páginas

Rosas H, Navas O (1989) Origen y evolución de la Laguna de Guatavita, Colombia, Boletín Geología. Universidad Industrial de Santander-UIS, Bucaramanga, Colombia, 18(33):47–61

Ujueta G (1969) Salt in Eastern Cordillera of Colombia. Geol Soc Americ Bull 80(11):2317–2320

10 Bogotá "Savanna"

José Henry Carvajal and Orlando Navas

Abstract

The "Sabana de Bogotá" high plain, one of the places where the geological and geomorphologic evolution of the northernmost Andes, from Jurassic to recent, is best evidenced. Part of this long evolution was preserved in the landforms, in the lithostratigraphic register and in residual soils found around Bogotá. The "Sabana de Bogotá" highland is a fluvio-lacustrine fill deposited between N and NE oriented folds and basins which formed during the successive uplift phases of the Eastern Cordillera and constitute now the Bogota protective hills and mountains. Incased between these ridges are lacustrine and fluvial plains formed locally by 200–600 m thick layers of predominantly clayey deposits intercalated with minor sands and gravels and some peat levels, which have permitted to unravel the recent regional evolution.

Keywords

High altitude lake filling • Sedimentary structures

10.1 Introduction

"Sabana de Bogotá," as it is locally known (i.e., Bogotá Savanna, a term which does not correspond to the geographical definition) is an old, slightly dissected plain of lacustrine origin located at an altitude of 2600 m a.s.l., in the central axis of the Colombian Eastern Cordillera. It occupies an area of 4780 km^2; its coordinates are between 4ª 11´31.3´´ and 5º16´36.6´´ N latitude and 73º21´33.4´´ and 74º26´28.3´´ W longitude (Fig. 10.1). Mountains surrounding the ancient lacustrine deposits may reach 4000 m a.s.l. The Sabana de Bogotá includes the city of Bogotá, the capital of the country, with an estimate of 7.8 million inhabitants (2014) and 20 more municipalities with about 1.2 million more inhabitants. (Alcaldía Mayor de Bogotá 2010). This represents about 25 % of the total population of the country.

The geographical extent of Sabana de Bogotá is limited and locally interrupted by mountainous and hilly ridges indicating structural control and defined as anticlines and homoclines associated with predominantly sandy rocks of marine and transitional origin deposited from the Early Cretaceous to the Early Cenozoic (Fig. 10.2). Its climate is cold and dry in the plain (by tropical standards, see Chap. 1), while a very cold humid climate predominates in the higher areas, with local variations to cold humid in the foothills (Ruiz 2003 in Carvajal et al. 2004a). NE–SW-oriented climatic belts associated with the direction of the ridges are characteristic.

In the center of the "Sabana," average temperatures are in the range of 12–17 °C and average precipitation is around 800 mm per year, decreasing to 500–600 mm per year toward the southwest, in the towns of Bojacá and Mondoñedo. In higher areas and foothills, particularly west of

J.H. Carvajal (✉)
Servicio Geológico Colombiano, Bogotá, Colombia
e-mail: jcarvajal@sgc.gov.co

O. Navas
Consejo Profesional de Geología, Bogotá, Colombia
e-mail: onavas2011@gmail.com

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_10

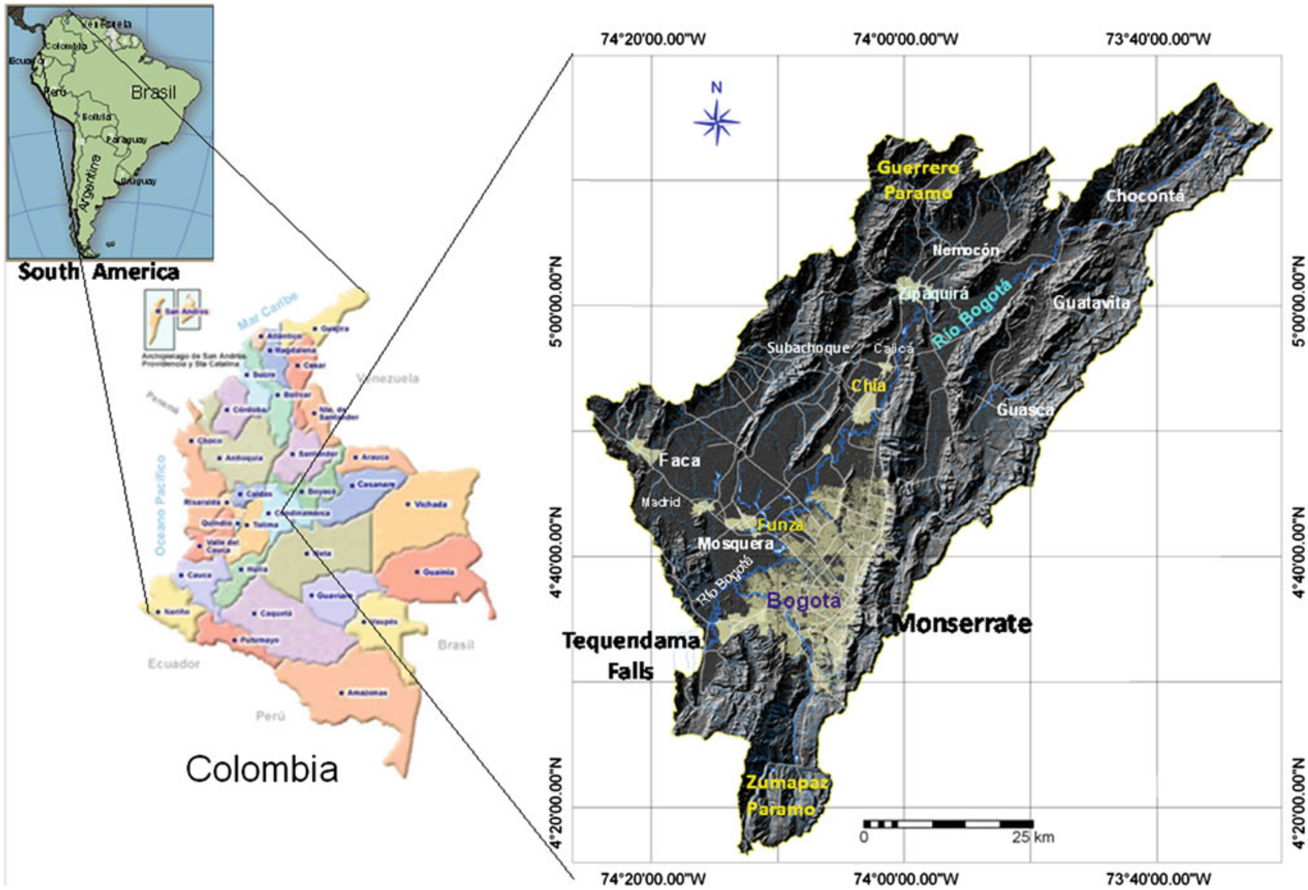


Fig. 10.1 Digital terrain model of the Sabana de Bogotá, showing places of oustanding interest

Bogotá and around Tenjo, Subachoque, Facatativá, and Cogua, climate is semi-humid and cold, with average temperatures between 10 and 12 °C and annual rainfall between 800 and 1000 mm.

In higher areas, colder climates occur, characteristics of sub-humid low *páramo*, with temperatures lower than 10 °C and annual rainfall above 1000 mm. These are the conditions in the eastern part of the Usme valley, southern and eastern part of Guasca, eastern region of Chocontá and Villapinzón, the northern part of La Pradera, northwestern region of Zipaquirá and Cogua in the Guerrero *páramo* and the Verde Lake (Fig. 10.1).

The distribution of original vegetation following Holdridge's classification (Espinal and Montenegro 1963) confirms these previous observations that in the "Sabana" region, precipitation is strongly influenced by topography. As in all mountainous regions of the world, average temperature is directly influenced by altitude.

This contribution arises from the compilation of research mainly carried out by the Servicio Geológico Colombiano (Colombian Geological Survey) and by Professor Van der Hammen and his collaborators in paleobotany and palinology since the 1950 decade.

10.2 Geology

Since the Late Miocene/Early Pliocene (Van der Hammen et al. 1973, in Helmens 1990; Wijninga et al. 2003), the Eastern Cordillera uplift folded the Upper Cretaceous to Lower Cenozoic rocks (Fig. 10.2), forming NE-oriented narrow anticlines, locally horizontal, associated with inverse longitudinal faults, slip faults and strike faults of NE–SW direction, along homoclinal ridge major structures with varying degrees of folding and erosion. Folding generated crustal shortening calculated to a minimum of 63 km, equivalent to 59 % of the original transverse section of the cordillera near the "Sabana de Bogotá" (Mantilla 1998 in Velandia and De Bermoudes 2002).

Longitudinal faults are considered by Velandia and De Bermoudes (2002) as thrust faults. Bogotá, Tunjuelito River, Porvenir, Madrid Mosquera, and El Dorado faults deserve special mention. In a transversal direction which interrupts the longitudinal NE trend, another fracture system occurs, with NW direction (Juan Amarillo, San Cristobal North, El Salitre and Bojacá-Soacha Faults) considered by these authors as sinistral faults locally related

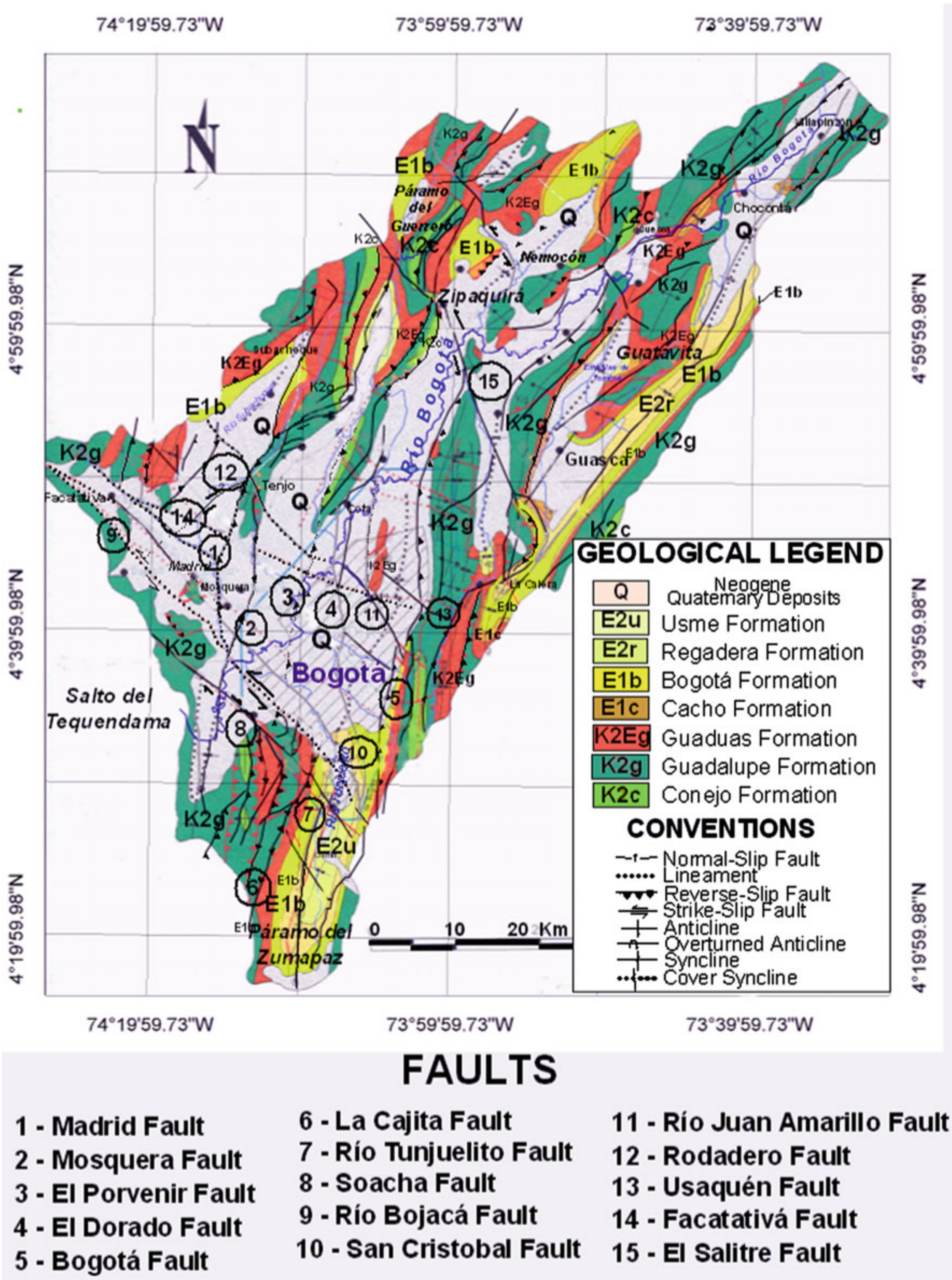


Fig. 10.2 Generalized geological map of the Bogotá High plane. Sources Caro et al. (2003), Montoya and Reyes (2007), Velandia and De Bermoudes (2002)

to salt diapirism processes, particularly on fault intersections (Fig. 10.2).

This diapirism may have influenced, at least locally, the structural framework of the Sabana (Carvajal et al. 2003). Examples may be found in the old salt mines of Zipaquirá and Nemocón. Diapirism as a mechanism of deformation fostered transpressive dynamics and morphostructural building of the "Sabana de Bogotá," together with the formation of anticlines with domal aspect in the Zipaquirá-Nemocón region. At the Zipaquirá salt mine, strong complex folding of the salt can be observed in pre-Cretaceous rocks formed in restricted marine environments. Salt was exploited there since pre-Hispanic times; the first cathedral was carved in 1953 and the second one in 1995, which can be visited all

Fig. 10.3 Details of the salt stalactites and stalagmites in the ancient saltmine cave of Nemocón (*Photo* Orlando Navas)

year round. Another related interesting site is the Nemocón abandoned salt mine, which was reopened in 2005 for touristic purposes and where stalactites and stalagmites formed from salt materials can be observed in detail (Fig. 10.3).

Transversal faulting has determined block tectonics associated with the basement that implies changes in the folding intensity along the anticline axes and the formation of sedimentary basins with different depths, now covered by the fluvio-lacustrine sediments. In the central south region, thicknesses around 200 m have been reported in the Universidad Nacional campus, while in Funza they reach 600 m. Sediments were deposited from the Late Pliocene to the Late Pleistocene (Van der Hammen 2003; Hooghiemstra 1995).

The oldest rocks found in the region are located in the cores of anticlines and homoclines and consist of shales with sandstone and siltstone intercalations; locally marine limestones belonging to the Chipaque-Conejo Formations occur. Sandstones, limestones, and claystones of the marine coastal Cretaceous Guadalupe Group are also present and control the occurrence of structural serrated ridges and hogbacks. Toward the major structural flanks generated on the sequences previously mentioned, spurs consisting of soft rocks of the Labor and Tierna Formations belonging to the Guadalupe Group are present.

In piedmonts and valleys, overlying the previously described rocks in faulted contact, Neogene-Cenozoic sedimentary rocks of transitional marine-continental and continental origin are found, as the Guaduas Formation which consists of claystone and sandstone intercalations, with sandstones predominating in the middle part. Coal beds are also common (Montoya and Reyes 2007). In the upper part of the sequence the following rocks are found (Fig. 10.2):

- Medium- to coarse-grained sandstones to conglomerates of the Cacho Formation, which form exposed structural hogbacks;
- grey greenish claystone of the Bogotá Formation, with sandy intercalations towards the base;
- fine-grained to conglomeratic quartzic sandstones of the Regadera Formation, with clayey intercalations toward the top.
- Light grey claystones of the Usme Formation, intercalated with coarse to very coarse-grained sandstones in the upper part. When the Usme Formation is located in syncline nuclei, differential erosion results in relief inversion and synclinal serrated ridges and structural mesas are present.

10.3 Geomorphology

The "Sabana de Bogotá," as a part of the Cundinamarca/Boyacá highlands, was formed by a fluvio-lacustrine fill now dissected by the Bogotá River and its tributaries: Subachoque, Tunjuelito, Balsillas, Frio, and Teusacá Rivers. This plain was developed in marginal basins formed by intense folding and faulting, evidenced by eroded anticlines which are locally overturned and affected by faults, forming NNE-oriented homoclinal ridges. The morphostructural ridges which form the western flank of the Eastern Cordillera have been locally affected by erosional processes connected with glacial fluvial and slope environments (Vargas 2004).

The geomorphological map (Fig. 10.4) is a synthesis of more detailed work (Carvajal 2012; Carvajal et al. 2004) and shows different morphogenetic environments. Among the units of morphostructural origin, some deserve special mention such as homoclinal and anticlinal ridges (Fig. 10.5). Some of these landforms have become favorite places for landscape observation, as Monserrate and Guadalupe Mounts (Figs. 10.6 and 10.7), east of Bogotá. South of Bogotá, the Usme Syncline (Fig. 10.7) is now a source for building materials, which are also obtained from alluvial materials in the Tunjuelito flood plain and in quarries which exploit the Cretaceous sandstones located South of Bogotá.

10.4 Geomorphic Evolution

The systematic observation of pollen contained in cores obtained from the 600-m-thick sediment layers in Funza and other localities enabled one to establish one of the most complete register of the Cordillera uplift and of Quaternary climatic fluctuations (Hooghiemstra 1984; Van der Hammen 1992). On the other hand, these events were also registered in fluvial and colluvial deposits and in soils. Surface materials were initially exposed to weathering processes under tropical conditions, which became colder during the cordillera uplift in the Mio-Pliocene. This process generated polycyclic type of soils, both in superposed positions or buried under more recent deposits (Helmens 1990; Wijninga et al. 2003; Gaviria et al. 2004). The presence of volcanic ashes originated in the Central Cordillera, which gave rise to independent soils or became integrated with soils derived from local materials, enables us to date the events (Toro et al. 2003). Gaviria et al. (2004), like earlier Helmens and Van der Hammen (1995), discriminate deposits unrelated to the present-day topography from fluvial basin and slope movements. Among the first is the Pliocene Marichuela

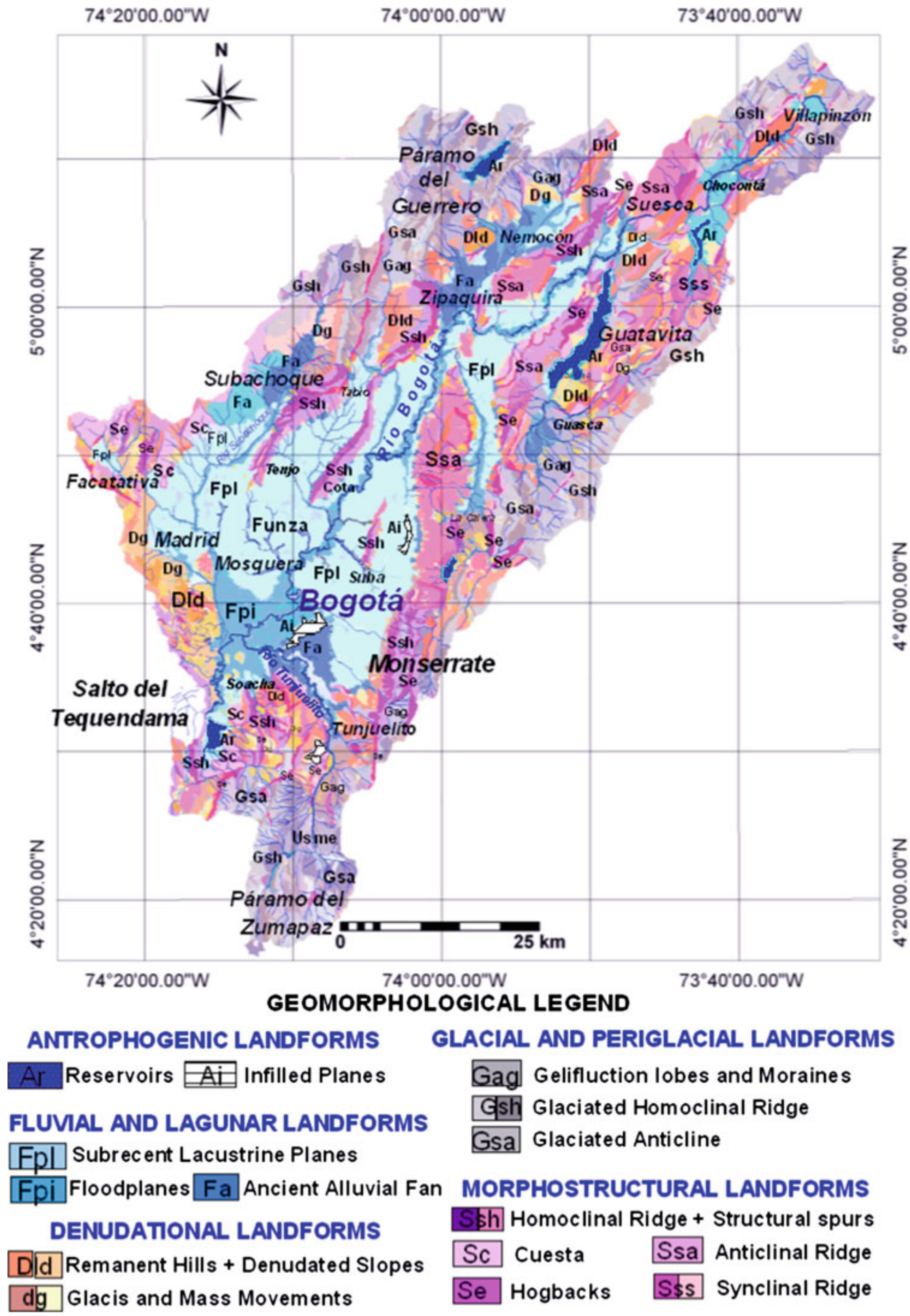


Fig. 10.4 Generalized Geomorphological map of the Sabana de Bogotá High Plain. Modified from Carvajal et al. (2004)

Formation (Toro et al. 2003) that forms muddy fans and consists of gravels and large sandstone blocks. Intercalated with it are sedimentary rocks of the Tilatá Formation (Pliocene-Pleistocene) and the Balsillas Formation (Early Pliocene), consisting of red, white, and grey clayey alluvial deposits with volcanic ash layers (Van der Hammen 1995).

Fluvial deposits include the Upper Tilatá Formation, consisting of grey and green sandy clays, silts and clayey sands from fluvio-lacustrine environments. In the most arid areas of the Sabana de Bogotá lies the later Pleistocene-Holocene Mondoñedo Formation, consisting of colluvial deposits formed by silts and sands with sub-angular scattered blocks and intercalated paleosoils. In the SW part of the Sabana, landforms indicative of intensive surface erosion are numerous (Fig. 10.8).

In the areas bordering the Sabana and overlying the Tilatá Formation deposits, fluvial and lacustrine Pliocene to Pleistocene Subachoque Formation deposits are found. They

Fig. 10.5 Western part of the Sabana Bogotá. Homoclinal and anticlinal ridges separate south running valleys. Bogotá River meanders in the lower part. (*Photography* J.H. Carvajal)

show glacial influence and consist of organic and sandy clays, intercalated with sands and gravels; overlying these beds are fluvio-lacustrine deposits of the Sabana Formation (clays and very fine sands with interdigitations of organic clay, peat, and sandy clay near the borders) of Middle to Late Pleistocene age (Helmens and Van der Hammen 1995; Gaviria et al. 2004). Mountains higher than 3000 m a.s.l. which encircle the Sabana de Bogotá were exposed to glacial or periglacial influence during Quaternary climatic fluctuations. This is notorious by the occurrence of landforms of glacier origin in the Sumapaz Páramo, south of Bogotá (Fig. 10.9), in the Guerrero Páramo in the NW, and in the Guasca region in the NE.

The influence of ice can be seen on structural landforms as evidenced by the presence of horns, glacial and nival cirques, glacial lakes, and glacial valleys. Guatavita Lake is a good example of glacial–periglacial erosion combined with tectonic influence (see Chap. 9). Accumulation landforms are also visible, represented by ablation, ground and lateral moraines, cryoclastic terraces, cones, and lobes, fluvioglacial fans, outwash and glacio-lacustrine plains which correspond to the Chisacá Formation (Gaviria et al. 2004). Slope deposits of different origins, compositions, and ages, developed as fans and cryoclastic lobes of the Chorrera Formation, are covered by gravel and cobbles with intercalations of organic clays and black paleosoils belonging to the Siecha Formation.

The lower part of the Sabana de Bogotá is associated with lacustrine plains and deltas and corresponds to an old fluvio-lacustrine fill from the Sabana Formation, now dissected and containing fluvial terraces and floodplains of the Tunjuelito and Chia Formations. These landforms are associated with the Bogotá, Subachoque, Siechá, Teusacá, Frio and Tunjuelito Rivers, where sedimentation basins and abandoned meanders are being rehabilitated as protected wetlands.

Abandoned meanders present in the Bogotá, Subachoque, and Tunjuelito Rivers are considered as evidence of channel migration possibly due to tectonic tilt of the high plain (Carvajal et al. 2005). The GEORED Project—Colombian Geological Survey, using GPS ground measurements both in urban and in some agricultural areas near Bogotá, evidenced land subsidence of 4.4 cm/year, which has been locally attributed to sediment compaction and groundwater extraction from local aquifers (Mora et al. 2013). However, it is considered that these processes can be linked at least partially to neotectonic activity.

Fig. 10.6 Homoclinal and anticlinal ranges with piedmont deposits associated with torrential fans, Eastern part of Sabana de Bogotá. Monserrate and Guadalupe Mounts seen as isolated *white dots* in the *center* of the photo. (*Photography* J.H. Carvajal)

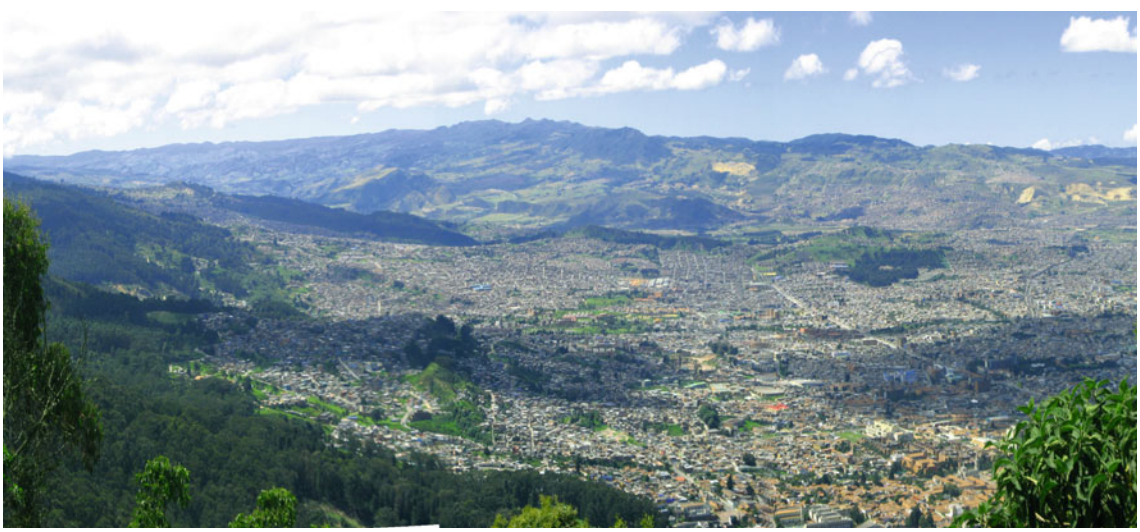


Fig. 10.7 Southern part of the Sabana as seen from Monserrate mounts. *Photo* taken from Monserrate. In the *bottom*, syncline valley limited by hogbacks can be seen. (*Photography* J.H. Carvajal)

Fig. 10.8 Badland formation in the Mondoñedo area. Southwest from Mosquera (*Photo* O. Navas)

Fig. 10.9 Glacial cirque with tarn in its basin and glacial deposits in the Sumapaz Paramo. *Photography* Orlando Navas

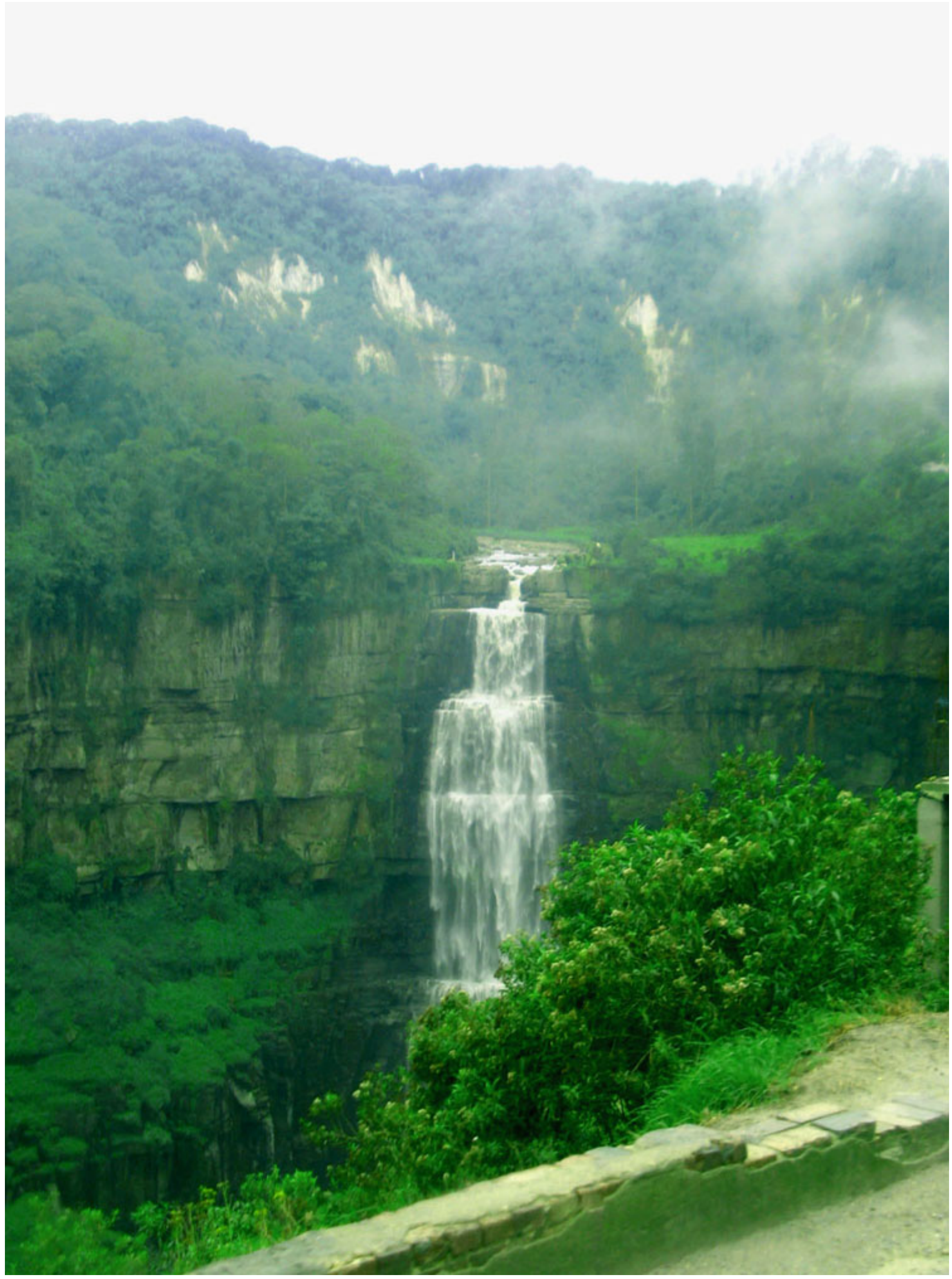


Fig. 10.10 Northwestern looking view of the Tequendama Falls. *Photography* Orlando Navas

10.5 Tequendama Waterfall

Among, the outstanding landmarks in the vicinity of Bogotá, and in fact in the Colombian landscape as a whole, is the Tequendama fall, even if its attractiveness has recently diminished. It is the place where the Bogotá River, after a slow flow on the Cundinamarca highlands, leaves the high plain and starts a tortuous and steep torrential stretch toward the Magdalena River, 2000 m below (Fig. 10.10).

Chibchas or Muiscas was the name of the Indian group who occupied the region. There is no doubt that from the standpoints of political and religious organization, agriculture, and commerce, this was the most advanced culture when the Spaniards invaded the place. In one of their traditions, collected by the Spanish chroniclers and cited by later travelers such as Humboldt, who visited the site in 1801, the Bogotá high plain was flooded due to influence of the wicked goddess Chia. Bochica, a benevolent god, son of the Sun, saved the Chibchas by opening the rocks which dammed the lake with his gold stick, in the place where is now the Tequendama fall. Chia was transformed into the Moon as punishment.

Humboldt (1801) gave a tentative altitude of 75 m for the fall; he was surprised to observe the amount of water vapor produced by the cascade and evaluated that about 2/3 of the liquid evaporated during the fall. Boussingault (1994) visited the fall in 1824. He mentioned that the best measurement was made by J. Acosta and Baron Gros and gave a height of 146 m. Holton (1981), in 1850, intended several times to reach the bottom of the valley. He speculated that a stream much larger than the present one had opened the Tequendama gorge. The great German geographer Hettner (1966, 1976) visited the area in 1882 and gave a good description of the stratigraphy of the Tequendama region, writing that “Bogotá River cut a deep gorge in the horizontal sandstones and mudstones of the Guaduas Formation, where some coal seams were found. The cascade is cut in Guadalupe Formation strata.” Hettner described in details the landscape and his frustrated attempts to reach the lower part of the cascade. Hubach (1929) gave a detailed description of the stratigraphy and geological structures found in the area, stressing the fact that the magnificent landscape deserved to be conserved for its aesthetical value. He also proposed that the gorge was excavated in the flat-lying Guadalupe sandstone strata by retrogressive erosion of the river, following a possible structural control. Van der Hammen (1958) wrote a short didactic essay on the origin of the eastern Cordillera and of the drainage of the lake which occupied most of the Sabana de Bogotá through the Tequendama fall.

The contemporary deterioration of the river is mainly due to two complementary causes. First, a large amount of water from the Bogotá River is used for hydroelectric power generation and captured by tunnels headwards of the fall. Second, tremendous pollution of the river by the Bogotá sewages typifies the river nowadays. A long planned treatment plant—or better a sequence of plants—has never been built. A recent sentence emitted by the State Council should improve the situation.

10.6 Conclusions

The immediate vicinity of the capital of the country offers a number of attractive options to see places of outstanding geomorphological interest and examine long-term relationships between geology, natural resources, landscape, and people. One of these is Mount Monserrate, which can be easily reached by funicular or cable car from the city of Bogotá. A splendid overview of most the west and the southwest of the Sabana can be seen from the top of the hill. Another place to visit is the Guatavita Lake, whose geomorphology is described in more detail in Chap 9. One-hour drive by bus or car allows the tourists to reach Zipaquirá and Nemocón salt mines (Fig. 10.3), both are now available for visiting to the public. More distant is the Chingaza Páramo, which offers magnificent remnants of glacial processes and well-preserved examples of *páramo* vegetation. A one day excursion is necessary to visit the place.

References

Alcaldía Mayor de Bogotá (2010) Caracterización socio-económica de Bogotá y la región in Formulación del Plan Maestro de Movilidad para Bogotá, C and M and Duarte Guterman and Cía Ltda, vol 8. Bogotá

Boussingault JB (1994) Memorias de Jean Baptiste Boussingault. Comisión para el Centenario del Descubrimiento de América. Biblioteca Nacional de Colombia. Memorias, capitulo XII, tomo 2. Bogotá

Caro P, Padilla J, Vergara H (2003) Geología del Cretácico y Paleógeno. Aspectos Geoambientales de la Sabana de Bogotá. Publ. Geol. Esp No 27; INGEOMINAS, Bogotá

Carvajal JH (2012) Propuesta de estandarización de la cartografía geomorfológica en Colombia. Servicio Geológico Colombiano. Colección guías y manuales. Anexos de ejemplos de nomenclatura geomorfológica, Bogotá, 56 pp

Carvajal JH (2005) Características geomorfológicas de la Sabana de Bogotá. Proyecto Compilación y levantamiento de la información Geomecánica- Zonificación geomorfológica de la Sabana de Bogotá, vol 1. INGEOMINAS, Bogotá, 78 pp

Carvajal JH, Carrillo E, Bernal L (2003) Visión integral de la geomorfología colombiana. Resumen poster. Memorias del IX Congreso Colombiano de Geología. Medellín, Colombia

Carvajal JH, Padilla J, Calderón Y (2004a) Geología y geomorfología aplicadas a la zonificación Geomecánica de la Sabana de Bogotá. Memorias Congreso Colombiano, Bogotá

Carvajal JH, Cortés R, Padilla J, Romero J (2004) Cartografía geomorfológica de la sabana de Bogotá. 46 planchas, escala 1.25000. INGEOMINAS. Proyecto compilación y levantamiento de la información Geomecánica - Zonificación geomorfológica de la Sabana de Bogotá. INGEOMINAS, Bogotá

Espinal LS, Montenegro E (1963) Formaciones vegetales de Colombia. Memoria explicativa sobre le mapa ecológico. Instituto Geográfico Agustín Codazzi, Bogotá, 221 pp

Gaviria S, Faivre P y Van der Hammen Th (2004) Origen y evolución de los Suelos de la sabana de Bogotá. Publicación Geológica Especial 27, 139168. INGEOMINAS, Bogotá

Helmens K (1990) Neogene-Quaternary geology of the high plain of Bogotá. Eastern cordillera, Colombia. Dissertaciones Botanicae. vol 163. J. Cramer (Borntraeger). Berlín Stuttgart, 202 pp

Helmens K, Van der Hammen Th (1995) Memoria explicativa para los Mapas del Neógeno Cuaternario de la sabana de Bogotá – Cuenca Alta del río Bogotá. Cordillera oriental de Colombia. Plioceno y Cuaternario del altiplano de Bogotá y alrededores. Análisis geográficos 24. IGAC, Bogotá, 142 pp

Hettner A (1966) La Cordillera de Bogotá Resultado de viajes y estudios (1892) Humboldt. Edición original en alemán, traducción por Ernesto Guhl. Banco de la República, Bogotá

Hettner A (1976) Viajes por los Andes Colombianos 1882–1884; Bogotá, Banco de la República, p 69

Holton IF (1981) La Nueva Granada: veinte meses en los Andes (1857). Banco de la República, Bogotá, 635 pp

Hooghiemstra H (1984) Vegetational and climatic history of the High Plain of Bogotá; a continuous record of the last 3.5 Millions years, In: The Quaternary of Colombia, vol 10. Bogotá, pp 1–368

Hooghiemstra H (1995) Los últimos tres millones de años de la Sabana de Bogotá: Registro continúo de los cambios de vegetación y clima. Análisis Geográficos, vol 24. Instituto Geográfico Agustín Codazzi. Bogotá, pp 35–50

Hubach E (1929) Geología de la hoya del salto de Tequendama. Informe, vol 180, Servicio Geológico Nacional, Bogotá
Humboldt A (1801) Alexander von Humboldt en Colombia. Extractos de sus diarios. Academia Colombiana de Ciencias Exactas, Físicas y Naturales y Academia de Ciencias de la República Democrática Alemana, (1982) Flota Mercante Gran Colombiana. Publicismo y Ediciones, Bogotá, 142 pp
Montoya D, Reyes GA (2007) Geología de la Sabana de Bogotá. Publicaciones Especiales del INGEOMINAS Nª 28, Bogotá, 103 pp
Mora H, Chuassard E, Wdowinski, Cabral E (2013) Space geodectic techniques for assessing land subsidence in Bogotá city. XIV Congreso Colombiano de Geología. Simposio Geodesia espacial GNSS y el estudio de la dinámica terrestre, Bogotá
Toro G, Van der Hammen Th, Gaviria S, Dueñas H, Poupeau G (2003) Dataciones por Trazas de fisión de circones provenientes de las formaciones Tilatá y Marichuela. Sabana de Bogotá – Colombia. Análisis Geográficos, vol 26. Instituto Geográfico Agustín Codazzi, Bogotá, pp 49–60
Vargas G (2004) Geomorfología de la sabana de Bogotá. Publicación Geológica Especial, vol 27. INGEOMINAS, Bogotá, pp 109–138
Van der Hammen Th (1958) El Salto de Tequendama, municipio de Soacha, Departamento de Cundinamarca, Informe 1301. Servicio Geológico Nacional, Bogotá
Van del Hammen Th (1992) Historia, ecología y vegetación. Fondo Fen Colombia, CoA, Fondo de Promoción de la Cultura, Bogotá
Van der Hammen Th (1995) Estudio del Plioceno y Cuaternario de la sabana de Bogotá – Colombia: Introducción histórica. Análisis Geográficos, vol 24. Instituto Geográfico Agustín Codazzi, Bogotá, pp 13–31
Van der Hammen Th (2003) La estratigrafía e historia del Neógeno y Cuaternario de la cuenca alta del río Bogotá: Una evaluación después de completar el mapeo. Análisis Geográficos, vol 26. IGAC, Bogotá, pp 101–126
Velandia F, De Bermoudes O (2002) Fallas longitudinales y transversales en La Sabana de Bogotá, Colombia. Boletín de Geología de la Universidad Industrial de Santander, vol 24(39). Bucaramanga, pp 37–48
Wijninga V, Hooghiemstra H, Van der Hammen Th (2003) Evolución Neógeno de la flora Norandina con base en el registro palinológico–paleobotánico de la sabana de Bogotá. Análisis Geográficos, vol 26. IGAC, Bogotá, pp 17–47

11 The Tatacoa Desert

Michel Hermelin

Abstract

The *Desierto de la Tatacoa* (the Tatacoa Desert), an extensive badland area related to dry climatic conditions due to a mountain barrier, lies on the eastern shore of the Magdalena River, 30 km north of Neiva, the capital of the Department (State) of Huila. It has been carved on the sub-horizontal strata of the Miocene La Victoria, Villavieja, and Gigante Formations, locally covered by Quaternary deposits. Detailed stratigraphic descriptions are available due to the presence of abundant vertebrate fossils in some of the layers. The present landscape offers a variety of landforms as badlands, pinnacles, and isolated erosional remnants forming curious figures produced by surface erosion and the different lithologies affected by the processes.

Keywords

Sub-desertic regions • Badlands • Surface erosion • Sedimentary rocks

11.1 Introduction

Known by most Colombians as the Tatacoa Desert (Tatacoa is an indigenous name for rattle snakes, which were supposedly abundant in the region), this regional natural park is located between the Magdalena River and the Eastern Cordillera, about 30 km north of Neiva, the capital of the Department of Huila. It can be reached on a paved road through the village of Villavieja (Fig. 11.1). Neiva is connected by plane and by highways (5 h from Bogota). Acceptable lodging and food can be found at Villavieja; camping grounds and local restaurants are also available in the park area. The *Desierto de la* Tatacoa is an extensive sub-desertic badland area covering about 330 km^2, which includes almost 50 % of the Villavieja municipality.

The first Spaniards who reached the area were the troops under Gonzalo Jiménez de Quesada in 1538, a few months after he founded Bogotá (Friede 2005). Apparently impressed by the aridity of the site, he called it *El Valle de las Tristuras*—the Valley of Sadness. Besides having to face the fierce hostility of the Indians, the Spaniards suffered enormously due to the lack of water and food and finally retired back to the Bogotá region. In 1550, the city of Neiva was founded for the second time at the site now occupied by Villavieja, but it was destroyed by the brave Pijao warriors in 1569. Neiva was finally established in its present location in 1612 and at that time Villavieja was occupied by a Jesuit mission named Santa Barbara.

The Tatacoa Desert, also known in previous geological reports as the La Venta Badlands (Fields 1959), is an area of great geomorphological and esthetic interest due to its aridity. Another attraction is the presence of an astronomical observatory that takes advantage of almost permanently clear sky. Star observations directed by a professional

M. Hermelin (✉)
Grupo Geología Ambiental e Ingeniería Sísmica, Universidad EAFIT, Medellin, Colombia
e-mail: hermelin@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_11

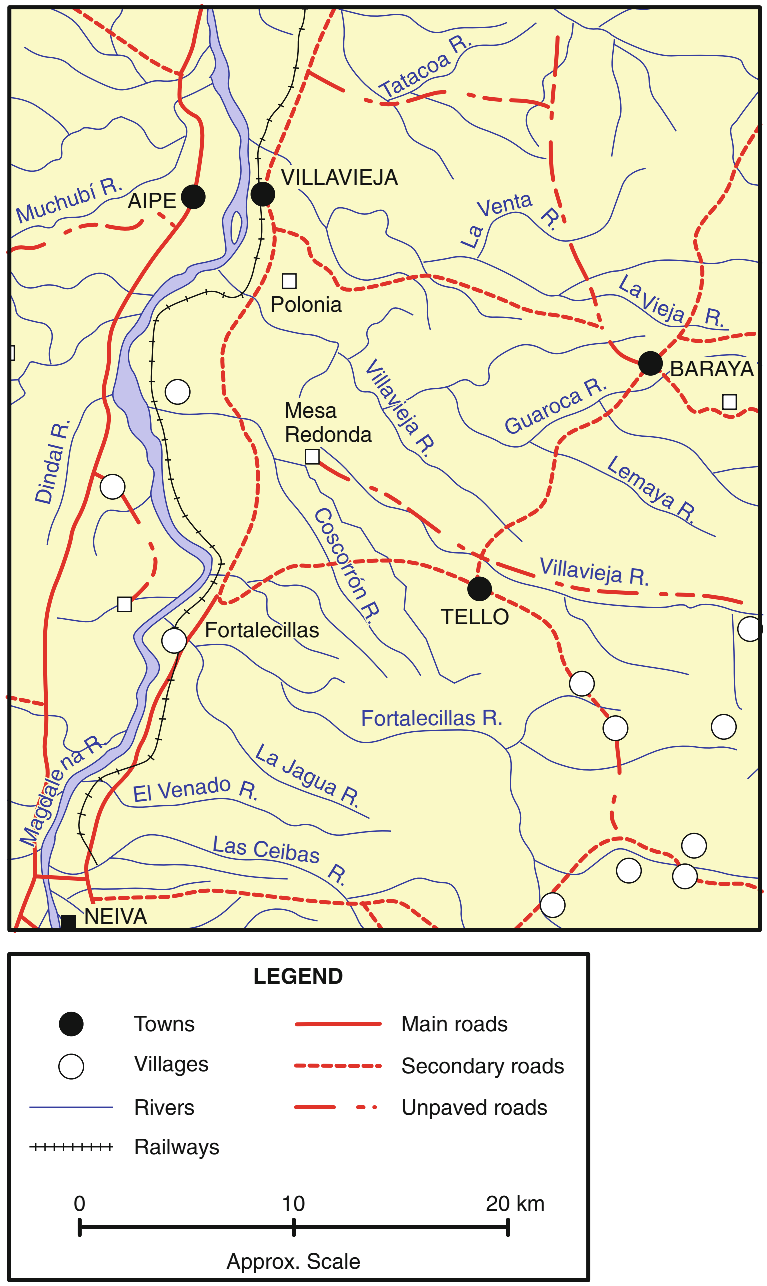


Fig. 11.1 Road access to the Tatacoa Deserty (Villavieja) from Neiva

astronomer and planet observation through telescopes are offered almost every night for a small charge. Furthermore, the region has been notorious among paleontologists for its wealth of Miocene fossils representing many species.

11.2 Climate

The outstanding characteristic of the *Tatacoa* area is its arid climate. Located on the eastern bank of the Magdalena River, it belongs to the vegetal formations called 'Tropical dry forest' and 'Tropical very dry forest' (Holdridge 1967; Espinal 1990), with temperatures above 24 °C and average annual rainfall from 1000 to 2000 and 500 to 1000 mm, respectively. This aridity is attributed by Espinal and Montenegro (1963) to a possible climatic barrier, due to the presence of the Eastern Cordillera, east of the area, which blocks the entrance of wet air masses. The *Tatacoa*, however, is not totally lacking in water, as it is crossed by several Magdalena River tributaries that come from the humid Eastern Cordillera slopes. Soils suitable for agriculture and cattle raising are thus found in the alluvial plains, but the

Fig. 11.2 Partial panorama of the Valley of the sadness. *Photograhy* Michel Hermelin

Table 11.1 Stratigraphic units found in the Tatacoa Desert. Adapted from Vargas (2001)

Age	Symbol	Members		Formation
Quaternary	Qal	Alluvial deposits and terraces		
	Ql			Gigante–Las Mesas Conglomerate formation
Neogene	Tm	Las Mesitas member	Cerro Colorado members	Villavieja formation
	Tct	Tatacoa member		
	Tcl	Las Lajas member	Baraya members	
	Tbr	Los Mangos member		
	Tbm	Molina member		
	Tlv			La Victoria formation

Fig. 11.3 Xerophytic vegetation characteristic of Tropical dry and very dry forest. *Photography* Michel Hermelin

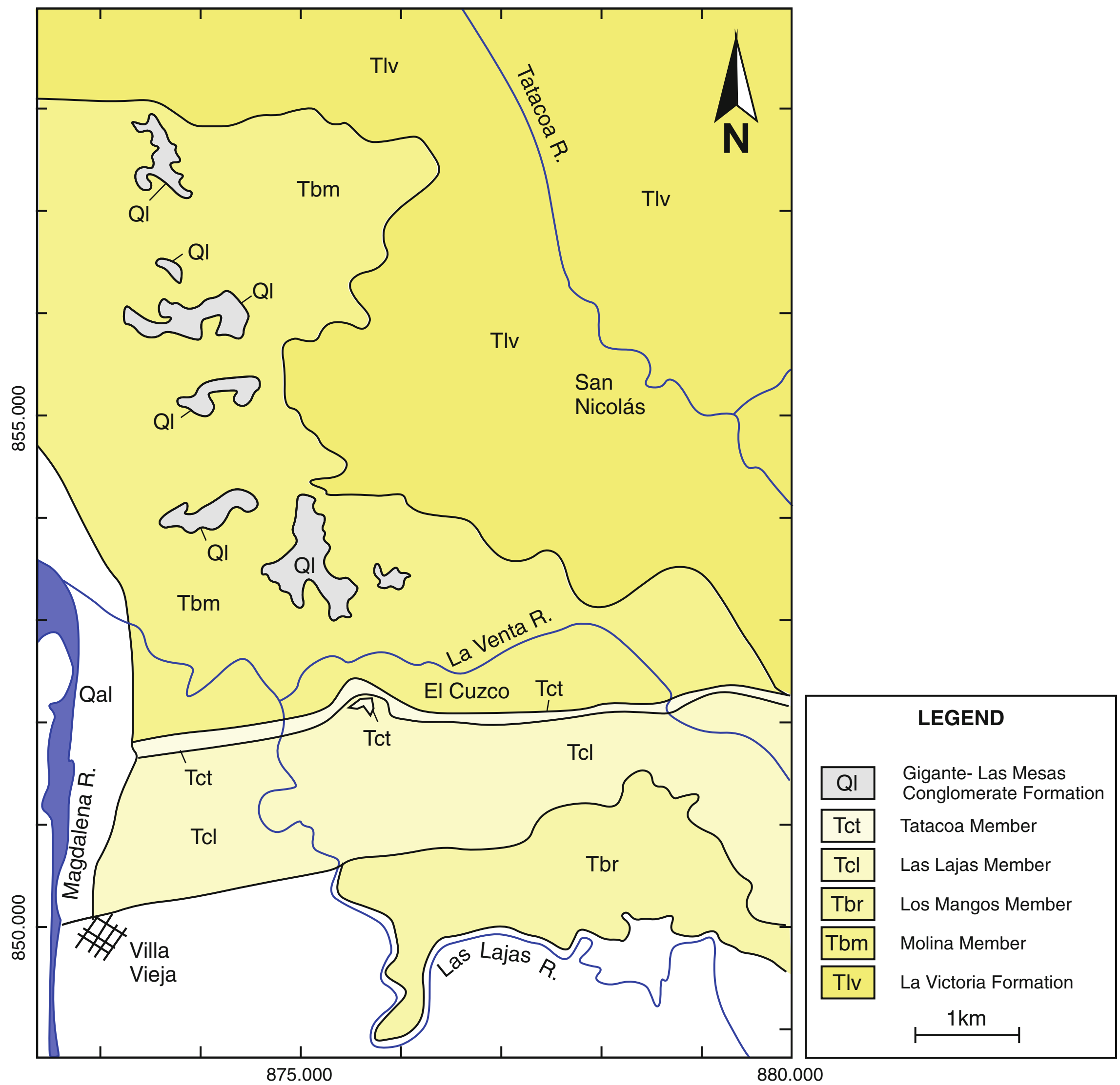


Fig. 11.4 Lithological map of the Tatacoa Desert. Adapted from Vargas (2001)

highlands remain dry, as they are not reached by the water table.

Measured average temperature in the area is around 29 °C and rainfall around 1100 mm, with zones receiving less than 1000 mm year^{-1}. Precipitation occurs mainly in two periods: April/May and October/November. Storms are usually very intense, which means strong surface erosion.

The typical vegetation consists of xerophytic shrubs and cacti, which have been affected by the grazing of cows and goats brought by the first European settlers. The result is that natural erosion has probably increased since the Spanish occupation in the sixteenth century (Fig. 11.2).

11.3 Geology

The first geological description of the *Tatacoa* area was made by Royo y Gomez (1942), who observed that the eastern bank of the Magdalena River had the appearance of fluvial terraces, which produced a landscape of even

Fig. 11.5 Xylopal trunk fragment, NW od Los Hoyos. *Photography* Michel Hermelin

topography deeply dissected by rivers. The underlying rocks, he noticed, were easily eroded and, together with the sub-desertic vegetation, contributed to conferring a "labyrinthic," "intricate" visual appearance to the area.

The local rocks consist of fluvial and lacustrine sediments forming sub-horizontal beds that belong to the Honda Formation, considered as Miocene (Wellman 1970). They are locally covered by Quaternary alluvial materials. The discovery of fossil mammals during petroleum explorations in the area triggered an interest from international schools. Stirton and later Fields (1959), from the University of California, carried out several field studies and mapped in detail stratigraphy of the area. Van Houten and Travis (1968) and Wellman (1970), from Princeton University, revised the stratigraphy of the *Honda* Formation. Setoguchi et al. (1989), Takemura (1983), Hayashida (1984), from the University of Kyoto, and Villarroel et al. (1996), Guerrero (1997) from the *Universidad Nacional de Colombia* and Vargas and Polanía (1995), from the *Universidad Surcolombiana*, among others, contributed to the knowledge of the paleontology and the stratigraphy of the area. All these studies allowed Vargas (2001, 2006) to offer a stratigraphic synthesis of geology of the area (Table 11.1).

Rocks found in the *Tatacoa* "Desert" basically belong to two Neogene Formations and to the Quaternary. The oldest Neogene formation is named La Victoria (TLV) (*Cervetana*) Formation and occupies the northern and north-western area of the Tatacoa (Fig. 11.3). It consists

Fig. 11.6 Incipient rill development on silty sanstone of the Victoria Formation. The metallic pencil (*right bottom*) is 13-cm long. *Photography* Michel Hermelin

Fig. 11.7 More advanced development of rills controled by concretions (Los Hoyos Creek). *Photography* Michel Hermelin

Fig. 11.8 Butte carved on sandy siltstones containing concretions in the Los Hoyos area. *Photography* Michel Hermelin

of conglomerates, sandstones, and siltstone intercalations and toward its lower part, it contains vertebrate fossils and xylopals, fossilized remants of tree trunks in which the entire organic material was completely replaced by opal, a hydrated variety of silica that solidified, preserving the structures of the original wood (Fig. 11.10); its thickness is 238 m. The younger Villavieja Formation is divided in the (lower) Baraya Members and the (upper) Cerro Colorado Members (Table 11.1). The Baraya Members include as follows, from older to younger:

- The Molina Member, also known as Los Micos Member, is found mainly in the northern part of the area, in the headwaters of Quebrada Balsillas and in the Dinde region. Some scarce outcrops are also found in the *El Desierto* area. This member is composed of alternate sandstones and siltstones with lens-shaped layers forming wedges. Sandstones have conglomeratic to fine sizes and pale to yellow colors. Siltstones are sandy and have gray and brown colors. These rocks have been assigned an age of 15 Ma using paleontological and radiometric methods; their thickness is from 54 to 58 m.
- The Los Mangos Member, with a thickness of 8–15 m. It is also known as the “Lower Red Bed” and it is composed of red claystones with small sandstone intercalations. These claystones are subjected to rapid erosion processes. They also have been given an age of 15 Ma by using radiometric methods.

Fig. 11.9 Erosion pillars carved in the slightly tilted silty sandstones of the Los Hoyos area. *Photography* Michel Hermelin

Fig. 11.10 Mesa developed under the protection of a harder layer, (Los Hoyos). *Photography* Michel Hermelin

- The Las Lajas Member has an approximate thickness of 40 m and is located along the La Tatacoa central zone. It consists of siltstones, claystones, and levels of sandstones. Siltstones are present as fine to medium strata with several colors: reddish, brown, green, and yellow.

The younger Cerro Colorado unit contains two members:

- The Tatacoa Member, found in the southern part of the area, has a thickness of 48 m and has been called the "Upper Red Beds." It consists of claystones with

Fig. 11.11 The Dog, one of the curious remnants left by erosion, Palmira-Los Hoyos site. *Photo* Michel Hermelin

Fig. 11.12 Red beds in the Cuzco area. *Photography* Michel Hermelin

thin intercalations of siltstones and sandstones. Claystones have been intensely eroded and form rills and gullies.

- The Las Mesitas Formation is located in the south of the area and is formed of sandstones with siltstone intercalations. Layers are thick to medium sized and they show cross-stratification. Its thickness is about 10 m.

Quaternary deposits include conglomerates, called by other authors *La Mesa* conglomerates, which may be correlated with the *Gigante* Formation. They form small tabular hills (*mesas*) following the north–south direction. Its thickness reaches a few meters. Alluvial deposits are present along the Magdalena River and along the La Venta and Tatacoa Creeks.

Fig. 11.13 Butte remnant of eroded red beds. *Photography* Michel Hermelin

Fig. 11.14 Erosional remnant from the red beds in the Cusco area. *Photography* Michel Hermelin

11.4 Geomorphology

The landscapes derived from the different sedimentary rocks known in the Tatacoa region are mostly the result of intensive surface erosion produced by rain impact and running waters. The occurrence of eolian processes seems very remote due to present atmospheric conditions and to the lack of evidence in the field, although wind is frequently mentioned by guides and tourist brochures as an active agent.

Scarce vegetational cover and poor soil development, both considerably affected by cattle grazing (Figs. 11.2 and 11.6) contribute to expose soft, poorly cemented sedimentary rocks to rain action. Furthermore, a recent publication on local paleosoils mentions the presence of swelling clays in several horizons, a fact which increases the susceptibility to water erosion (Florez et al. 2013). In addition to the previous considerations, Tropical dry forest is characterized by intense downpours occurring after prolongated dry periods, a fact that increases their erosive capacity.

Peculiar erosive landscapes and landforms develop in each one of the lithologies, depending on their composition and texture. In the gray silty, poorly consolidated sandstones of the Victoria Formation, the initial incision of rills is well (Fig. 11.6). Further cutting may generate knife edge forms often controlled by calcite rich calcium carbonate-rich concretions or horizons which form or lintels and accumulate in the floor after they are dismantled (Figs. 11.7 and 11.8). In horizontal or sub-horizontal bedding, pillars may reach heights of 7–8 m (Fig. 11.8). The presence of thick and more extensive hard cover favors the development of Mesas (Fig. 11.10). Further erosion and dismantlement of zones where concretions are abundant may produce curious remnants figures which have inspired local dwellers and tourists (Fig. 11.11).

In the Cusco area (Astronomical Observatory), the red siltones and claystones form remarkable badlands carved by almost complete erosion of these horizontal red beds (Fig. 11.12), giving rise to a dissected landscape which has been correctly called the Labyrinth (El Laberinto). The erosion process apparently stops when it reached a harder underlying stratum and in some areas apparently harder or with a protected surface, left pinnacles (Fig. 11.13) and more complex remnants (Fig. 11.14). No studies have been carried out on the erosion type and the rate of retreat of these interesting and beautiful landforms.

11.5 Itineraries

The most important aspects of the Tatacoa Desert can be seen in one day if a car is available. The area can also be visited by hiking. In both cases, it is advisable to hire a local guide, who for a reasonable fee will accompany tourists.

The best places to visit are:

- The Cuzco area
  Located near the Astronomical Observatory, it is perhaps the most spectacular badland landscape in the entire country; it is called the Labyrinth and was carved in the "red beds" consisting of claystones and siltstones (Figs. 11.4 and 11.5). Unfortunately, no measurements were taken of the rate of the processes.
- The Valle de las Tristezas (Valley of Sadnesses) and Los Hoyos
  This way gives access to a good panorama on the northeastern part of the region, where the Spanish troops became lost five centuries ago (Fig. 11.6).
- A short walk will take the visitor to the Los Hoyos area, where strange figures have been engraved by erosion in the gray upper layers of the Victoria Formation Sandstones (Figs. 11.7, 11.8 and 11.9).

Other sites of interest are the Xylopal Valley where tree remnants are visible in many outcrops (Fig. 11.10); fossiliferous areas are numerous in the region.

The Paleontological Museum, located in the Villavieja central park, and which contains collections of fossils obtained at the Tatacoa and some hint on its evolution, deserves a visit. The Astronomical Observatory, located in the way to the Cuzco area at a 10 min car ride from Villavieja offers programs of star description and identification several times every week. Planet observation through telescopes is also offered for a small fee. The spectacle of a sunset in the desert and the transparency of the night sky are unforgettable.

References

Espinal LS (1990) Notas ecológicas sobre el Huila. Universidad Nacional, Medellín

Espinal LS, Montenegro E (1963) Formaciones Vegetales de Colombia. Memoria explicativa sobre el mapa ecológico. Instituto Geográfico Agustín Codazzi, Bogotá

Fields RW (1959) Geology of the La Venta Badlands, Colombia, South America. Univ Calif Publ Geol Sci 32(6):405–444

Florez MT, Parra LN, Jaramillo JM, Paleosuelos del mioceno en el Desierto de la Tatacoa. Revista Academia Colombiana de Ciencias Exactas, Físicas y Naturales XXXVII(143):229–244

Friede J (2005) El adelantado do Gonzalo Jiménez de Quezada. Intermedio Editores, Bogotá 666 p

Guerrero J (1997) Stratigraphy, sedimentary environments and the Miocene uplif of the Colombian Andes. In: Kay R et al (eds) Vertebrate Paleontology in the Neotropics: the Miocene Fauna of La Venta, Colombia. Smithsonian Institution Press, Washington D.C., p 592p

Hayashida A (1984) Estudio paleontológico de los depósitos continentales del mioceno en las tierras desérticas en LaVenta, Colombia. In: Kyoto University Overseas Research reports of New World Monkeys, vol 4, pp 85–88

Holdridge LR (1967) Life zone. Ecology Tropical Science Center, San José. Costa Rica

Royo y Gómez J (1942) Contribución al conocimiento de la geología del valle superior del Magdalena (Dep. del Huila) Comp. Est. Geol Ofic. Colombia. 5:261–326

Setoguchi et al (1989) New specimen of cebupithecia from La Venta, Miocene of Colombia, South America. In: Kyoto University overseas research reports of new World monkeys, vol VI. pp 1–6

Takemura K (1983) Geology of the east side hills of the Rio Magdalena from Neiva to Villavieja, Colombia. In: Kyoto University overseas research reports of new Worlds monkeys, vol V. p 25.30

Van Houten FB, Travis RB (1968) Cenozoic deposits, upper Magdalena Valley. Colombia AAPG Bull 52:675–702

Vargas R (2001) Geología del desierto de la Tatacoa. In: Olaya A, Sánchez M, Acevedo JC (eds) La Tatacoa ecosistema estratégico de Colombia, Universidad Surcolombiana

Vargas R (2006) Formulación del plan de manejo y declaratoria como Área Natural Protegida del Desierto de la Tatacoa. Línea Bases Geología, Hidrología y Paleontología. Universidad Surcolombiana, Facultad de Ingeniería

Vargas R, Polanía M (1995) Geología del desierto de la Tatacoa, Huila, Colombia, Neiva, Universidad Surcolombiana, Museo Geológico

Villarroel C et al (1996) Geology of the La Tatacoa "Desert" (Huila, Colombia: precisions on the stratigraphy of the Honda group, the evolution of the "Pata High" and the presence of the La Venta fauna. In: Memoirs of the faculty of science, Kyoto University series of geology and mineral, vol LVIII(1 and 2). pp 41–66

Wellman SS (1970) Stratigraphy and Petrology of the nonmarine Honda Group (Miocene) Upper Magdalena Valley. Colombia GSA Bull 81:2353–2374

Inselbergs Near Medellín

12

Carolina García and Michel Hermelin

Abstract

The northernmost part of the Central Cordillera is characterized by plateaus stretching from 1900 to 2700 m a.s.l. which were formed by erosion before the uplift of the cordillera, their different altitudes is an evidence of the successive pulses which were separated by quiet periods. One of the results of these tranquil epochs was the appearance of bornhardts at different altitude. Carved during Miocene and Pliocene in the Antioquian Batholith, a granodiorite intrusive which crystallized in the Upper Cretaceous. Main inselbergs are the Peñol de Guatapé (1900 m s.a.l.) the Tabor Mount (1880 m a.s.l.) in San Carlos and the Peñol de Entrerrios (2300 m a.s.l.).

Keywords

Granite landscape • Inselbergs • Erosion surfaces

12.1 Introduction

In northern Colombia, the Central Cordillera has a N–NW trend and is limited in the west by the Cauca River and in the east by the Magdalena River. Between 6º and 7º N latitude, its steep, dissected topography gives place to a series of plateaus lying between 1800 and 2700 m a.s.l., with a much more massive relief incised by the deep valley of the Aburrá Valley, where the Medellín River flows at an average altitude of 1500 m a.s.l. Eastward, the plateaus are limited by a pronounced scarp named by Botero (1963) "the Magdalena River erosion front". Westward, the Romeral–Espiritu Santo Fault System abruptly truncates the highlands. These plateaus are characterized by deep saprolite mantles and several erosion surfaces were identified by Page and James (1981). Several spectacular inselbergs sit on the top of some of these surfaces at different altitudes and these belong to the most impressive singular landforms in Colombia.

12.2 Historical Background

The first earth scientist who visited the region was probably the French mining engineer Boussingault (Castro and Hermelin 2003),\ traveling here in 1825. He mentioned the presence of three distinctive residual hills which were a "rocky cone" in Entrerrios, a "syenite pyramid" in Guatapé; and a rocky mount in San Carlos. The latter was called at that time *La Teta de la Vieja* (The Old Woman's Breast), but has since been renamed with a more respectable name of "the Tabor Mount" (*El Cerro El Tabor*).

No pre-Hispanic tradition is known related to these outstanding landforms. The generic name originally given to them by the rural farmers of Spanish origin is *peñol*, an old Spanish word that has been now replaced in Spain by the term *peñón*. Botero (1963) kept the word *peñol* and its use has been preserved in the region. A second description of these inselbergs was given by Codazzi, who led the first

C. García (✉)
Corantioquia & Major College of Antioquia, Medellín, Colombia
e-mail: cargalon@gmail.com

M. Hermelin
EAFIT University, Medellín, Colombia
e-mail: hermelin@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_12

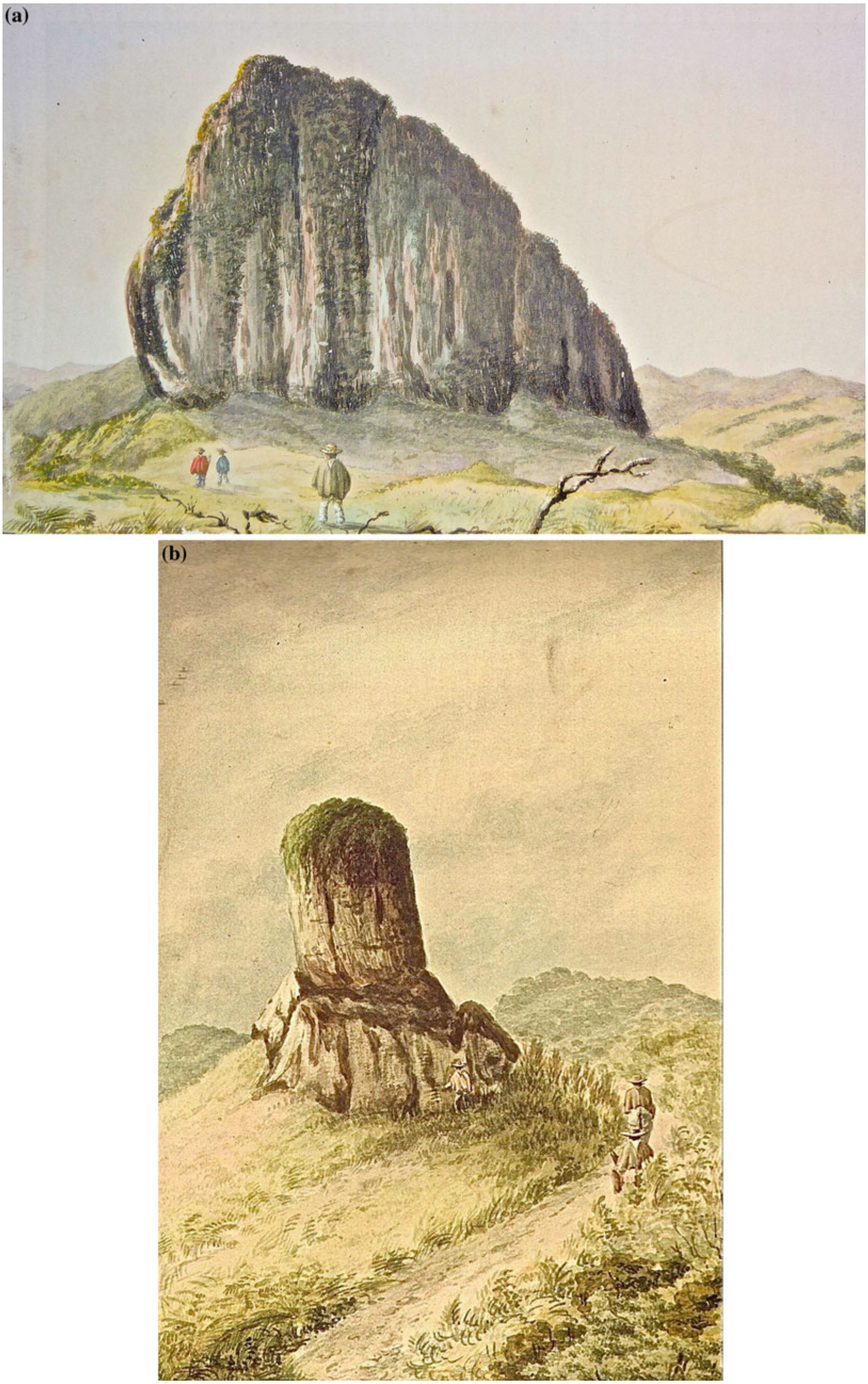


Fig. 12.1 **a** El Peñol de Guatapé (The Guatapé Inselberg, watercolor painted in 1852, Comisión Corográfica, Codazzi 2005). **b** The Entrerrios Inselberg, watercolor painted in 1852, Comisión Corográfica, Codazzi 2005)

official geographical survey of Colombia in 1852 (Codazzi 2005) (Fig. 12.1a, b).

12.3 Geological and Geomorphological Description

The regional geology is dominated by the enormous Antioquian Batholith, which covers more than 7200 km^2 with outcrops at altitudes from 750 to 2700 m a.s.l. (Botero 1963; Feininger and Botero 1982). The composition of this batholith is extremely homogeneous from both textural and compositional standpoints, with 97 % of its volume consisting of quartz diorite and granodiorite. Its petrographical composition is andesitic plagioclase, potassium feldspar, quartz, hornblende, and biotite, with secondary chlorite and some accessory minerals (Feininger and Botero 1982). It was intruded into the preexisting Paleozoic and Precambrian metamorphic rocks that form the core of the Central Cordillera (Fig. 12.2).

Many age determinations have been obtained for crystallization of the Antioquian Batholith: they range from zircon fission track ages from 49.1 ± 2.5 to 67.1 ± 2.1 Ma (Saenz 2003), passing through biotite K/Ar dates around 68 ± 3 Ma (Feininger and Botero 1982) to the Rb–Sr age of 98 ± 27 Ma (Ordóñez and Pimentel 2001). The last age has been proposed as the best estimate of crystallization age for the Antioquian Batholith (Ordóñez and Pimentel 2001). Recent zircon U–Pb spot analyses (LA–ICP–MS) indicate crystallization in the Late Cretaceous, close to the Campanian–Maastrichtian transition (Restrepo-Moreno et al. 2007).

Due to the humid tropical weather of the region, but also in response to apparently low rates of surface erosion, the saprolite covering the Antioquian Batholith has an average thickness of 40 m and can reach up to 200 m (Liégeois 1958; Hoyos et al. 2000; Page and James 1981; Rendon and

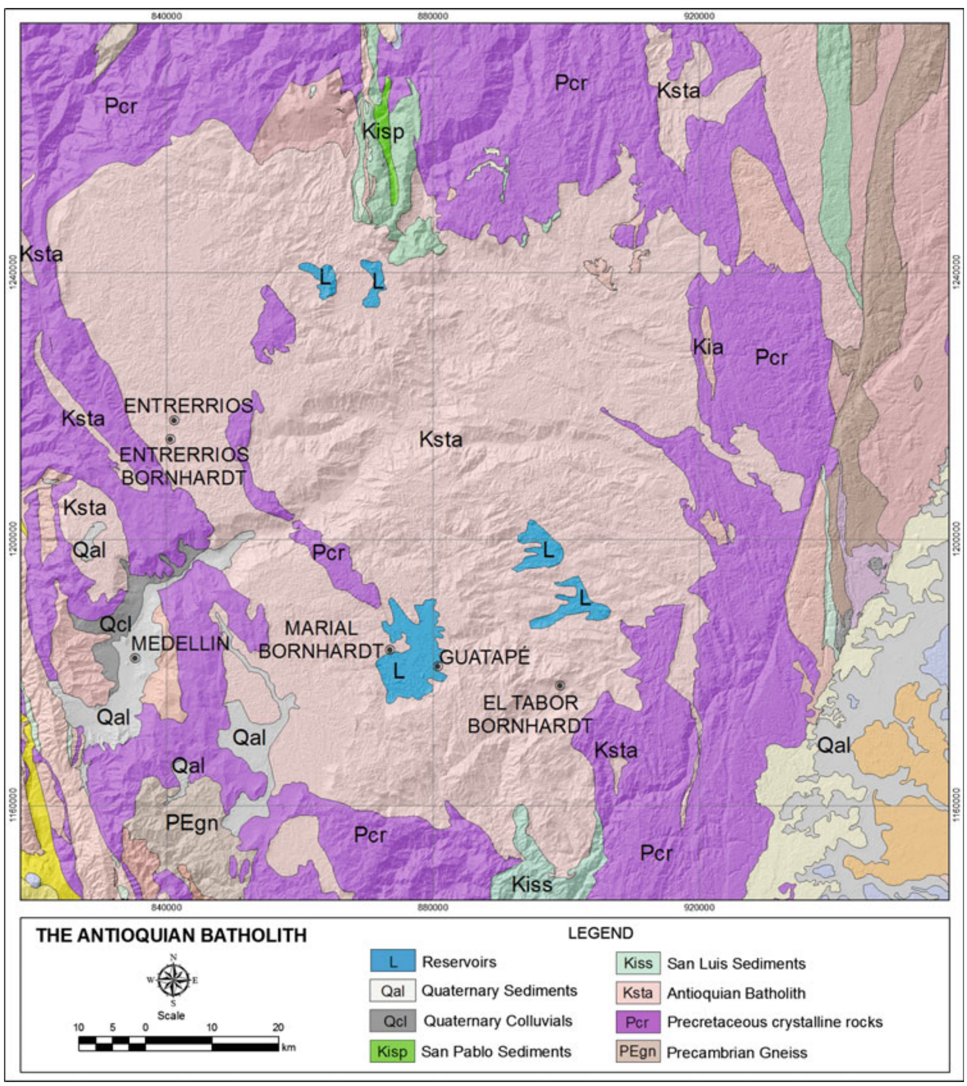


Fig. 12.2 Simplified geological map of the Antioquian Batholith region (adapted from INGEOMINAS 1999)

Hermelin 2015). The weathered quartz diorite profile includes bioturbated horizons, where the influence of vegetation and burying animals has erased the structure of the original rock. Below these horizons the true saprolite consists of well-preserved pseudomorphs of biotite and hornblende, transformed into iron hydroxides, kaolinite clay replacing plagioclases, and quartz grains sometimes showing slight saccharoidal alteration. The saprolite is totally isovolumetric, as it conserves the structures present in the original rock. Its specific gravity can be as low as 1.3. Under the saprolite lies the gruss zone alternating with remnant blocks. This horizon generally coincides with the water table and is underlain by fresh rock (Toro et al. 2006). Maximum saprolite thicknesses are observed in areas with gentle slopes and they become thinner in steeper topographies.

The Antioquian Batholith is the main geologic body of the Antioqueño Plateau, the largest high-elevation erosional surface in the Northern Andes (INGEOMINAS 2005; Restrepo-Moreno et al. 2009). This plateau is described by Restrepo-Moreno et al. (2009) as an extensive (>5000 km^2) geomorphic domain of low relief, which appears to be a relict surface located in the northernmost portion of the Central Cordillera (Arias 1995). Dominated by a dendritic drainage network, the mean elevation of the Antioquian Plateau is ~2500 m; its topography is characterized by rolling hills with local relief from 40 to 100 m and slopes of around 10º. Prominent topographic features within the Antioqueño Plateau, like the Las Baldías Range and Páramo de Belmira in the western margin of the plateau, are underlain by metamorphic units, more resistant to weathering than the Antioquian Batholith itself.

Scheibe (1919), Page and James (1981) and Arias (1995) suggest that the Antioqueño Plateau was developed as an erosion surface near the sea level in the Paleocene and was later uplifted in discrete episodes during the Cenozoic, and finally modified by fluvial activity combined with the unique weathering processes acting upon of granitic rocks in a humid tropical setting. Page and James (1981) were the first to interpret the different plateau levels which they called erosion surfaces, as a result of successive uprisings of the Cordillera. The three identified erosion surfaces and two erosion stages, defined as incomplete developments of erosion surfaces (Fig. 12.3) are:

- The Pre-Cordillera Central erosion surface (Pre–S–I), a few hundred meters above the Cordillera Central erosion surface (Páramo de Belmira, Llanos de Cuivá), possibly formed in the Late Cretaceous (~65 Ma)
- The Cordillera Central erosion surface (SI) visible in Santa Rosa de Osos and La Unión, with the period of formation bracketed by ages from 22 to 10 Ma.
- The Rio Negro surface (SII), located 200–400 m below SI and found in Rio Negro and Ovejas. Page and James (1981) used stream incision rates to propose an age of 5–3 Ma for this surface.
- Erosion stage III surface (Stage III) observed near El Peñol, some 250 m below the SII surface, formed possibly 0.5–1.5 Ma ago.
- Erosion stage IV surface (S IV) at the altitude of San Carlos (1000 m a.s.l.).

Rendón and Hermelin (in preparation) carried out geoelectric surveys at several localities of the Antioquian Batholith and found that average saprolite thicknesses are proportional to altitude above sea level. Measurements performed at the highest location (c. 2700 m a.s.l.) indicated a thickness of about 110 m whilst those at the lowest elevation (1900 m a.s.l.) revealed about 50 m of weathered rock. Data

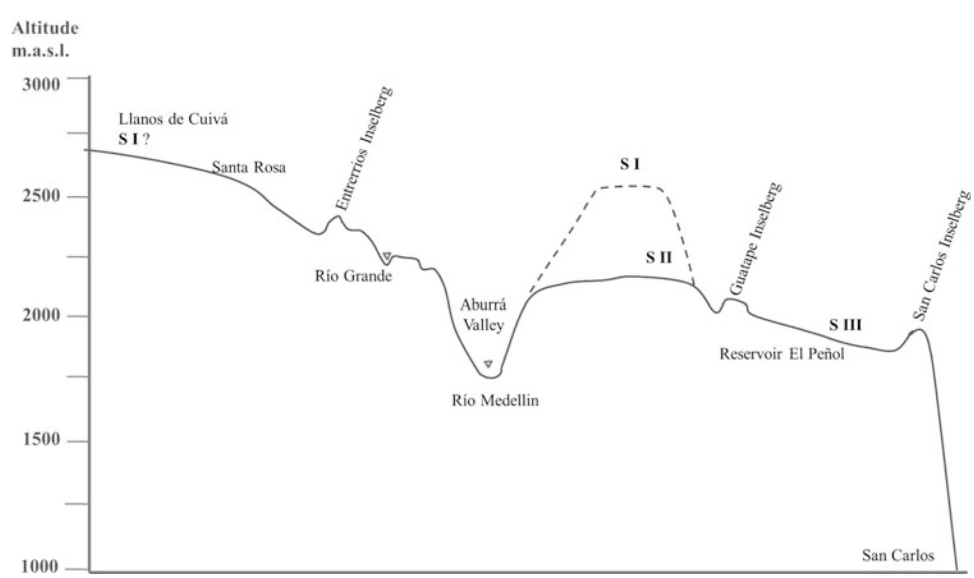


Fig. 12.3 Tentative denudation chronology scheme

Table 12.1 Erosion surfaces in the Rio Negro area (Adapted from Rendon et al. 2011)

Erosion surfaces	Altitude above sea level (m a.s.l.)	Page and James (1981) Equivalent erosion surfaces
Belmira surface remnant	3000	Pre–S–I
Santa Elena-La Unión	2400–2700	S–I
San Ignacio	2220–2350	–
Rio Negro	2000–2200	S II
El Peñol-Guatapé	1890–1910	S III

from intermediate locations yielded values between these two extremes, indicating clear trends. These data apparently favor an origin of the plateaus in relation to successive phases of uplift of the Cordillera.

Rendon et al. (2011) proposed that five erosion surfaces separated by erosion scarps exist in a much more limited area, comprising only the Rio Negro region (Table 12.1). It is probable that further research will increase the number of identified surfaces.

In synthesis, the Antioquian Plateau is composed of several erosion surfaces cut in Paleozoic metamorphic and Cretaceous igneous rocks, which, following Widdowson (1997), "evolved in response to a particular combination of geomorphological processes."

12.4 Origin of the Inselbergs

The present population of the region consists mainly of rural inhabitants of Spanish origin who came to the region as gold miners at the beginning of the seventeenth century. A tradition still heard at present time in the El Peñol and Guatapé rural areas attributes its origin to a half-buried meteorite!

Botero (1963) was the first geologist to study the Guatapé inselberg from a scientific standpoint. On the basis of numerous petrographical analyses carried out on many samples from the batholith, he concluded that a differential behavior with respect to weathering and erosion due to composition should be ruled out for both the Guatapé and Entrerrios Inselbergs. He favored a two-stage hypothesis based on contrasting fracture density (see also Twidale 1989). A lower density of fractures in the area of the inselberg precludes the penetration of weathering infiltrated waters. On the other hand, the well-fractured surroundings are much more susceptible to weathering resulting in the formation of saprolite. This saprolite, formed between the surface and the weathering front was later removed by erosion (Fig. 12.4), in a sequence considered valid by numerous authors dealing with the origin of residual granite landforms, such as Thomas (1994), Twidale and Vidal Romani (2005), Migon (2006) and Wirthmann (2010).

12.5 The Guatapé Inselberg (E*l Peñol de Guatapé*)

El Peñol de Guatapé inselberg can be easily reached by car from Medellin on a paved road called the Medellin–Bogota Highway; the drive takes about 90 min toward the east crossing the village of Marinilla. San Carlos, located further east, is 3 h from Medellin (Fig. 12.5).

One of the attractive features of the landscape around this inselberg is that its surroundings were flooded when a hydroelectric dam was built in 1968, resulting in an aesthetically appealing water reservoir (Fig. 12.6), which required the relocation of the El Peñol village. The inselberg is a private property and it has been exploited for commercial purposes for a long time, with unfortunate transformations (stairs, a tower, and letters engraved on one of its sides) that have defaced it (Fig. 12.7). Referring to terminology of granite residual relief (e.g., Twidale and Vidal Romani 2005), the Guatapé inselberg may be classified as a bornhardt, i.e., a hill built of extremely massive, poorly jointed rock, convex in overall shape, with steep bare slopes and almost nonexistent boulder mantle. It is also characterized by a sharp contact between rock slopes of the residual and the adjacent surface cut across the weathered mantle. The relative height of the bornhardt is 130 m, whereas in plan it measures approximately 290 by 75 m. However, the bare rock part crowns from a larger elevation which is c. 250 m in total and elongated in N–S direction. A detailed topographic map and profiles made by Botero (1963) are reproduced as Fig. 12.8.

The summit of the inselberg was originally covered by a layer of volcanic ash about 1 m thick, as most of the surrounding landscape. This andesitic-dacitic ashes were produced during the Late Pleistocene by volcanoes of the Ruiz-Tolima massif, located about 150 km in the southeast and was transformed into andosols (Toro and Hermelin 1990 and Toro et al. 2006). Flutings or crenulations, which may reach a width of 2 m at the base of the slope, are directly related to rain waters that, after percolating the volcanic soil, became more acidic and slowly dissolved the quartz diorite.

If the regional scheme of erosion surfaces proposed by Rendon et al. (2011) is accepted, the Guatapé Inselberg

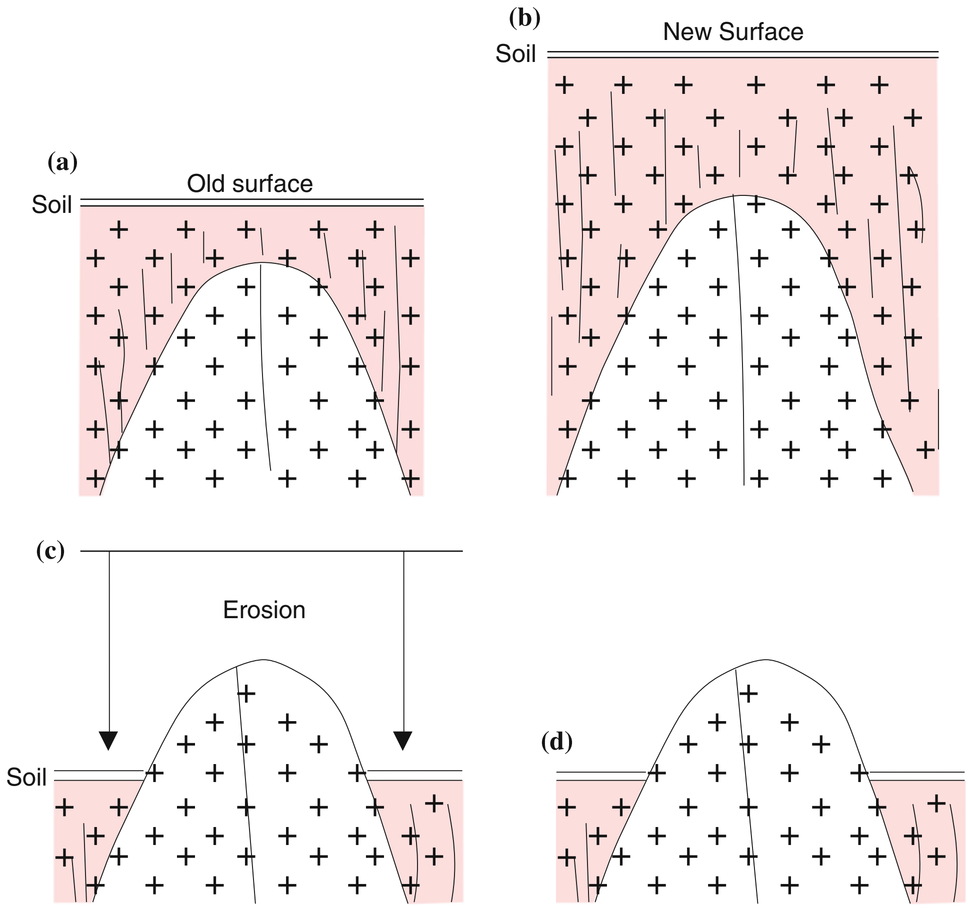


Fig. 12.4 Inselberg formation scheme. **a** Initial weathering favoured by fractures, **b** uplift and further weathering, **c** erosion of saproliteuncovering Bornhardt, **d** present situation

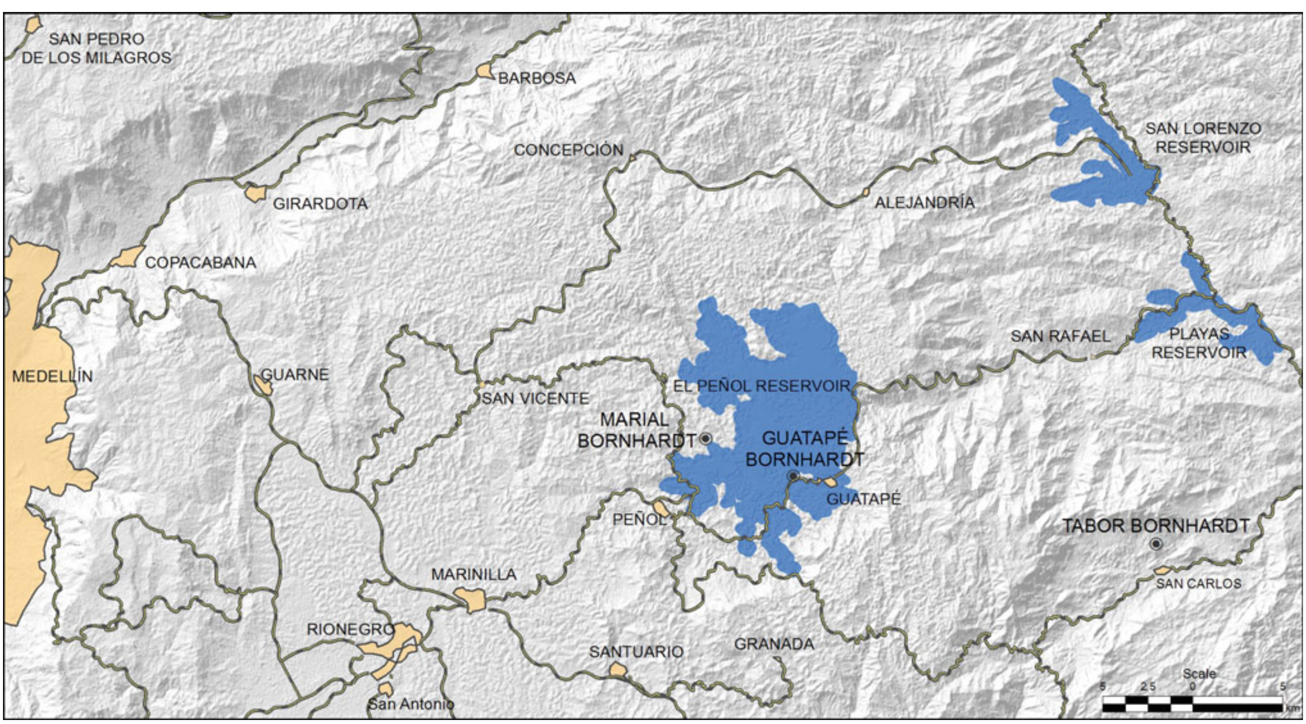


Fig. 12.5 Regional road map showing access to El Peñol de Guatapé, El Marial an El Tabor Bornhardts from Medellín

Fig. 12.6 The Guatapé Inselbert surrounded by the reservoir waters. *Photography* Michel Hermelin

Fig. 12.7 The Guatapé Inselberg seen from the NE. Michel Hermelin

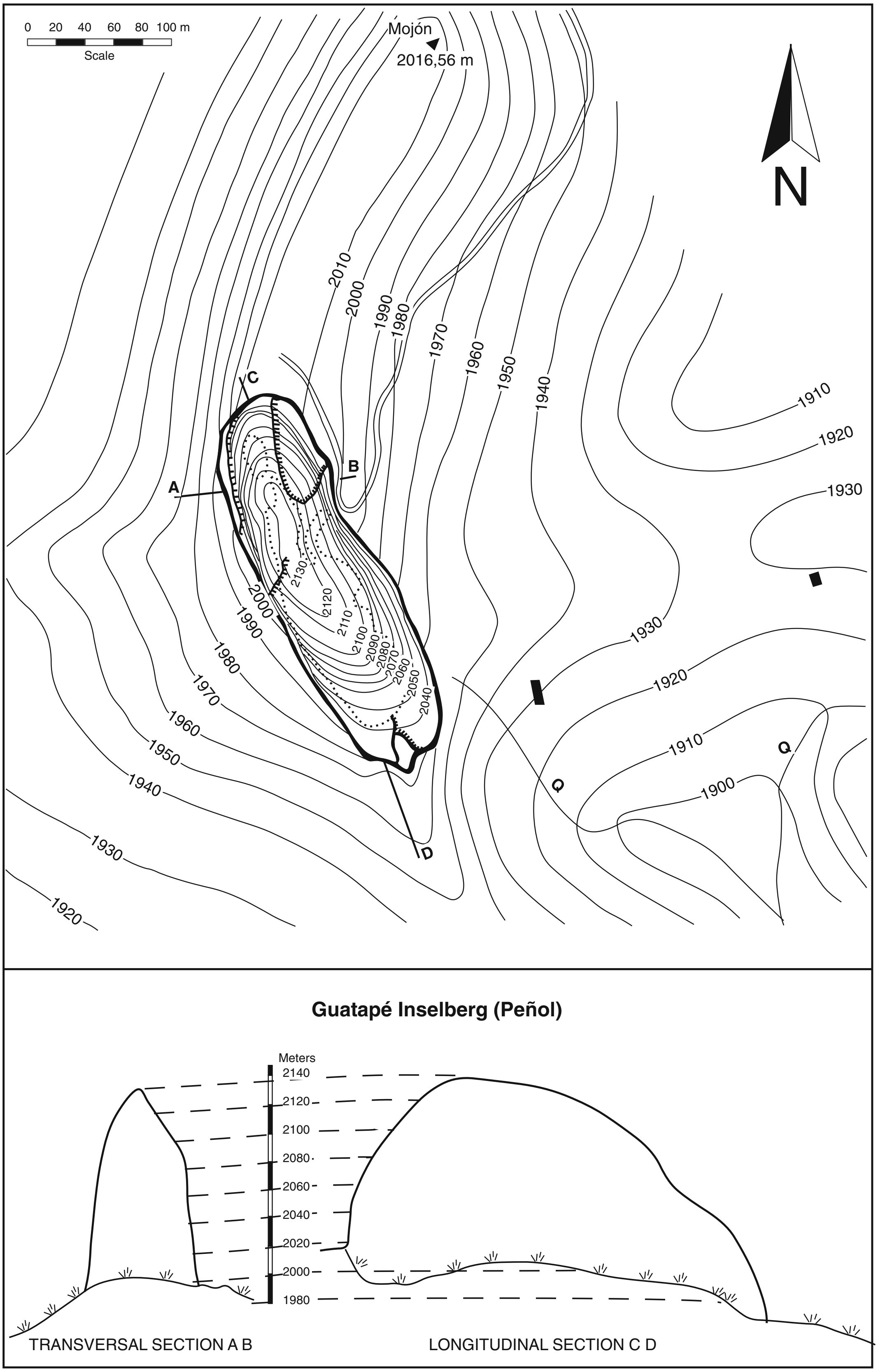


Fig. 12.8 Guatape Inselberg topographic map and profile (Botero 1963)

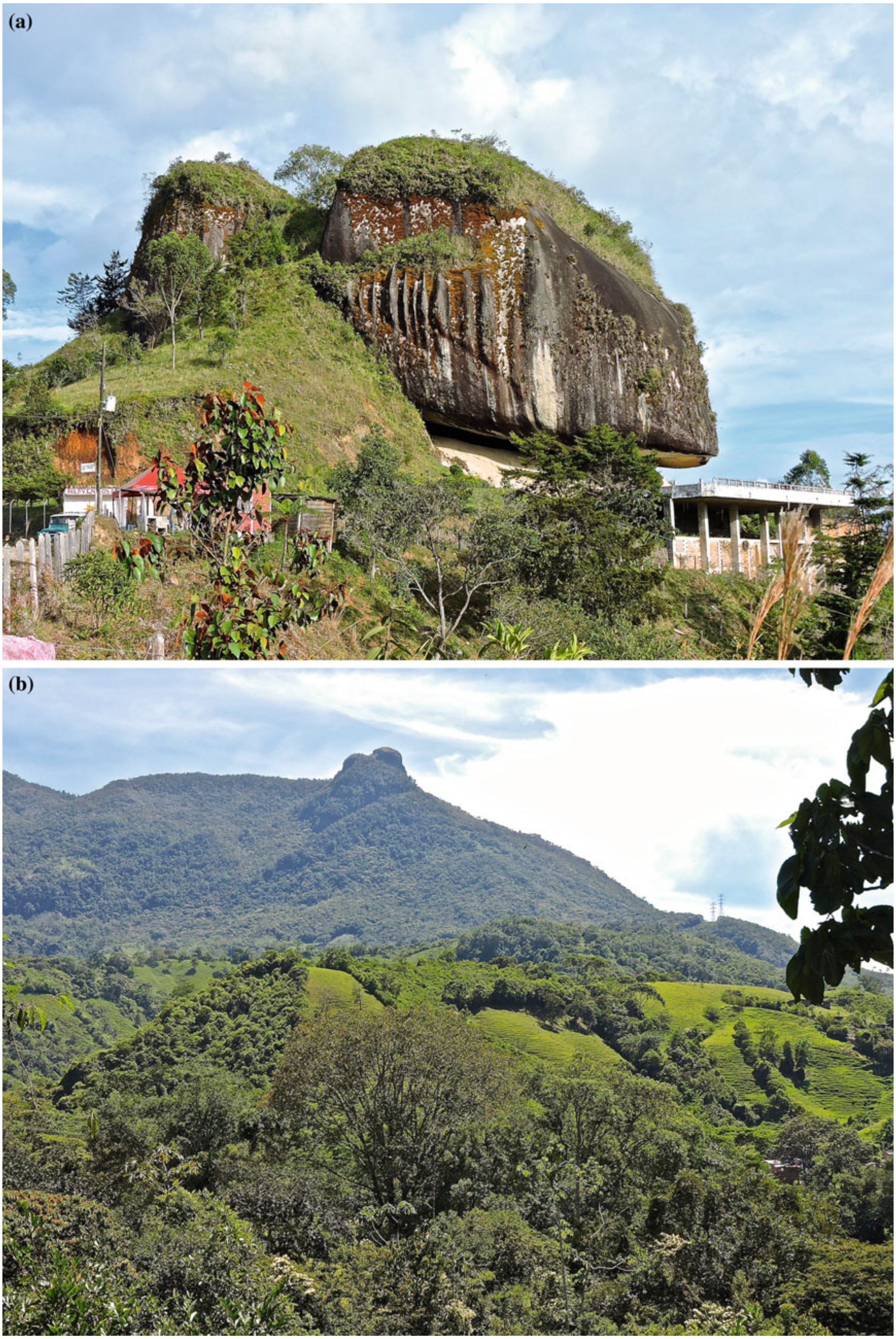


Fig. 12.9 **a** El Marial Inselberg. *Photography* Michel Hermelin. **b** El Tabor Inselberg, San Carlos. *Photography* Michel Hermelin

should have been carved when the El Peñol Erosion Surface was excavated at the expense of the Rio Negro surface, during Erosion Stage III, following the nomenclature of Page and James (1981).

12.6 Other Neighboring Inselbergs

The El Marial Inselberg is visible from the foot of the Guatapé Inselberg, at a distance of approximately 5 km; its dimensions are much smaller than those of Guatapé, approximately 10 m high and a base diameter of 40 m, but it is an interesting place to visit. It also shows flutes incised into its steep rock slopes. In contrast to Guatapé, it is more vegetated and displays a prominent sub-horizontal fracture that forms a sort of roof (Fig. 12.9a). San Carlos, a village that can be reached by a 2 h car ride from El Peñol, also has its own bornhardt called Cerro El Tabor. It dominates the village, located at about 1000 m a.s.l., and rises to an altitude of 1884 m a.s.l., but protrudes from the slope rather than from a plain and displays only a few tens of meters of bare rock (Fig. 12.9b). According to their location and altitude, El Marial Inselberg should be coetaneous with Peñol de Guatapé, while El Tabot bornhardt would correspond to the the excavation of Erosion Surface S-III.

12.7 The Entrerríos Inselberg

Entrerríos is a village located on the northern Antioqueño plateau. The region was an important mining area during the eighteenth and nineteenth centuries, but now the main

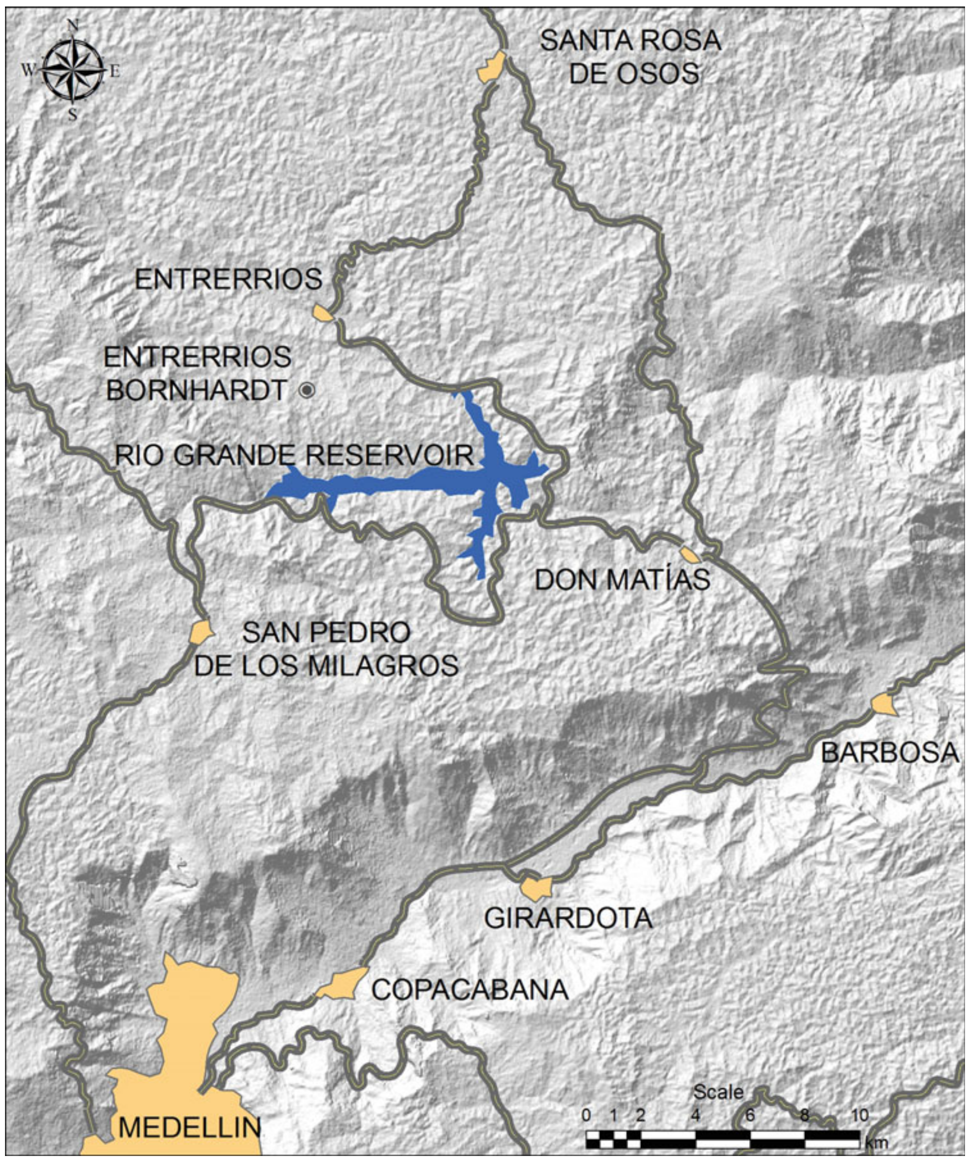


Fig. 12.10 Road access to Entrerrios Bornhardt

Fig. 12.11 Entrerrios Inselberg seen from the W. *Photography* Michel Hermelin

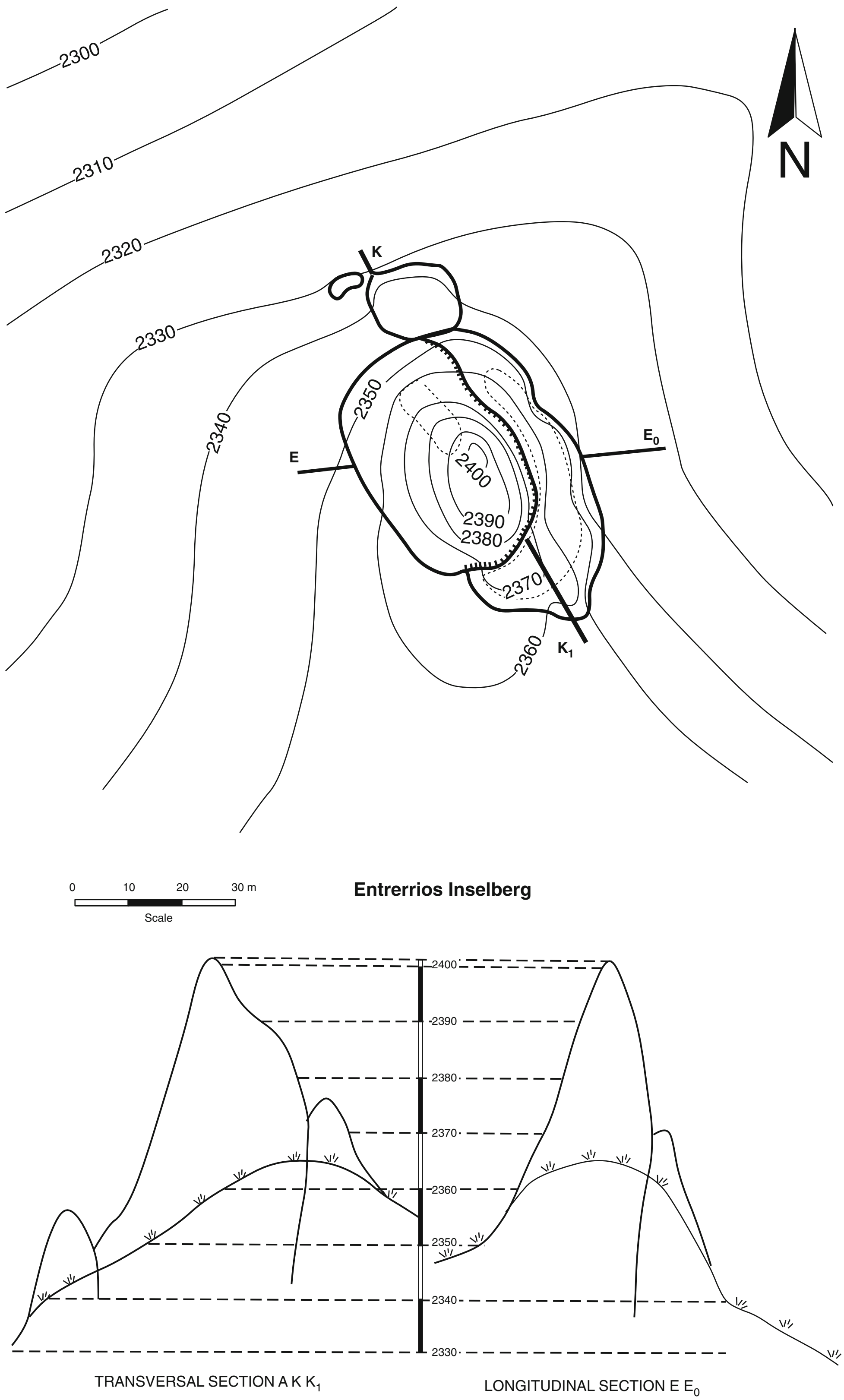
activity is cattle raising and agriculture. About 25 years ago, a new cattle raising method was adopted by farmers: pigs were brought to the region, fed with industrial concentrates, and the manure was used as a fertilizer for pastures. This method permitted the development of a prosperous milk industry and the aspect of the region has changed completely: yellowish grasses are now replaced by flourishing herbages where healthy cattle feed. The Peñol de Entrerrios (*Entrerríos* means "in the middle of the rivers") is located in the summit of a hill, surrounded by the undulating landscape of the Santa Rosa erosion surface at approximately 2500 m a.s.l. The Entrerríos Inselberg can be reached by paved road from Medellin toward the north. It is a 90 min trip, passing through the village of San Pedro. After visiting Entrerríos and its *peñol,* the circuit can be completed through the villages of Santa Rosa de Osos and Don Matias to reach Medellin from the northwest (Fig. 12.10).

After mining activities ceased almost completely in the middle of twentieth century, the region subsisted on agriculture and extensive cattle raising. High precipitation and acid soils contributed to the poverty of the region. About 25 years ago, a new cattle raising method was adopted by farmers: pigs were brought to the region, fed with industrial concentrates, and the manure was used as a fertilizer for pastures. This method permitted the development of a prosperous milk industry and the aspect of the region has changed completely: yellowish grasses are now replaced by flourishing herbages where healthy cattle feed.

Although the dimensions of the Entrerríos Inselberg are smaller than those of Guatapé (c. 50 m high and with a base of 30 m by 60 m), it is visible from the road, a few kilometers after the village of San Pedro, and the Rio Grande hydroelectric project, completed in the 1980s (Fig. 12.11). The hill was surveyed by Botero (1963) (Fig. 12.12) and can also be considered as an example of a bornhardt. Its outline is slightly elongated, and its cross-section profile gives the impression of an inclined body (Fig. 12.13). The rock slopes are steep, especially on the southern side where they are nearly vertical. Isolated boulders occur at the footslope, testifying to the contribution of occasional rock fall in the geomorphic evolution of the hill, although some smaller isolated inselbergs can be observed in the surrounding areas.

The Entrerríos Inselberg is surrounded by the Santa Rosa de Osos surface (Fig. 12.14). Its origin, following the reasoning presented earlier, can be attributed to an incomplete destruction of the Pre-Cordilleran Surface (the Belmira

Fig. 12.12 Entrerrios Inselberg topographic map and profile (Botero 1963)



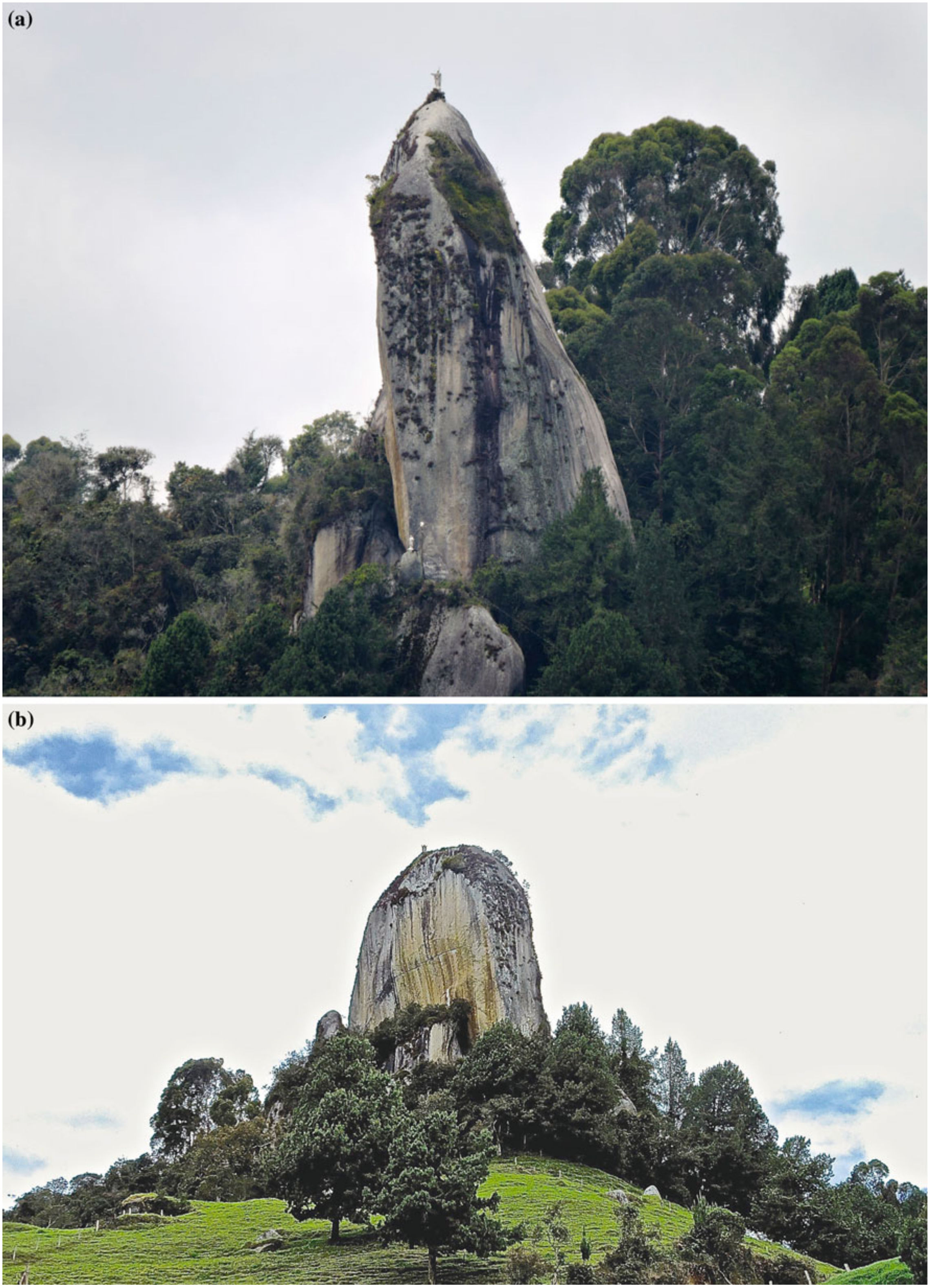


Fig. 12.13 **a** Enterrrios Inselberg from the NW. *Photography* Michel Hermelin. **b** Entrerrios Inselberg from the N. *Photography* Michel Hermelin

Fig. 12.14 The Santa Rosa de Osos erosion surface. *Photography* Michel Hermelin

surface following the Page and James (1982) scheme) during a phase of etchplanation that produced the Santa Rosa de Osos Erosion Surface.

12.8 Conclusions

There are several inselbergs located in the Central Cordillera, all associated with the periods of uplift, erosion and weathering of the Antioquian Batholith. The best known and most visited are the Guatapé and Entrerríos inselbergs. However, there are several others located in different areas of the Antioquian Batholith that are worth visiting. In spite of being a touristic attraction, inselbergs have been relatively poorly studied in Colombia. Further research on this topic is therefore recommended, in order to clarify details about their origin but also to contribute to the understanding of erosion surfaces.

References

Arias A (1995) El relieve de la zona central de Antioquia: Un palimpsesto de eventos tectónicos y climáticos. Revista Facultad de Ingeniería Universidad de Antioquia 10:9–24

Botero G (1963) Contribución al conocimiento de la Geología de la zona central de Antioquia. Anales Facultad de Minas 57, Medellín, p 101

Castro P, Hermelin M (2003) Breve historia de la cartografía geológica en el Departamento de Antioquia, Colombia. Rev Acad Colomb Cienc 27(103):245–261

Codazzi A (2005) Geografía física y política de la Confederación Granadina, v. 4, Estado de Antioquia, Antiguas provincias de Medellín, Antioquia y Córdoba. Barona G., Gómez A. and Domínguez C., Eds., Universidad Nacional–EAFIT University–Universidad del Cauca

Feininger T, Botero G (1982) The Antioquian Batholith, Colombia. Publicación Geológica Especial INGEOMINAS, Bogotá, pp 1–50

Hoyos F, Múnera JC, Arias DE, Vélez MV (2000) Investigación de aguas subterráneas, Región Valle de San Nicolás. Convenio de Cooperación en Ciencia y Tecnología, CORNARE Universidad Nacional de Colombia, Medellín: 71 p

INGEOMINAS (1999) Mapa Geológico del Departamento de Antioquia, escala 1:400 000

INGEOMINAS (2005) Geología de la Plancha 147, Medellín Oriental. Explicación del mapa geológico (Escala 1:50 000), Bogotá

Liégeois PG (1958) Structure et morphologie de le Cordillère Centrale des Andes Bull. Soc Belge Géologie 67(3):529–569

Migon P (2006) Granite landscapes of the world. Oxford University Press, Oxford

Ordóñez O, Pimentel M (2001) Consideraciones geocronológicas e isotópicas del Bartolito Antioqueño. Revista Academia Colombiana de Ciencias Exactas Físicas y Naturales 25:27–35

Page WD, James ME (1981) The antiquity of the erosion surfaces and the Late Cenozoic deposits near Medellin, Colombia: implications to tectonics and erosion rates. Rev CIAF 6(1–3): 421–454

Rendón AJ, Caballero JH, Arias A, González A, Arenas JA, Gallego JJ (2011) Estudio geológico–geomorfológico en el oriente cercano a Medellín, como apoyo a la búsqueda de Actividad tectónica reciente. Boletín de Ciencias de la Tierra 29:39–54

Rendon DA, Hermelin M (2015) Interpretation of saprolith thickness determined by geoelectrical methods on granitic plutons, Northern Central Cordillera, Colombia

Restrepo-Moreno, SA, Foster DA, Kamenov GD (2007) Formation age and magma sources for the Antioqueño and Ovejas batholiths derived from U–Pb dating and Hf isotope analysis of zircon grains. GSA Abstr Progr 39(6)

Restrepo-Moreno SA, Foster DA, Stockli DF, Parra-Sánchez LN (2009) Long–term erosion and exhumation of the “Altiplano Antioqueño”, Northern Andes (Colombia) from apatite (U–Th)/He thermochronology. Earth Planet Sci Lett 278(1–2):1–12

Saenz EA (2003) Fission track thermochronology and denudational response to tectonics in the north of the Colombian Central Cordillera [Masters Thesis]: Matsue-shi, Shimane University Japan

Scheibe R (1919) Informe sobre resultados de la comisión científica nacional en Antioquia. Compilación Estudios Geológicos Oficiales en Colombia 1:95–165

Thomas MF (1994) Geomorphology in the tropics. Wiley and Sons Ltd, Chichester

Toro GE, Hermelin M (1990) Stratigraphy of volcanic Ashes from Southern Antioquia: possible paleoclimatic implications. Quat S Am Antart Penins 8:201–217

Toro G, Hermelín M, Schwabe E, Posada B, Silva D, Poupeau G, Restrepo JJ (2006) Fission-track datings and geomorphic evidences for long-term stability in the Central Cordillera highlands, Colombia. Zeitschrift für Geomorphologie 145:1–16

Twidale CR (1989) The subsurface initiation of granitic landforms and implications for general theories of landscape evolution. Cuaderno Lab. Xeolóxico de Laxe 13:49–68

Twidale CR, Vidal Romani JR (2005) Landforms and geology of granite terrains. Balkema, Rotterdam

Widdowson M (1997) The geomorphological and geological importance of palaeosurfaces. In: Widdowson M (ed) Palaeosurfaces: recognition, reconstruction and palaeoenviromental interpretation. Geological Society Special Publication, vol 120. Geological Society, London, pp 1–12

Wirthmann A (2010) Geomorphology of the tropics. Springer, Berlin

Inter-Andean Cauca River Canyon

13

José Humberto Caballero, Albeiro Rendón, John Jairo Gallego, and Nathalia Vanessa Uasapud

Abstract

A section of the Cauca River canyon passing through the Department of Antioquia in northwestern Colombia is considered to be of great interest due to its geological and geomorphological characteristics, which give rise to stunning landscapes. The canyon is divided from south to north into three geomorphological segments. Erosion and accumulation processes are dominant in the first segment, highlighted in the Támesi*s* Scarp and landforms, such as Los Farallones de La Pintada. Morphotectonic features associated with the Cauca-Romeral Fault System and represented by the Cerro Bravo, El Sillón and Tusa Mounts are significant in the second segment. The third segment is characterized by fluvio-lacustrine to torrential accumulation processes and there are also evidences of neotectonic activity expressed by active mountain fronts along with seismites. This portion of the Cauca River is quite diverse and there are few places in Colombia that concentrate so much geodiversity in so few miles. Additionally, it has a high esthetic value because of the marked geomorphological contrast and the existence of panoramic landscapes.

Keywords

Canyons • Tropical mountain rivers • Recent tectonics

13.1 Introduction

The segment of the Cauca River canyon, a great geomorphological and natural heritage of the country, is located in the northwest of the country, west of the city of Medellin. It is famous for both its majestic scenery and great scientific interest.

The Cauca River rises at the *Macizo Colombiano* in southwestern Colombia and flows northward through contrasting geomorphological regions; it joins the Magdalena River and, together, they flow out into the Caribbean Sea. The segment described in this chapter is a part of the great intra-range valleys that characterize the Colombian Andes. Locally, it is an impressive depression formed by a 2000-m-deep canyon incised into extensive, well-preserved erosion surfaces of the Central Cordillera.

The Cauca River canyon can be reached by two main roads, from Medellin or from Manizales. Several towns in the region offer a variety of lodging and additional attractions, such as the historical town of Santa Fe de Antioquia.

J.H. Caballero (✉) · A. Rendón · J.J. Gallego · N.V. Uasapud
Universidad Nacional Medellín, Medellín, Colombia
e-mail: jhumberto.caballero@gmail.com

A. Rendón
e-mail: arendonr@unal.edu.co

J.J. Gallego
e-mail: jjgm89@gmail.com

N.V. Uasapud
e-mail: nadkoaol@gmail.com

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_13

13.2 Geodynamic Setting

The northern part of the Colombian Andes has been formed by a complex structural converging interaction at the northwest corner of the South American continental plate, at its junction with the Nazca and Caribbean oceanic plates (Fig. 13.1). It has also been affected by regional fault systems, the product of subduction and strike slip faulting (Page 1986).

In the study area, the fault pattern is dominated by the Cauca-Romeral Fault Systems, which cross the Northern Andes from Guayaquil up to the Caribbean Sea. This SSW–NNE to S–N trending fault system is inherited from a complex sequence of accretions that occurred since the Cretaceous. At a local scale, these fault systems are represented by a series of parallel to subparallel fault segments, sometimes anastomosed (Suter et al. 2008). Between 4°N and 5°N, its kinematics changes from right-lateral in the south to left-lateral in the north (Taboada et al. 2000).

The Romeral Fault System in the east is distributed as an elongated strip of variable width, bounded on the east by the San Jerónimo Fault and on the west by the Sabanalarga Fault, whereas the Cauca, Anzá and Peque Faults are the most important of the Cauca Fault System in the west, located on the western side of the Cauca River, in the eastern foothills of the Western Cordillera. In general, they are inverse strike slip faults and many of them are considered to be active, with low to moderate activity.

13.3 Geology

Geographically, the Cauca River divides the Western and Central Cordilleras that are markedly different in terms of both lithology and ages of main rock complexes, ranging from Paleozoic to the present (Fig. 13.2).

The core of the Central Cordillera consists of Paleozoic metamorphic rocks of continental environments, such as

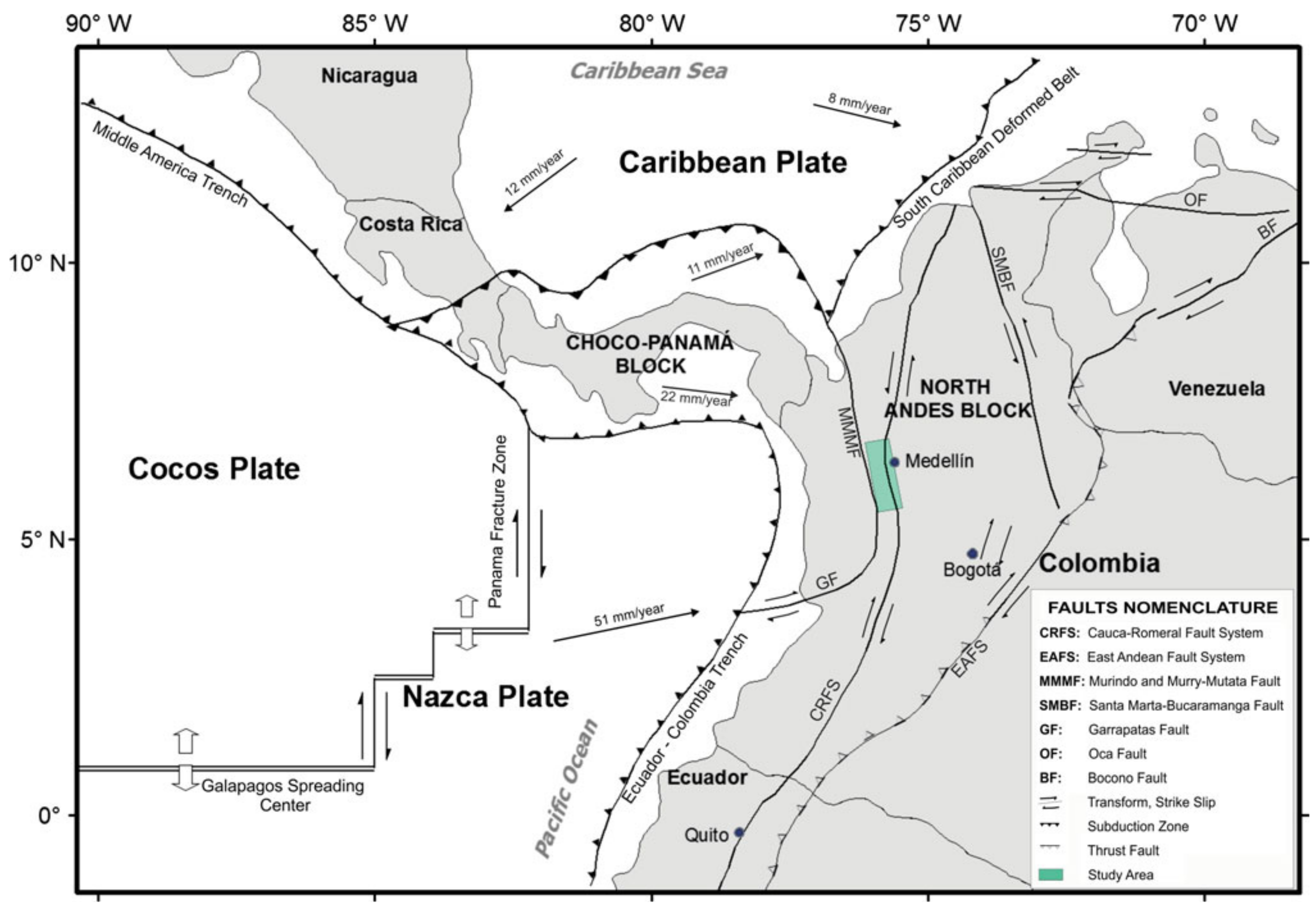


Fig. 13.1 Geodynamics of the north-western part of South America. Tectonic data modified from Rendón (2003), Monsalve and Mora (2005), Suter et al. (2008)

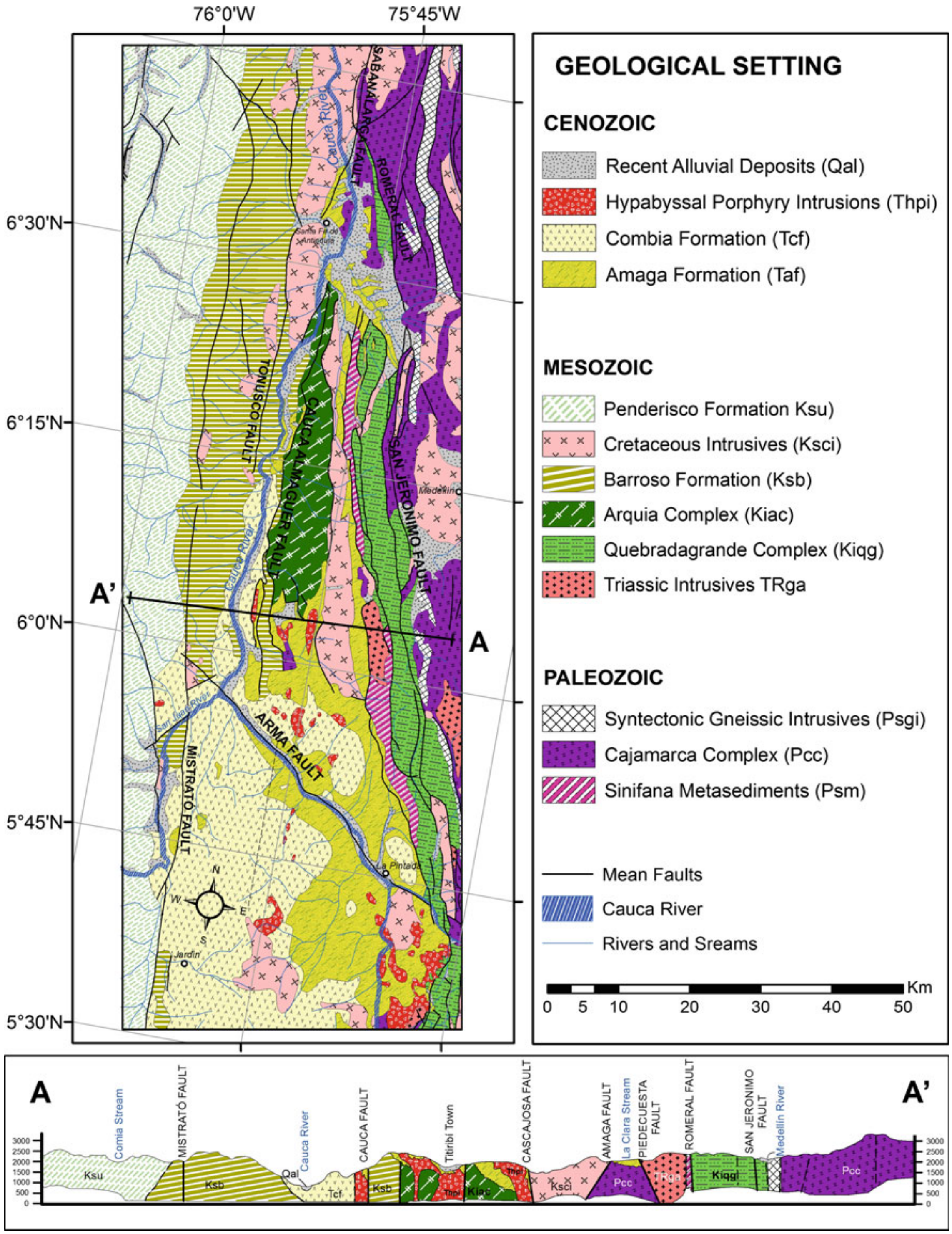


Fig. 13.2 Main geological units of the study area (Ingeominas 1990, 2001)

Sinifaná metasediments, along with schists, gneisses, quartzites, and marbles of the Cajamarca Complex. These rocks were intruded by granitic bodies, which were tectonically affected during their emplacement. During the Mesozoic, contrasted geological events occurred. Several stocks were intruded during the Triassic and this activity continued more intensely during the Cretaceous, resulting in the intrusion of the Antioquia and Sabanalarga Batholiths. Marine sedimentation in the Central Cordillera began during the Cretaceous and was followed by periods of intense seafloor volcanism, as recorded by the Quebradagrande Complex. Around the same time, the Arquía Complex appeared as a strip of medium-pressure, tectonized metamorphic rocks and related dismembered ophiolitic sequences along the Romeral Fault System (INGEOMINAS 2001).

The Barroso Formation and the Cañas Gordas Group, which contains the Penderisco Formation, represent an intense, late Cretaceous basic oceanic volcanism and constitute the oldest units of the Eastern Cordillera that are geologically separated from the Central Cordillera by the Romeral Fault System (INGEOMINAS 2001).

The Cenozoic began with the intrusion of sub-volcanic bodies of andesitic composition and porphyritic texture. Sedimentation in the Cauca River Basin was controlled by tectonics; a graben formed, resulting of pulling movements along the Romeral Fault System. Sediments from the Amagá Formation were deposited during the Neogene and are characterized by the presence of beds and lenses of coal. Lava flows and pyroclastic sequences of Combia Formation were deposited on top of these sediments, signaling the beginning of intense volcanic activity that extends to the present-day.

The Amagá Formation unconformably underlies the Combia Formation and is intruded by late Miocene porphyry bodies. This unit is dismembered along the Cauca River Canyon by the Cauca-Romeral Fault System, representing the clearest evidence of active tectonics at least until Late Miocene.

During the Quaternary, the high-energy morphodynamics of the Cauca River slopes and tributary watersheds, related to the Andean orogeny, generated numerous bodies of unconsolidated deposits composed of coarse materials (boulders, pebbles, gravel). These are mainly alluvial fans and slope deposits. Fluvio-lacustrine terraces are associated with ancient damming of the Cauca River and have been affected by recent tectonic activity. Some soft sediment layers show deformation structures as seismites, tilted horizons, and vertical faulting with movements less than 1 m in active mountain fronts.

13.4 Geomorphologic Setting

The central area of the Department of Antioquia is characterized by the presence of highlands embedded by two major N–S trending fault systems, Palestina in the east and Cauca-Romeral in the west. The highlands are a sequence of stepped erosion surfaces, which show a predominant southeastward tilt. The internal low relief of the highlands is a relict landscape, preserved due to low erosion rates since the late Cenozoic uplift (Page and James 1981).

The Cauca River Canyon marks the western boundary of the area where the erosion surfaces are preserved. Landforms

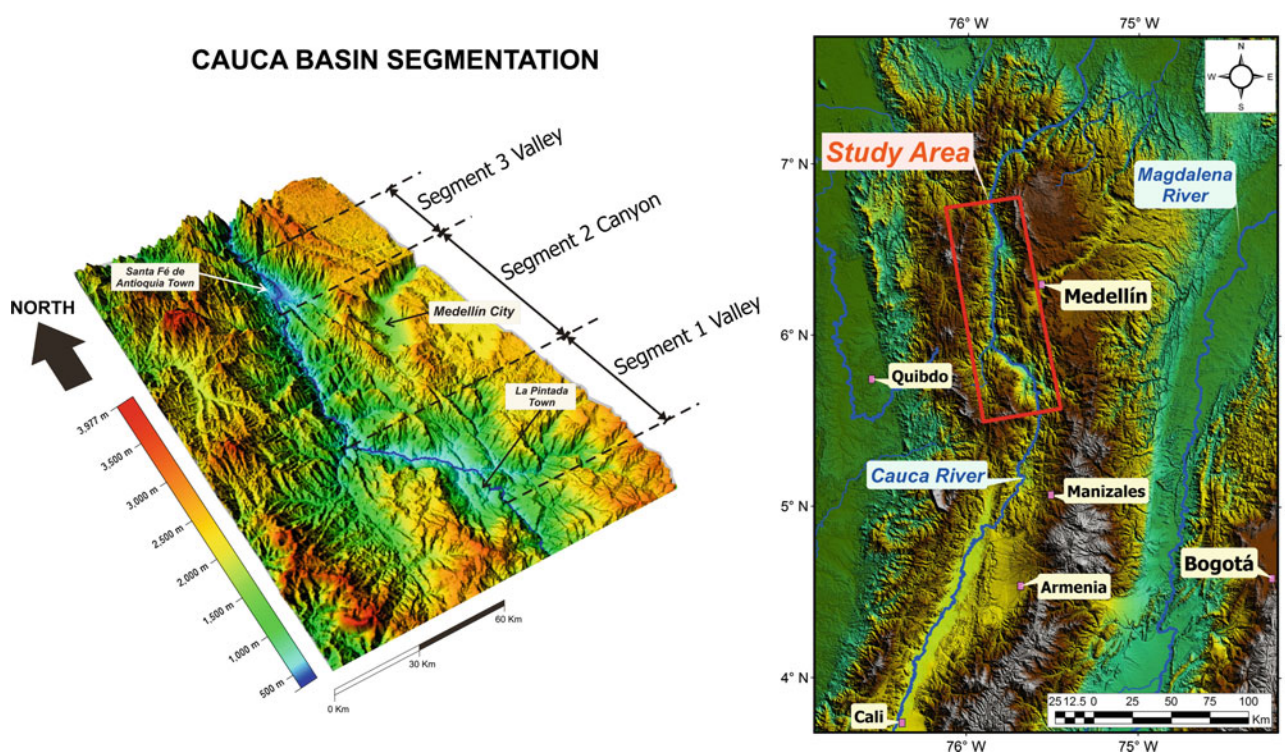


Fig. 13.3 The Cauca River basin segmentation and regional geomorphological setting

associated with intense morphodynamic processes such as slides, mud, and debris flow and intense gullying are common in the canyon slopes. It is also important to mention strong altitudinal gradients associated with abrasion zones and removal of large slope deposits.

The canyon geomorphology is complex, consisting of superimposed landscapes that have been associated with recent tectonic processes and climate variations during the Quaternary. There are noticeable morphotectonic features, such as deflected drainage systems and aligned hills and valleys. In addition, there is evidence of recent tectonic activity in the Holocene unconsolidated sediments of the Cauca River terraces (Suter et al. 2010), suggesting that earthquakes played an important role in the evolution of the landscape.

Figure 13.3 shows the regional geomorphology and a 30-m resolution DEM of the three selected sections. Several segments exhibit marked structural control, where openings and closings coincide, in many cases, with anastomosing strike slip fault traces and pull-apart structures.

13.4.1 Segment One: From Canyon to Valley

In the southeast of the area, the Cauca River incised a narrow canyon into bedrock and local relief is more than 1000 m. Deep fluvial erosion has uncovered hypabyssal rocks more resistant than their embedding sediments from the folded Tertiary sediments of the Amagá Formation and volcano-sedimentary materials of the Combia Formation (Fig. 13.4a).

Three hills formed in porphyritic rocks trending N–S, known as Los Farallones de La Pintada (Pintada Rocky Peaks) stand out as the result of the Cauca River incision (Fig. 13.4b). They are parts of ancient volcanic necks and

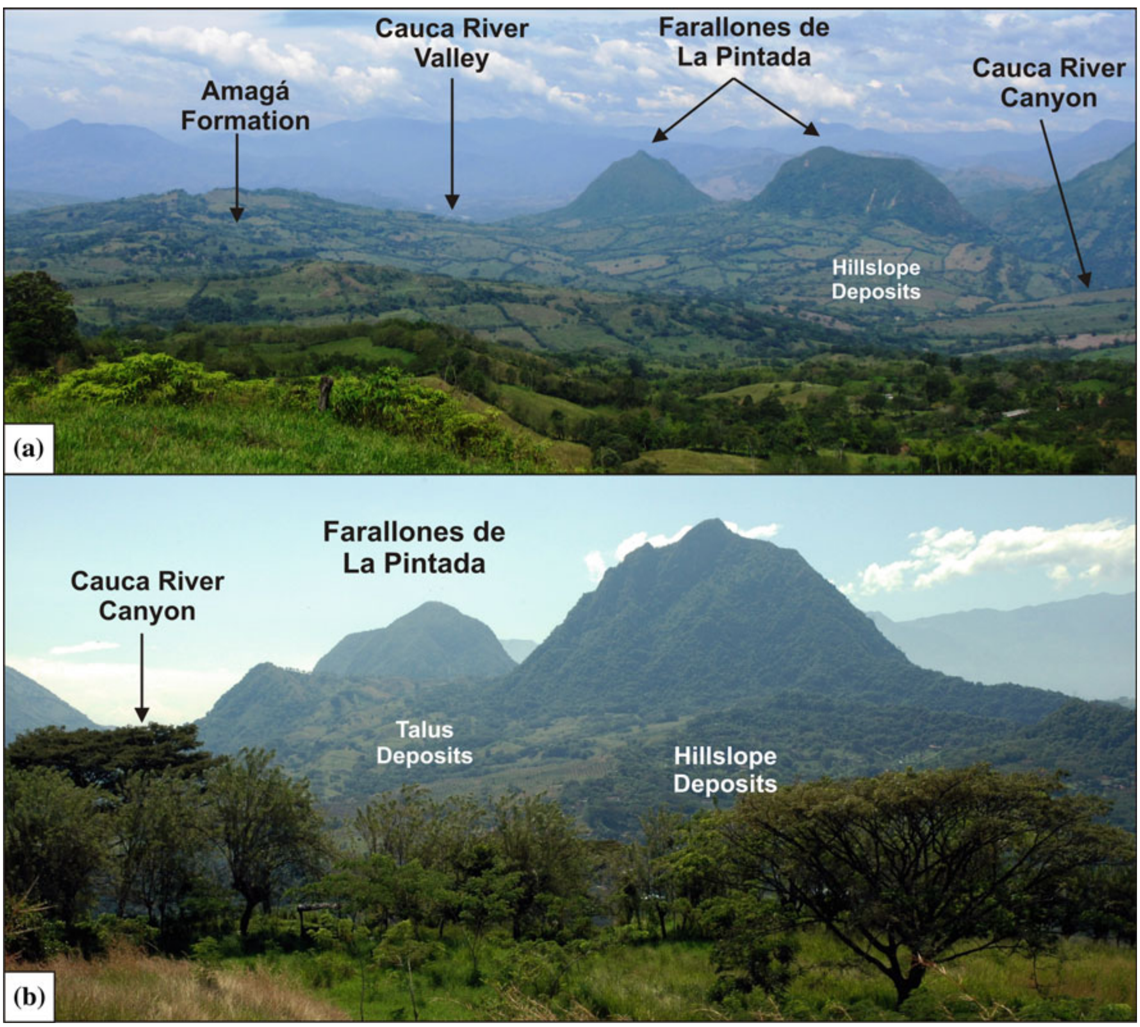


Fig. 13.4 Features of the segment 1 of the Cauca River valley and the morphology of Los Farallones de La Pintada

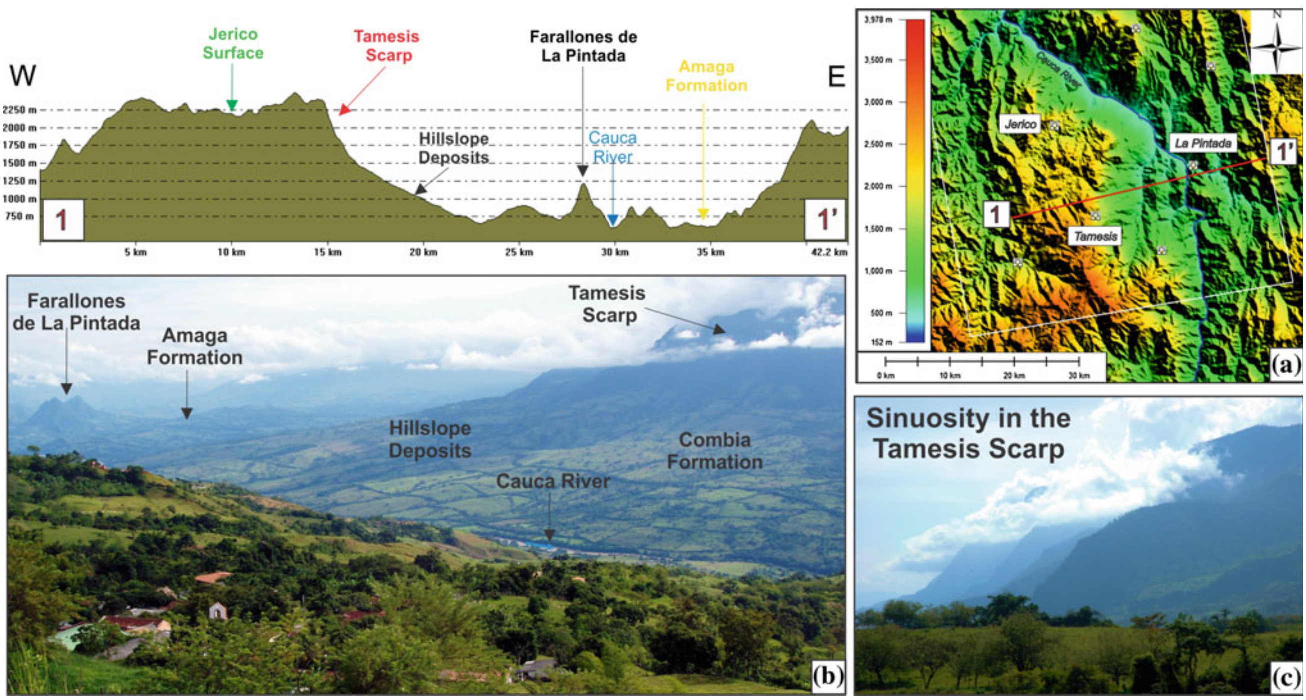


Fig. 13.5 Geomorphological profile of Segment 1 and linear valley features

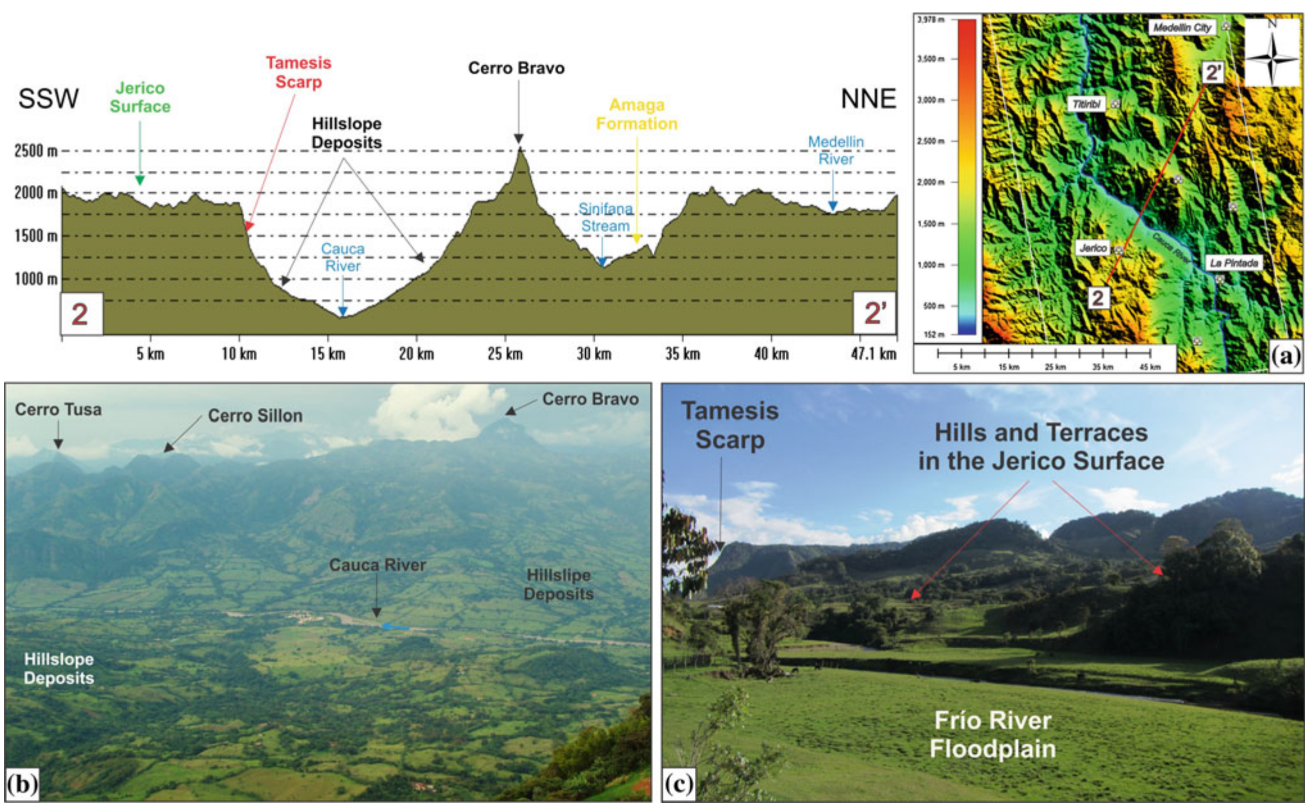


Fig. 13.6 Hill slopes of the Cauca River valley and the Jericó surface

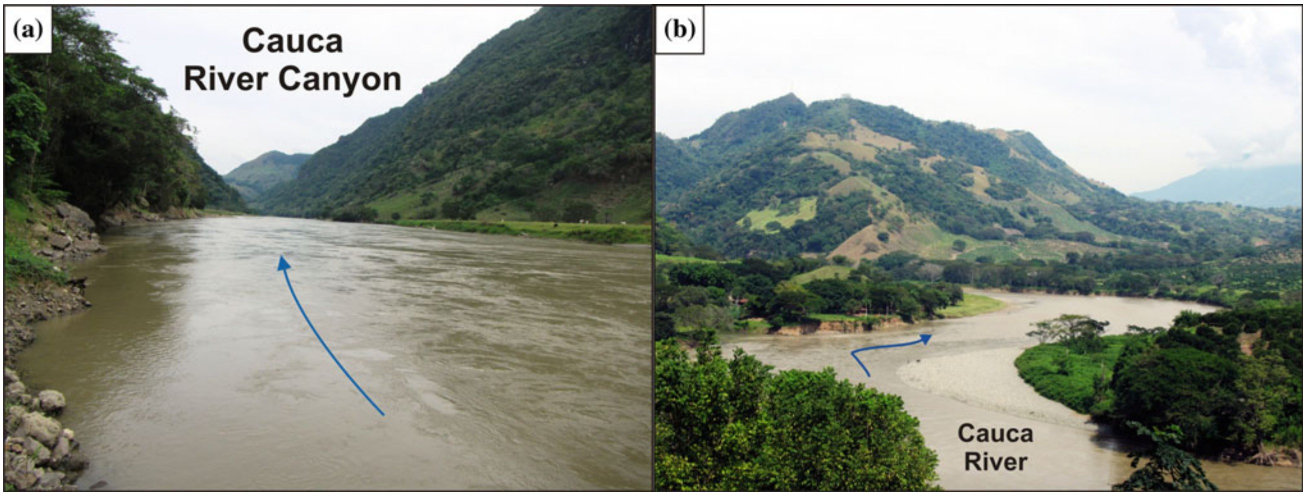


Fig. 13.7 The Cauca River Canyon in segment 2

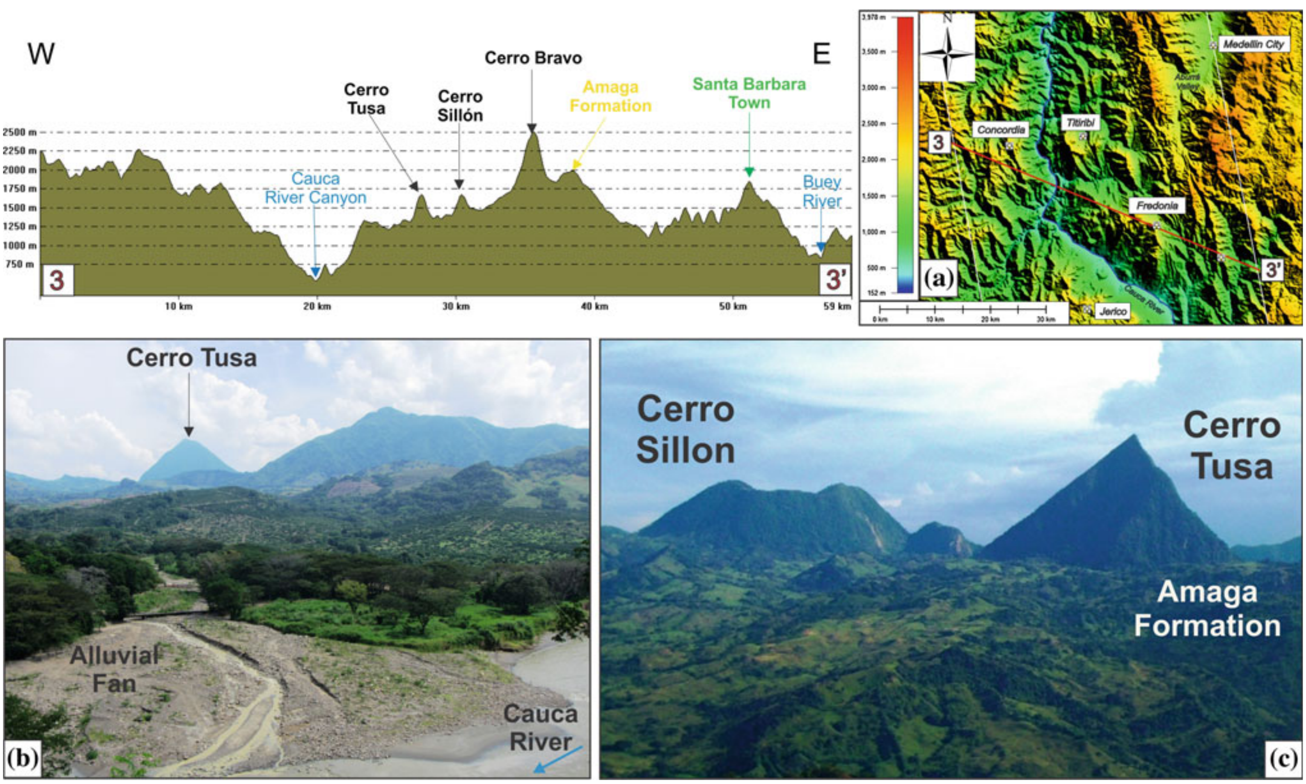


Fig. 13.8 The Cauca Basin geomorphological features in segment 2

have an abrupt morphology with high and steep slopes. Due to very active erosion produced by rapid cordillera uplift, they show little weathering. Translational slides and rock falls have contributed to the recent talus deposits west of these bodies.

There is a profound morphological change in the Cauca river valley downstream from the mouth of the Arma River. The narrow basin changes drastically to a wide, linear valley characterized by a strong structural control as exemplified in the now N50 W trending Cauca River. The course of the river in this section is related to the trace of the Arma Fault (INGEOMINAS 2001).

Characteristic features of this valley section are the broad valley floor, Los Farallones de La Pintada, and the Tamesis scarp (Fig. 13.5a). Along the base of the scarp thick slope deposits have accumulated. The sinuosity of the Tamesis

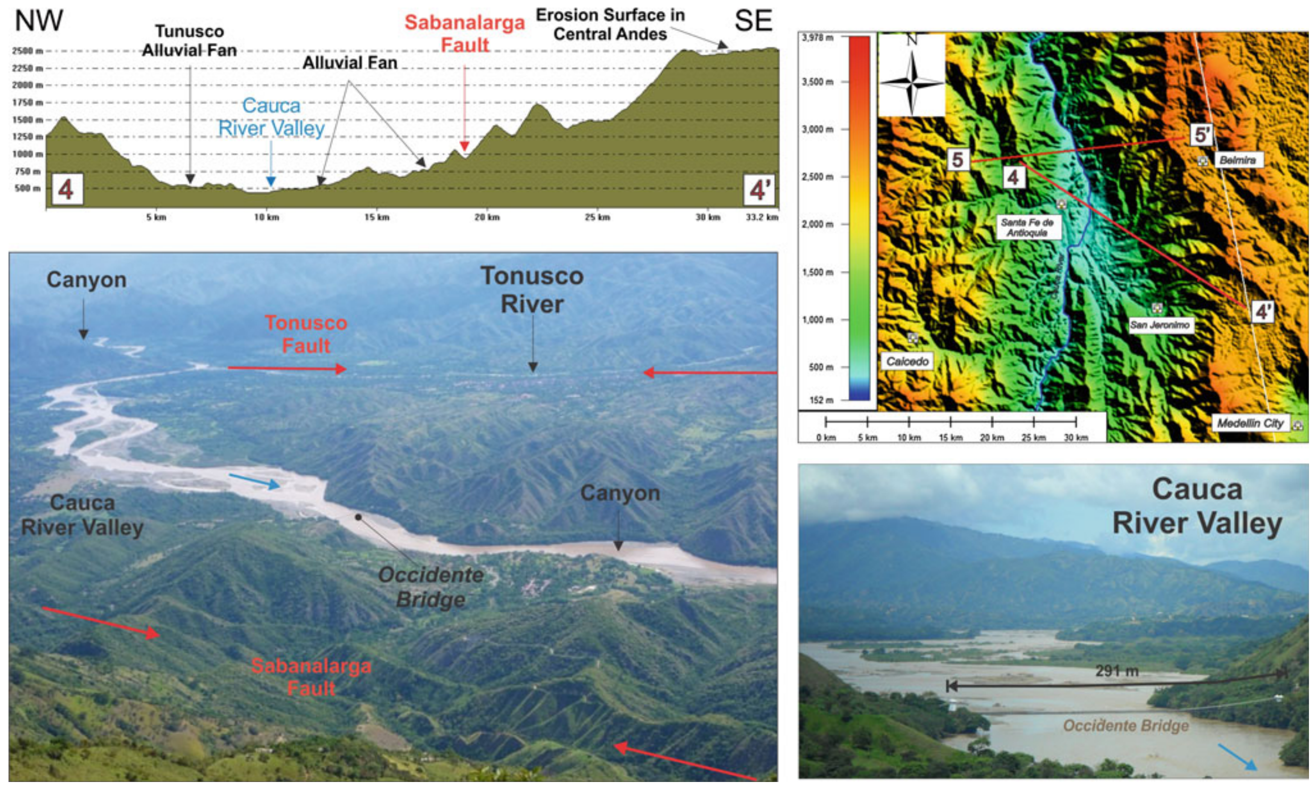


Fig. 13.9 The broad section of the Cauca River valley and its morphotectonic features. Cross section 5–5′ is presented on Fig. 13.11

scarp results from progressive erosion that has formed horseshoes and pediments as the evidence of enlargement of the valley and escarpment retreat (Fig. 13.5b, c).

The Cauca River valley width is about 20 km and it has a significant relative relief of 1300 m (Fig. 13.6a; Profile 2–2′). Likewise, the highest isolated hill is 2,500 m high and it is known as Cerro Bravo (Fig. 13.6b), which evidences the magnitude of Neogene volcanism that have occurred and significant erosion and exhumation rates in the basin.

Both hillslopes of the Cauca River are covered by slope deposits that consist of thick mud and debris flow materials, eroded by various tributaries. This erosion has exposed decametric-sized boulders from the base of the escarpment to the distal area near the Cauca River. These bodies could not have traveled over such long distances due to their volume. It is therefore suggested that they are remnants of the evolution and erosive retreat of the vertical talus that composed the Támesis Scarp.

The Jericó surface is a highland cut across an accumulation of volcanoclastic sediments of the Combia Formation. This surface has suffered less incision than the slopes of the Cauca River. Nevertheless, it shows a low hilly relief, which provides evidence of inverted relief given by multiple levels of alluvial terraces of the Frío River valley (Fig. 13.6c).

13.4.2 Segment Two: From Valley to Canyon

The Cauca River drastically changes its trend from the mouth of the San Juan River in the Peñalisa village, where it again becomes a canyon with strong N–S trend, controlled by the course of the Cauca-Romeral Fault System. In this section, the river narrows to a deep canyon with changeable extent from hundreds of meters to 10 km. Furthermore, its relative relief is higher than 2000 m.

The overall hydraulic behavior of the river is given by a straight pattern with high incision and abrasion rates (Fig. 13.7a). The river cuts into bedrock and accumulation of alluvial deposits is unusual. However, as the river flows north, the canyon widens and the channel tends toward a meandering behavior, with deposits of gravel-sized sediments, marked lateral erosion and toe scour (Fig. 13.7b). Another feature of the canyon is the extensive alluvial fans from most of the tributaries, which have higher gradients and torrential behavior. Toward the Cauca River valley floor they merge into one, gently sloping surface. Figure 13.8 shows fans of the Sinifaná and Amagá Rivers, with several dissected terrace levels.

Furthermore, various rocky hills and peaks protrude in the landscape. The most representative are known as El Sillón and Tusa mounts, the latter with an amazing geometric pyramidal morphology, which used to be used for rituals and worship by the natives who inhabited the region. Currently, Cerro Tusa is one of the most important and widely recognized landforms within the geomorphological and archaeological heritage of Colombia and it is considered as one of the largest natural pyramids in the world.

Profile 3–3′ (Fig. 13.8) identifies the westward tilting of the Amagá Formation and rocky andesite porphyry hills with striking geometric shapes, which protrude among sedimentary rocks. The intrusion of these hypabyssal rocks of the Combia Formation into the sandstone strata is a part of the Neogene magmatism in northwestern Colombia.

13.4.3 Segment Three: From Canyon to Valley Again

This section is characterized by a broad valley, in which there is a sizeable accumulation of alluvial materials, along with torrential and fluvio-lacustrine deposits. In this area, there are no rock outcrops, in contrast to what was observed in the previous segments. The Cauca River undergoes a noticeable change, turning eastward after passing the mouth of the Tonusco River. In addition, its bed expands to reach a width of about 1 km.

Undoubtedly, this large valley presents the most notorious morphotectonic features associated with recently active

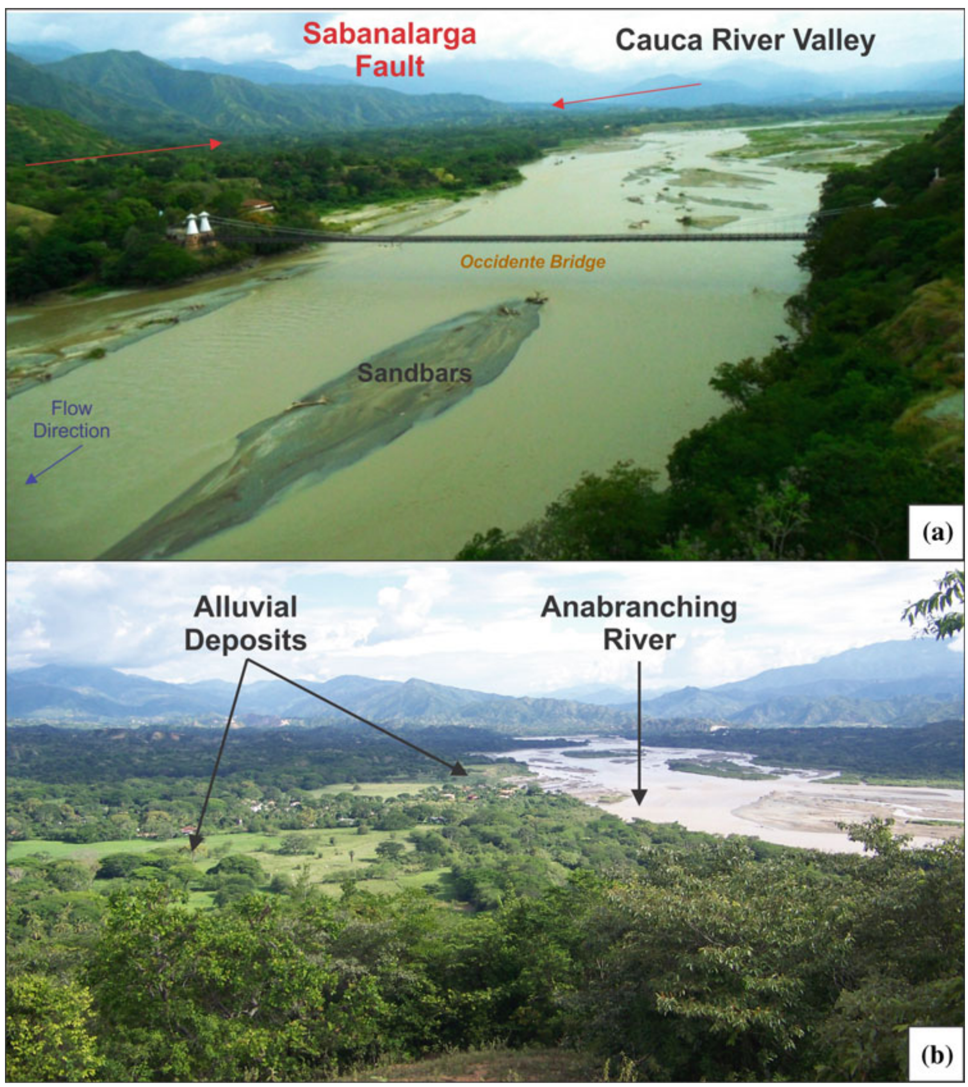


Fig. 13.10 Alluvial deposits and the amplitude of the Cauca River valley in segment

faults west of Medellin. The landscape is dominated by the mountain front of the Sabanalarga Fault (Fig. 13.10a), the marked fault lineament of the Tonusco River, and the trace of satellite faults associated with the Cauca Fault System (Fig. 13.9).

This sector of the Department of Antioquia, and especially the town of Santa Fe, due to its auriferous wealth and tropical dry climate has been favored among post-conquest settlers. Santa Fe is one of the oldest towns found by Spaniards in this part of the country. It has well-preserved colonial architecture and churches that are considered an important part of the country's cultural and historical heritage. Furthermore, the Puente de Occidente is a 291-m-long bridge, built between 1887 and 1895 and at that time considered as the largest wooden suspension bridge worldwide (Figs. 13.9c and 13.10a).

In this segment, the Cauca River channel has an anabranching pattern, with many sand and gravel oversized bars, in which informal gold panning has been carried out since Colonial times (Fig. 13.10b). In this portion of the basin, recent silt deposits on both banks of the river, suggesting a calm depositional environment, are possibly related with a fluvial-lacustrine regime. These fine deposits are not resistant to erosion and have been rapidly entrenched by the river. Recent studies indicate that their origin may be associated to the Cauca River damming by mega-landslides generated by earthquakes and/or instability of rock slopes further downstream. It is also important to mention the evidence of neotectonic activity determined from morphotectonic features and the displacement of recent deposits, liquefaction phenomena and seismites on the silt terraces in the surroundings of the towns of Santa Fe de Antioquia and Olaya.

The Cauca Basin again changes its morphology after crossing the Occidente Bridge and once again becomes a deep and narrow canyon until it leaves the northern foothills of the Cordillera Central. About 100 km downstream from this segment, there are impressive morphotectonic features related to faults such as straight mountain fronts and triangular facets (Fig. 13.11). Furthermore, it is possible to identify aligned saddles and considerably dissected alluvial fans, such as the one left by the Tahamí Stream in the town of Sucre.

The morphology in this segment of the valley is characterized by mountain ranges on both sides of the river. The lower is located in the bottom of the valley and shows low

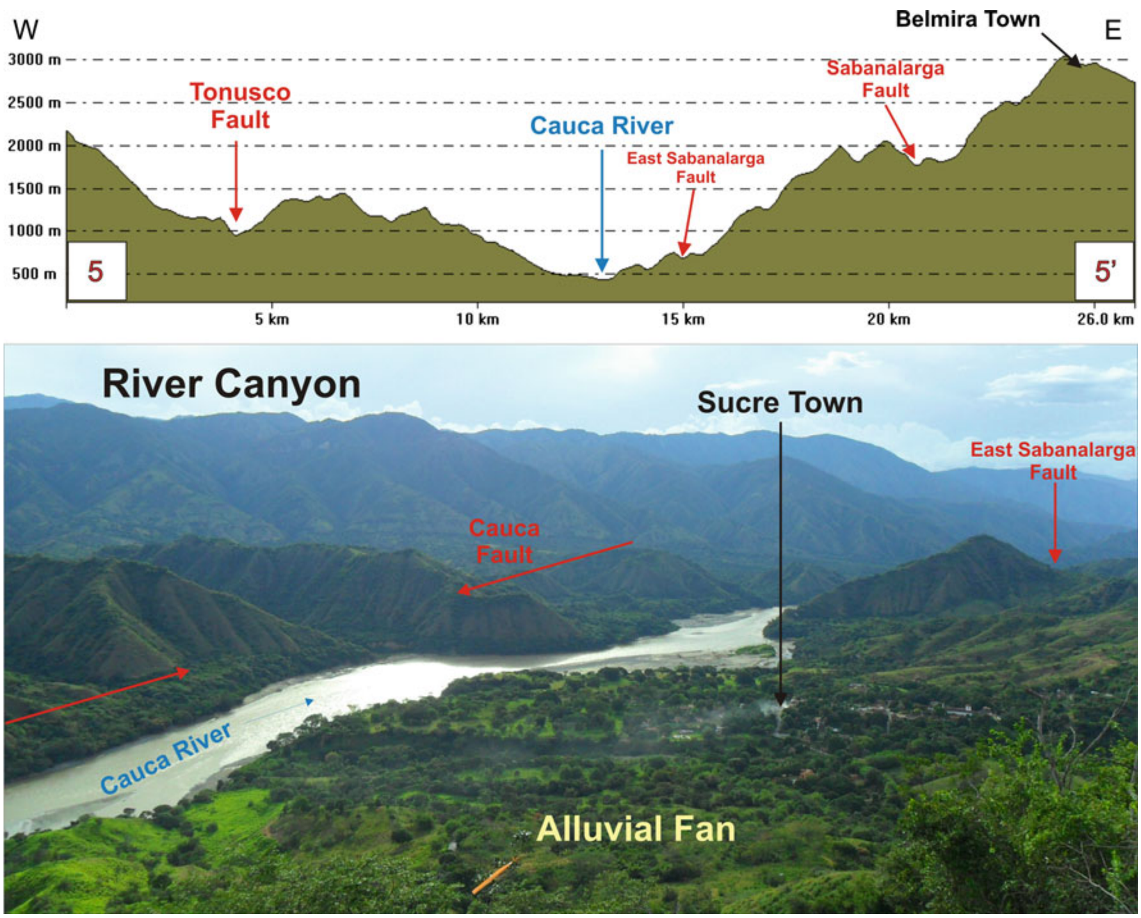


Fig. 13.11 Features of the Cauca River canyon downstream from the Occidente Bridge

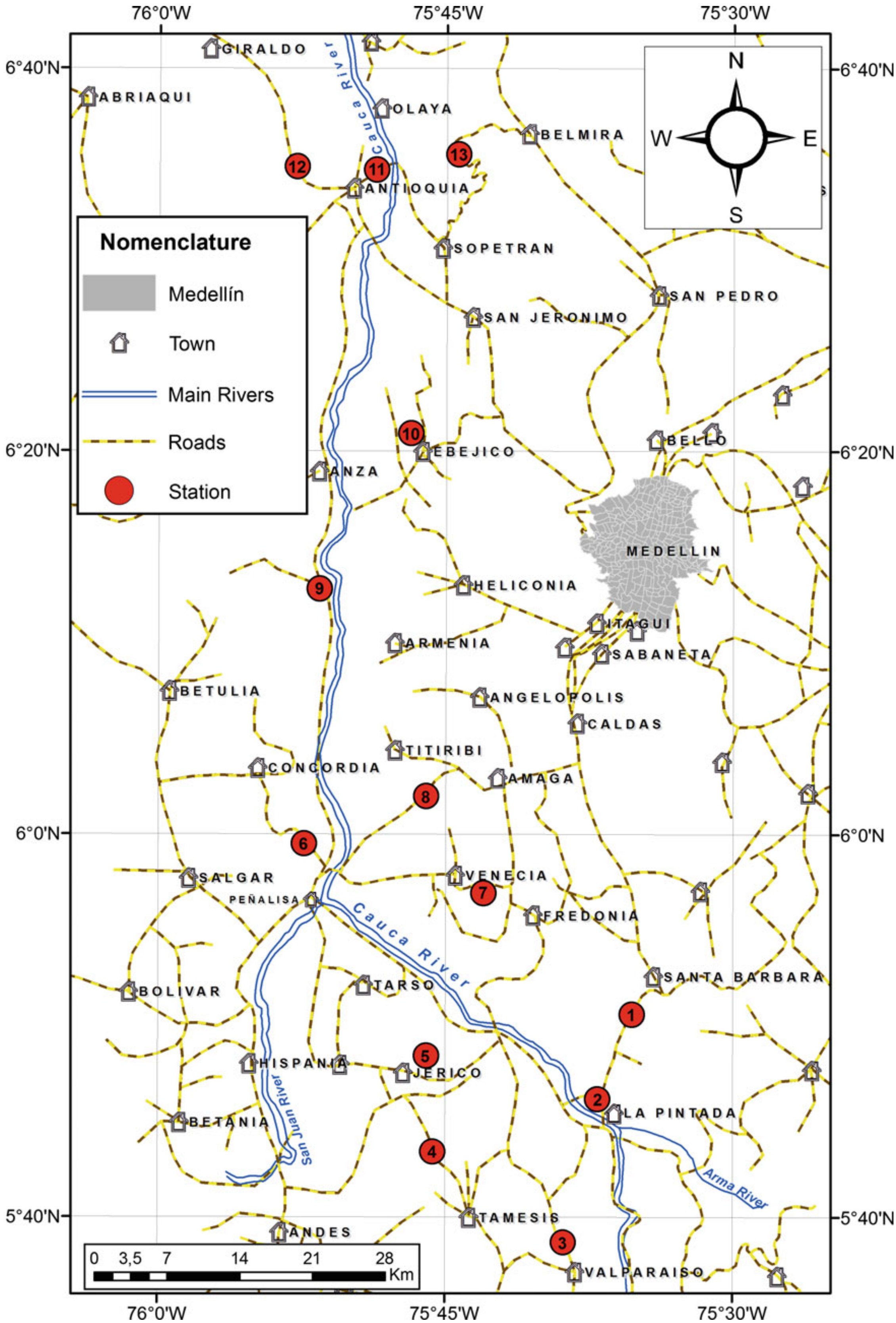


Fig. 13.12 Itinerary and proposed geomorphosites

Table 13.1 Location of points of interest for observing the landscape

Stop	Longitude (W)	Latitude (N)	Locality	Landscapes
1	75°35′ 17.06″	5°50′ 39.17″	Midway between Santa Bárbara and La Pintada	Segment 1 of the Cauca River Valley, Támesis Scarp and Amagá Formation
2	75°36′ 54.25″	5°45′ 40.17″	La Pintada	Segment 1 of the Cauca River Valley, *Farallones de la Pintada*
3	75°38′ 48.91″	5°38′ 40.38″	Midway between La Pintada and Valparaiso	*Farallones de La Pintada*, Amagá Formation and Támesis Scarp
4	75°45′ 26.48″	5°43′ 29.21″	Támesis to Jericó	Segment 1 of the Cauca River Valley, Támesis Scarp, Jerico Surface and Frio River waterfall
5	75°45′ 53.50″	5°47′ 38.93″	Puerto Arturo-Jericó Highway	Segment 1 of the Cauca River Valley, Tamesis Scarp and Combia Formation
6	75°52′ 23.25″	5°59′ 26.93″	Road to Concordia	Segment 2 of the Cauca River Canyon, mouth of the San Juan River and the Romeral Fault System
7	75°43′ 26.01″	5°57′ 14.433″	Venecia	Segment 2 of the Cauca River Canyon and Cerro Tusa climbing
8	75°46′ 06.20″	6°02′ 9.15″	La Siria-Bolombolo Highway	Hypabyssal porphyry intrusion and Amagá Formation
9	75°51′ 28.30″	6°12′ 59.14″	Peñalisa to Anza road	Segment 2 of the Cauca River Canyon and alluvial fans
10	75°45′ 59.92″	6°20′ 12.43″	Quebrada Seca-Ebéjico	Cauca-Romeral Fault System
11	75°49′ 50.48″	6°33′ 43.01″	Santa Fe de Antioquia	Segment 3 of the Cauca Cauca River Valley and Occidente Bridge
12	75°52′ 51.44″	6°34′ 49.16″	Antioquia-Giraldo Highway	Segment 3 of the Cauca Cauca River Valley and Cauca-Romeral Fault System
13	75°44′ 12.95″	6°35′ 30.25″	Llanadas	Segment 3 of the Cauca Cauca River Valley, Tonusco River and Cauca-Romeral Fault System

edges and ridges; the higher is situated over 3000 m a.s.l. and constitutes the flank of the erosion surface remnants in the Central Cordillera. This marked contrast can be interpreted as the differential action of individual faults within the Cauca-Romeral Fault System during uplift of the Cordillera, as well as the result of erosion and intense Cauca River incision in response to the recent pulses of uplift.

13.5 Proposed Geotouristic Itinerary

In order to appreciate the landscapes of each segment, the following itinerary from Medellin is proposed (Fig. 13.12). The recommended circuit would take 2 days and include sites listed in Table 13.1.

References

INGEOMINAS (1990) Mapa geológico generalizado del departamento de Caldas a escala 1:250.000

INGEOMINAS (2001) Mapa Geológico del departamento de Antioquia a escala 1:400.000. Memoria Explicativa

Monsalve H, Mora H (2005) Esquema geodinámico regional para el noroccidente de Suramérica (modelo de subducción y desplazamientos relativos). Boletín de Geología 27(44):25–53

Page WD (1986) Seismic Geology and Seismicity of Northwestern Colombia: Report to Integral Ltda, ISA y Woodward Clyde Consultants, 156 p

Page WD, James M (1981) The Geology of the Erosion Surfaces and Late Cenozoic Deposits Near Medellin, Colombia: Implications to Tectonics and Erosion Rates. Revista CIAF vol 6 No (1–3), pp 421–454, Bogotá

Page WD, Mattson L (1981) Landslide lakes near Santa Fe de Antioquia. Revista CIAF 6(1–3):469–478

Rendón DA (2003) Tectonic and sedimentary evolution of the upper Aburrá Valley. Northern Colombian Andes. Master Thesis, Shimane University. Japan, pp 1–60

Suter F, Martínez J, Vélez M (2010) Holocene soft-sediment deformation of the Santa Fe-Sopetrán Basin, northern Colombian Andes: Evidence for pre-Hispanic seismic activity? Sedmin Geol 235:188–199

Suter F, Sartori M, Neuwerth R, Gorin G (2008) Structural imprints at the front of the Chocó-Panamá indenter: field data from the North Cauca Valley Basin, Central Colombia. Tectonophysics 460:134–157

Taboada A, Rivera LA, Fuenzalida A, Cisternas A, Philip H, Bijwaard H, Olaya J, Rivera C (2000) Geodynamics of the Northern Andes: subduction and intra-continental deformation (Colombia). Tectonics 19:787–813

14 Geomorphological Characteristics of the Ruiz Volcano and Surroundings

Gloria Elena Toro, Ricardo Méndez, Michel Hermelin, and
Miguel Angel Tavera

Abstract

Landforms related to the Ruiz Volcano, the northernmost active volcano in South America, are both of volcanic and glacial origins. A brief historical account includes several eruptions and culminates with the catastrophic one which occurred in November 13th, 1985. A description of the geological evolution of the area is complemented by an itinerary which will permit the observation of the more important landforms.

Keywords

Volcanic landforms • Glacial landforms

14.1 Introduction

The VolcánNevado de Ruiz (Snowy Ruiz Volcano, SRV, also called Kumanday Volcanic Chain) is an active stratovolcano with a diameter of 15 km at its base, an active, almost circular crater (the Arenas), measuring 870 × 830 m with a depth of 243 m (Méndez 1989; Mora et al. 1996). Two adventice craters are associated: the Olleta (Small Pot) located westward and the Piraña, eastward. The Ruiz is covered by an ice cap with a volume evaluated in 1200–1500 millions m^3. It belongs to the Cerro Bravo (Bravo Mount)–Cerro Machin Volcanic Complex (CBCMVC, Méndez and Patiño 1994) and is one of the most remarkable landforms of the country, located in the axis of the Central Cordillera, 150 km northwest of Bogotá and 28 km southeast of Manizales, the nearest city (Fig. 14.1). It reaches an altitude of 5321 m a.s.l. and its origin is associated to the Nazca Plate subduction under the South American Plate (Murcia 1982) in a tectonic environment of active continental margin, characteristic of the Andean region (Wilson 1989). It belongs to the northern segment of the Colombian volcanoes, classified as calc-alkaline and the composition its lava products is essentially from andesitic to dacitic (Sigurdsson et al. 1990; Rayo-Rocha and Zuluaga 2011). It is well known in the world due to the November 1985 tragedy (Parra and Cepeda 1990).

Several Spanish chroniclers mention the existence of snowy mountains in the Central Cordillera, but the first description of a local eruption was written by de Simon (1625) who relates the consequence of the one that occurred in 1595. Boussingault (1903) relates some activity observed during the 1830 decade. The first scientific account of an eruption in 1845 was published by Acosta (1846, 1851) and

G.E. Toro (✉) · M. Hermelin
Grupo de Geología Ambiental e Ingeniería Sísmica, Universidad EAFIT, Medellín, Colombia
e-mail: gtoro@eafit.edu.co

M. Hermelin
e-mail: hermelin@eafit.edu.co

R. Méndez
Servicio Geológico Colombiano, Manizales, Colombia
e-mail: ricardomendezfajury@gmail.com

M.A. Tavera
Universidad EAFIT, Medellín, Colombia
e-mail: mtavera@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_14

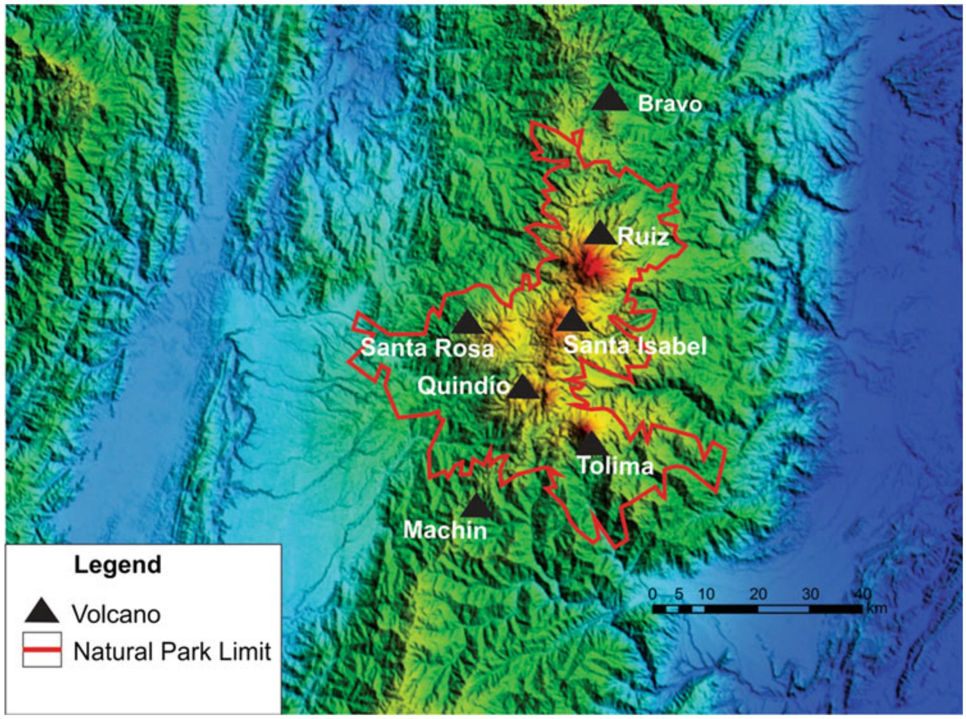


Fig. 14.1 Colombia Northern Volcanic Segment (NASA Radar image edited by Ana Maria García, Colombian Geological Survey, Manizales)

the first official geographic study of the region made by the Colombian Government "Comisión Corográfica" (Chorographic Commission) dates from 1852 (Codazzi 2005) (Fig. 14.2).

Some relatively modern studies were carried on the Ruiz Massif by Murcia (1982), Herd (1982), CHEC (1983), and James and Murcia (1984) but the interest on this volcanic massif was triggered by the deadly occurred on November

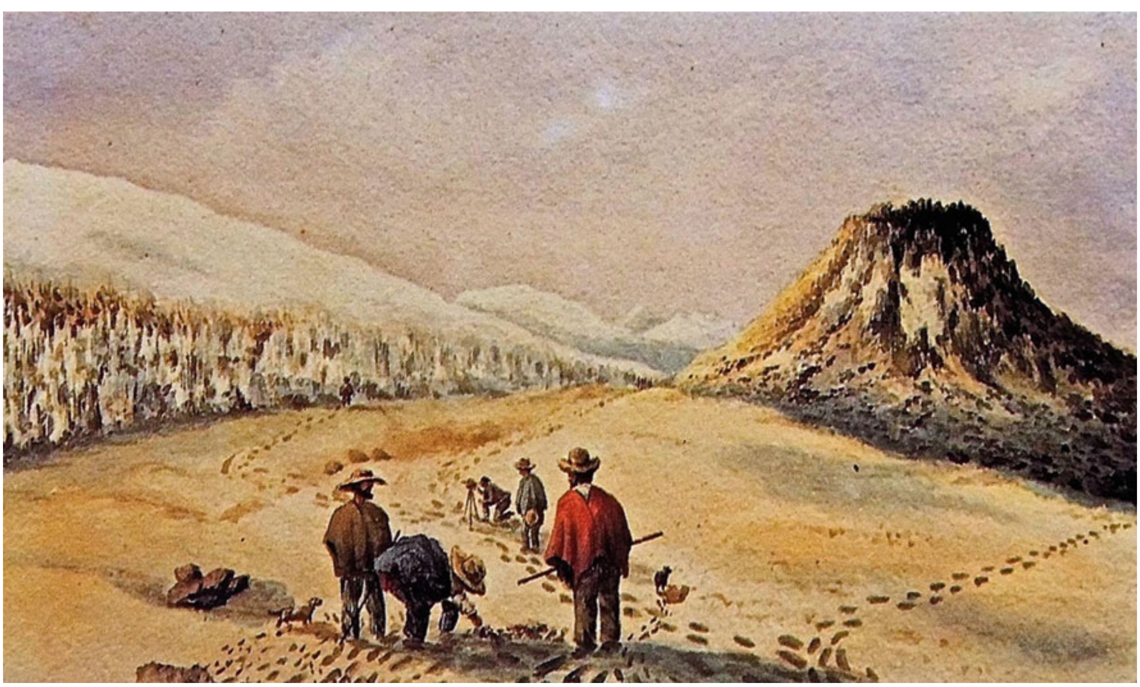


Fig. 14.2 Water color painted by Henry Price in 1852. Mesa de Herveo, Ruiz, Tolima, Large Crater (Cordoba Province). Collection Comisión Corográfica, Banco de la República

Table 14.1 Synthesis of the historical eruptive activity of the RSV (Ingeominas 2000)

Date	Eruption type	Volcanic explosivity index
1595, March 2	Sub glacial explosion of adventice crater with lahars and destruction	4
1623	Central crater explosion	1?
1805 March 14	Explosion	2
1828 June	Adventice crater explosion	2
1829 June 18	Adventice crater explosion	2
1831	Adventice crater explosion	2
1833	Adventice crater explosion	2
1845 February 19	Subglacial radial eruption with lava flow (?) lahars and destruction, more than 1000 deaths	3
1916	Phreatic explosion	2
1984 December	Emission of sulphuric gases Reactivation	
1985 September 11	Ash emission and mudflow	
1985, November 13	Phreato-magmatic eruption with lahars Extensive destruction, 25,000 deaths	
1986, January 4–6	Ash emission	
1986, July 20 and 29	Ash emission	
1987 June 9–11	Ash emission	
1988 March 22–25	Ash emission	
1989 September 1	Phreato-magmatic eruption	2
1988–1991	Sporadic ash emission	
1994 March–April	Seismic reactivation	
1994–1996	Sporadic increases in seismic signals	
2010–2012	Sporadic increases in seismic signals	
2012 May 29 and June 30	Ash emission	

Fig. 14.3 Aerial view of Armero taken a few hours after its destruction by lahars originated by the Arenas Crater eruption on November 13th, 1985. About 20,000 people died. *Photography* U.S. Geological Survey

13th, 1985 (Miletí et al. 1991), which caused one of the major catastrophes due to a natural event in the history of the country. About 24,000 people were killed by lahars which went down the eastern and the western flanks at velocities which reached 45 km/h and destroyed Armero in the east and several settlements in the western side. Other catastrophic events produced by lahars were associated to the March 12th, 1595 and the February 19th, 1845 eruptions (Parra and Cepeda 1990; Mileti et al. 1991; Espinosa 2001).

Among the relatively recent publications are those by Cuellar and Ramirez (1986), Thouret (1989), Vatin-Pérignon et al. (1990). The Journal of Vulcanology and Geothermal Research (v. 40 and v. 41, 1990) published an excellent series of papers: Thouret et al. (1990), Borrero and Naranjo (1990), Rayo-Rocha and Zuluaga (2011), Mejía et al. (2012) related to this subject.

With respect to the origin of the volcanic massif, Thouret (1989) indicates the existence of three building periods:

- The first, older than 3 Ma.
- The second, from 2.3 to 2 Ma, characterized by lava flows.
- The third, between 0.4 and 0.2 Ma, during which the summit volcanoes were built.

This activity was separated by at least two erosion phases. With respect to the Ruiz Volcano, three stages have been recognized:

- Ancient Ruiz, between 1.8 and 1 Ma, when the NW aligned domes were emplaced (Fig. 14.9)
- Old Ruiz, between 0.8 and 0.2 Ma
- Present Ruiz, during the last 0.15 Ma, with an evolution in the volcanic activity from stratovolcano building to the present activity, characterized by andesitic lava flows and pyroclastic deposits (Thouret et al. 1990; Lescinski 1990; Young 1991 and Schaefer 1995, in Vargas et al. 2011).

14.2 Recent Eruptive History

Following the 1985 tragic event, several authors collected and commented the historical information available on the eruptive history of the Colombian volcanoes (Cuellar and Ramirez 1986; Hermelin et al. 1986; Mendez 1989). Worth of mention are the complete descriptions given by Espinosa (2001) from publications of Stuebel (1906), Fabo (1926) and Hantke and Parodi (1966), among others. Table 14.1 summarizes the SRV activity during historical times. More detailed information can be found in the web at the Vulcanologic and Seismologic Observatory in Manizales operated by the Colombian Geological Survey (Servicio Geológico Colombiano, SGC, known until 2012 as Ingeominas) (www.sgc.co/Manizales.aspx).

The description of the 1985 eruption by Parra and Cepeda (1990) is summarized below:

Fig. 14.4 September 1st 1989 eruption of the Ruiz Volcano. The column reached an altitude of about 8 km. *Photography* Ricardo Mendez

- A small phreatic eruption occurred in the in the Arenas crater on December 22nd, 1984. This prompted INGEOMINAS (now SGC) to install four portable seismographs in July 1985.
- On September 11th, 1985, after numerous earthquakes, a phreatic eruption occurred with ash emission. A lahar formed and went down the Azufrado River for 20 km.
- On October 7th, 1985, the first's hazard map a 1:50,000 scale was completed under the guidance of UNDRO (United Nations Relief Organization (Crandell et al. 1984).
- On November 13th, 1985 the main eruption occurred. The following sequence was established by Calvache (1990) and Barberi et al. (1990):
  – 15:05: seismic activity
  – 9:00: an important emission of ash and lapilli occurred and produced a lahar which destroyed the bridge on the road from Gualí to Murillo

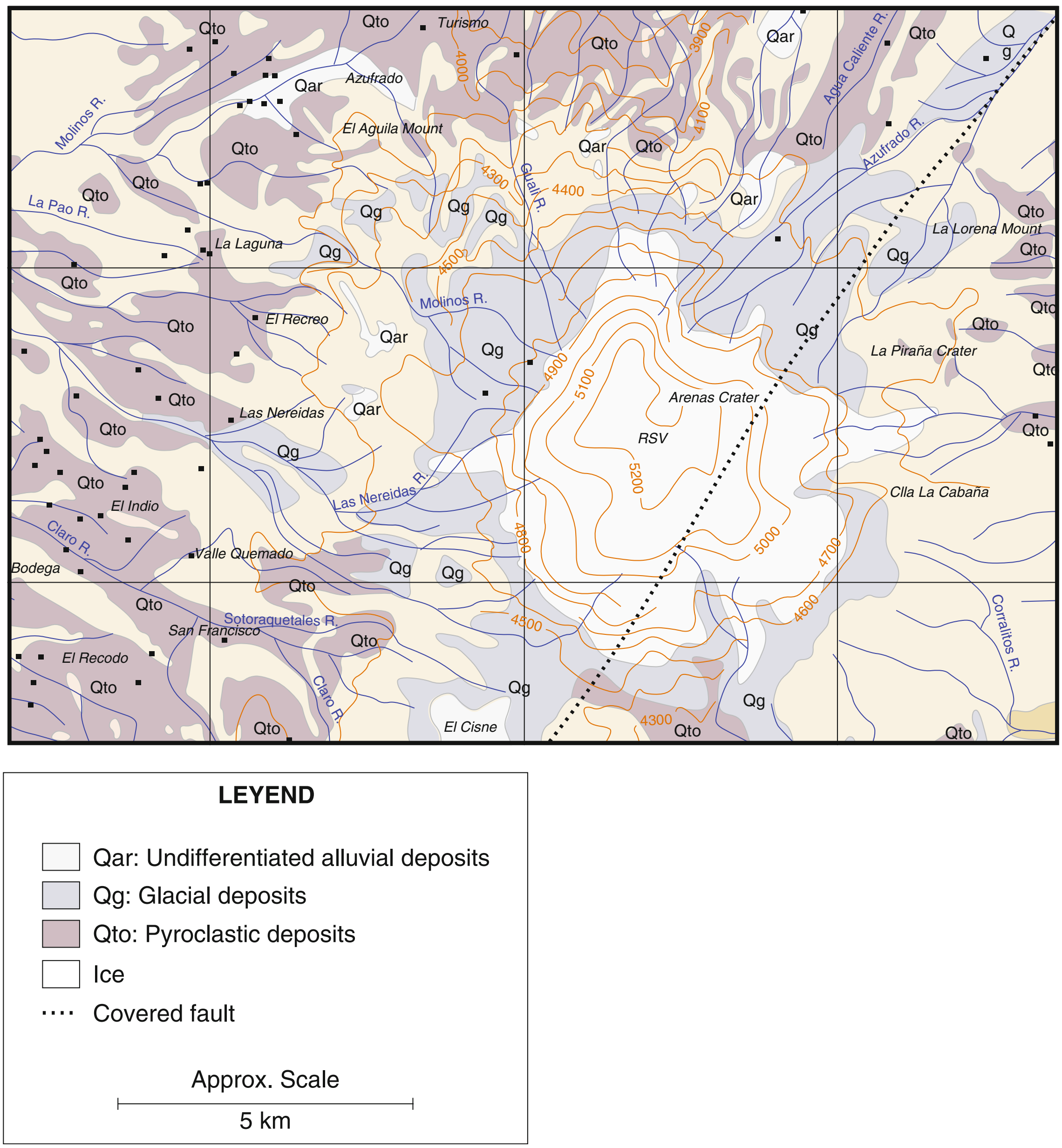


Fig. 14.5 Geologica map of the Ruiz area (Ingeominas 1998)

– between 21:08 and 21:30 strong explosions occurred and emission of ash, lapilli and blocks with diameters up to 4 cm reached a distance of 10 km (Naranjo et al. 1986). Lahars ran down the Gualí and Lagunillas Rivers (Fig. 14.3, the lahars which destroyed the city of Armero). The stratigraphical study of the deposits

Fig. 14.6 Metamorphic substratum, Guali River, La Florida District. *Photography* J. Ceballos, SGV.OVS Manizales

Table 14.2 Glacial activity in the Ruiz Massif (adapted from Martinez et al. 2004)

	Herd (1982)	Thouret and van der Hammen (1983)	Thouret and van der Hammen (1983)	James et al. (1990)
Age (years)	RSV	Snowy Mountain Natural Park	RSV and Santa Isabel Snowy Volcano	Otún River Basin
400–150 years ago	Neoglaciation (4000 m)	Late Ruiz (4500 m)	Ruiz (4200–4600 m)	G-6 (4500 m)
		Early Ruiz		
4750 BP		Late Santa Isabel (4150 m)	Santa Isabel (4100–4600 m)	G-5 (4200 m)
6000–7400 BP		Early Santa Isabel (4100 m)		G-4 (4100 m)
12,500–20,000 BP		Late Otún (3500 m)	Late Otún (3800–4000 m)	G-3 (3820 m)
		Early Otún (3600 m)	Early Otún (3800 m)	G-2 (3600 m)
14,000–20,000 BP	Pleistocene (3450 m)	Murillo (3500 m)	Late Murillo (3500–3600 m)	G-1 (3200–3400 m)
			Early Murillo (3400–3500 m)	
34,000–40,000 BP		Late Recio (2900–3300 m)		
>48,000 BP		Early Recio (2900–3300 m)		

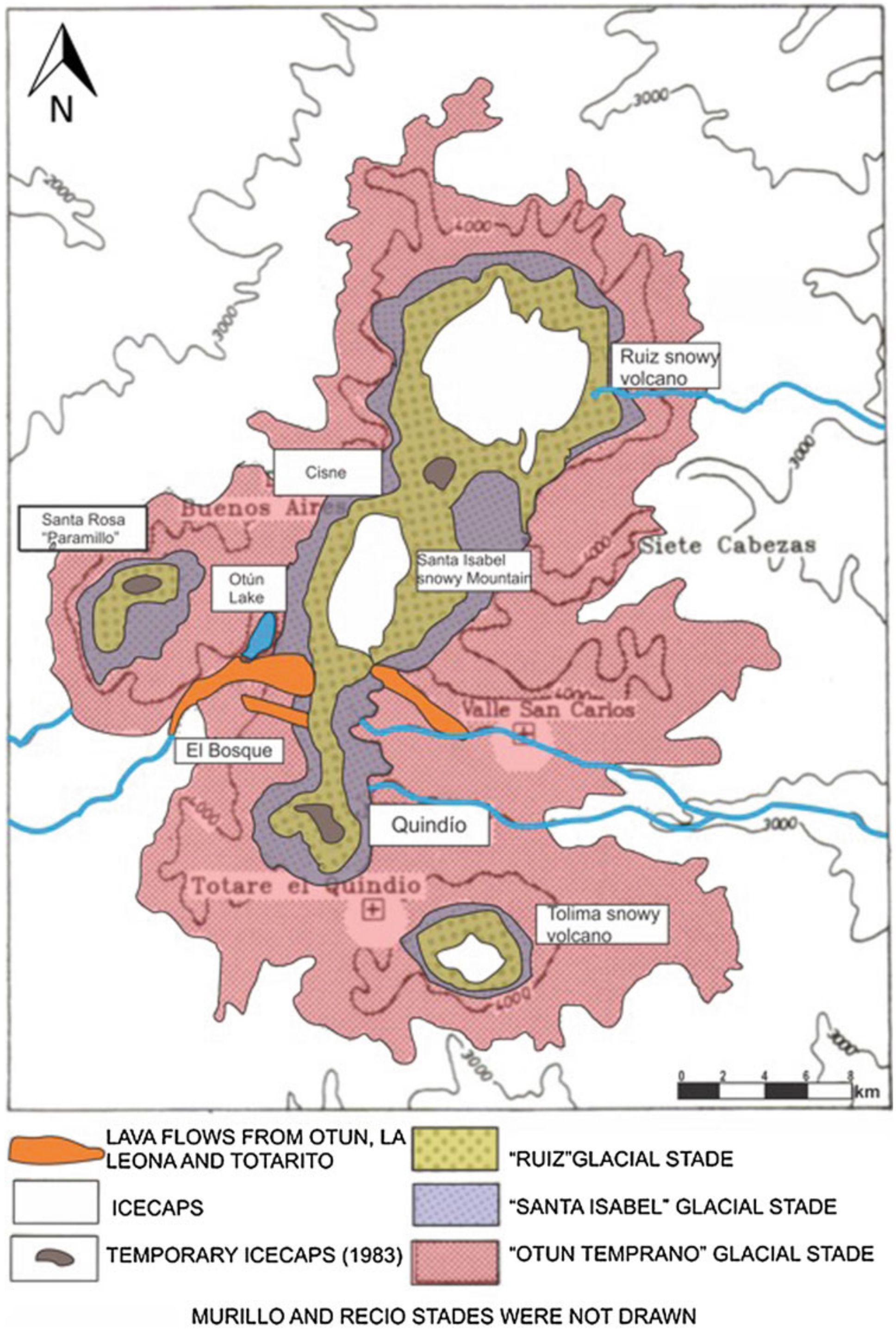


Fig. 14.7 Ruiz-Tolima Volcanic Massif showing the three main glacial stades, present ice caps and recent lava flows (adapted from Thouret and van der Hammen 1983)

emplaced by the eruption (Borrero and Hincapié 2001) permits the identification of the following events:

- Fallout of fine ash, large blocks and generation of ice bearing surges
- Emplacement of at least two non-welded pyroclastic flows
- Emplacement of welded tuff
- Emplacement of pyroclastic flows, surge and fallout of accretionary lapilli "The eruption column reached and altitude of 31 km above sea level during the climax of the eruption and some tephra

Fig. 14.8 The Otún lake formed by a lava flow and flanked by moraine deposits. Aerial *photo*, M. Hermelin 1992

Fig. 14.9 Aligned volcanic domes which follow a N–NW orientation along the Termales-Villamaría Fault. *Photography* Michel Hermelin

injection into the stratosphere may therefore have occurred" (Naranjo et al. 1986). The eruption tefras reached the city of San Cristobal (Venezuela), located 480 km in NE direction.

- September 1st, 1989: a phreatomagmatic eruption occurred during 2 h 24 min. It generated an 8 km high column which was dispersed by strong winds (Fig. 14.4). Pyroclastic materials were deposited between N 30ºW and S

Fig. 14.10 La Olleta (The Small Pot) Crater. Aerial *photo* looking southward. The road *zigzag* traject appears in the foreground. *Photo* Ricardo Méndez 2013

Fig. 14.11 Arenas Crater looking SE, *Photo* taken in March 2011. A thin volcanic ash layer covers one the crater slope (Ingeominas)

80ºW and reached distances of 80 km; they were composed of lithic ashes, young ashes and pumice; calculated volume was 16×10^6 m^3 (Méndez and Valencia 1995)

14.2.1 Geomorphology

The Ruiz and its fellow volcanoes of the northern volcanic segment were built on the top of an igneous–metamorphic

Fig. 14.12 Lava deposits associated with the Old Ruiz Volcanic Stage seen from the eastern slope. In the upper part, ice covered Recent Ruiz Stage volcanic buildings

Fig. 14.13 Sequence of Holocene pyrolastic layers intercalated with buried soils in the RSV vecinity. *Photo* Michel Hermelin

substratum (Fig. 14.5) which have been uplifted up to 4000 m a.s.l. in some places (Fig. 14.6). Thus, the thickness of the volcanic materials does not exceed 1300 m. The altitude reached by these buildings was sufficient to permit the preservation and accumulation of snow and the formation of glaciers and many related evidences can be found down to 3200 m a.s.l. on the western flank and 2700 m a.s.l. on the eastern one (Thouret 1978; Thouret and van der Hammen 1983, Herd 1982, van der Hammen et al. 1989, 1995)

Herd (1982) using fission track dating of tephras intercalated in moraine deposits, found evidence of a pre-Wisconsin glaciation and deduced that the lowest altitude reached by ice during Pleistocene was 3200 m in the western flank of the Central Cordillera and 2700 m in the eastern one. Thouret et al. (1989) identified five glacial stadia (Table 14.2) on the basis of well-defined moraine systems with lateral and frontal arcs (Fig. 14.7).

The most recent morraine system (historical Ruiz or Neoglacial is composed of the smaller visible moraines (Thouret 1989): the older or outer substage, which belong to the Little Ice Age and a more recent one (1880–1950). The outermost is covered by volcanic ashes, while the innermost shows no ash cover nor soil development. Its origin was assumed by Herd (1982) to be later than the 1595 eruption (de Simon 1625)

The Santa Isabel moraine systems shows lateral, terminal and ablation moraines. Its earlier sub-stage (Early Santa Isabel) is a reatreating one and the Later Santa Isabel was emplaced during re-advancing ice (Thouret 1989).

Moraines emplaced during the Otun stage are the best known morraines in the Ruiz-Tolima Massif: they are lateral or terminal and may reach several kilometers (Fig. 14.8).

Fig. 14.14 U-shaped valley in the vecinity of Cerro Bravo Volcano. *Photo* by Ricardo Méndez

Fig. 14.15 Laguna Negra (Blak Lake) or Laguna de Chinchiná, formed by a front moraine against the Chinchiná Dome. *Photography* Michel Hermelin

The Late Otún ones contain pyroclastic sequences which may reach thicknesses of more than 2 m.

Landforms of volcanic origin

•Aligned domes

Between Manizales and the Ruiz Volcano lies a chain of aligned volcanic domes which follows the Termales-Villa María Fault north–northwest orientation (Fig. 14.9). Sancancio and Tesorito Mounts protrude in the landscape. The origin of these well-rounded, steep, and little dissected mounts is related to old emission centers and they are considered as volcanic neck remnants (Flórez 1986; Robertson et al. 2002; Ceballos et al. 1994) formed by the injection of viscous lavas. They may also be the erosional remnants of old volcanic buildings (Ceballos et al. 1998) which were emplaced during the Ancient Ruiz activity (Borrero et al. 2009).

• Olleta (Little Pot) Volcano (Fig. 4.10)

This is one of the outstanding landforms of the massif, found at an altitude of 4300 m a.s.l. It is a crater formed mainly by fine pyroclastic materials, which rises several hundred meters above the surrounding topography and can be seen even from Manizales on clear days. It was recognized as an

Fig. 14.16 Ruiz Snowy Volcano seen from El Arbolito locality. The melting of ice permits to distinguish features of the Kumanday volcanic chain. *Photography* Ricardo Méndez

Fig. 14.17 Sand dunes in the Valle de las Tumbas (Valley of the Graves), before reaching the *zigzag* road, June 6th, 2012. *Photo* taken in NE direction. Ingeominas

adventitious crater by Monsalve and Méndez (1997) on the basis of deposits found on its vecinity (Fig. 14.10).

• **Arenas Crater**

The Arenas Crater is the Ruiz Volcano main crater, located in the middle of the ice cap (Fig. 14.11). It was named after a surveyor of the National Institute of Geography who was the first to map it, in the middle of twentieth century. It has a diameter of 830–850 m and a depth of 247 m. Its continuous fumarolic activity was first described by Boussingault (1903), who observed it from Marmato, a mining locality situated at about 75 km in the NW in the Western Cordillera.

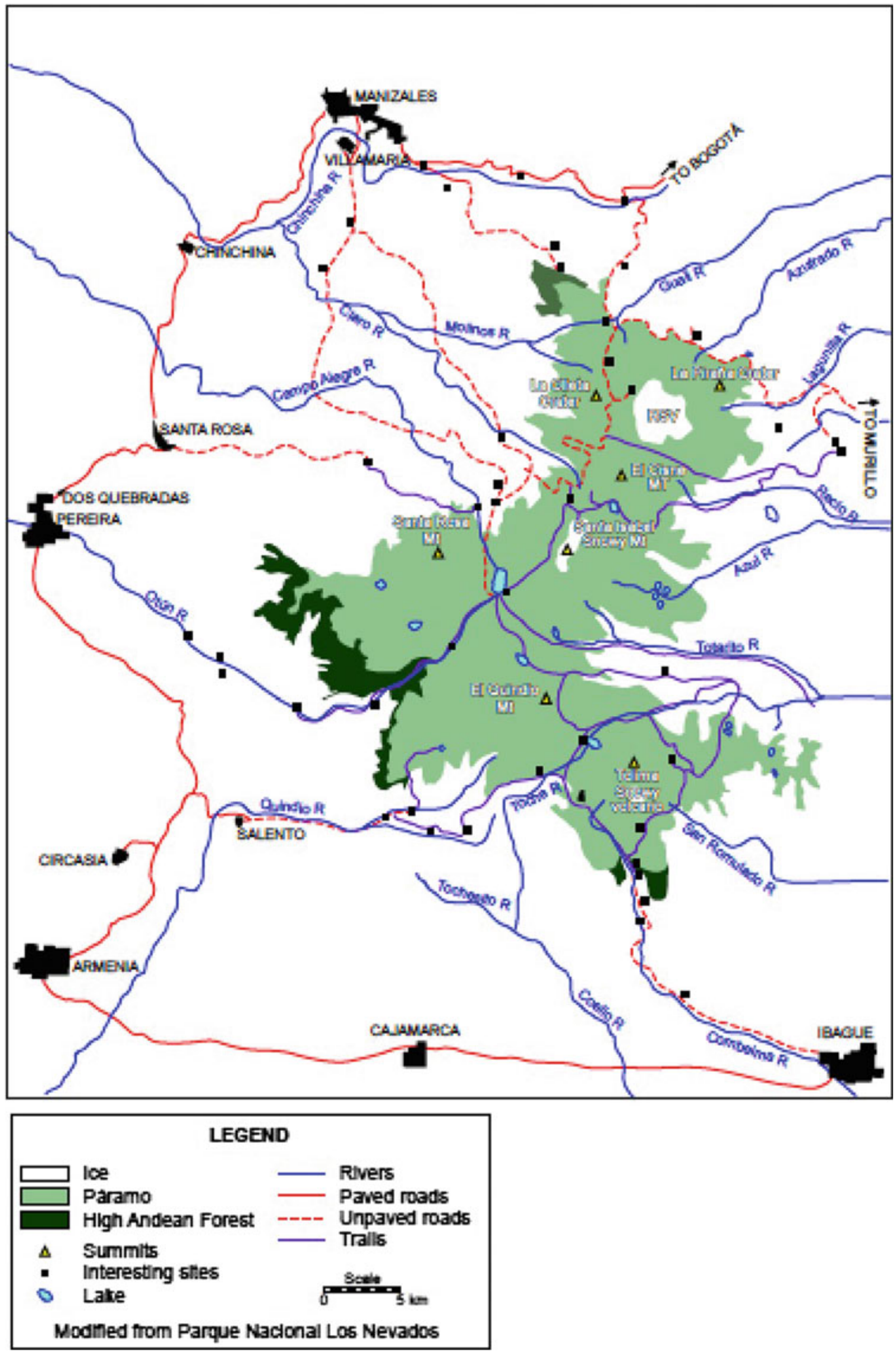


Fig. 14.18 Road map to the Nevados National Natural Park

This crater originated the 1985 eruption and corresponds probably to the 1845 one. (Fig. 14.12)

• **Lava flows**

Subhorizontal lava flows associated with older volcanic stages can be observed on Fig. 14.2.

• **Pyroclastic deposits**

Pyroclastic deposits consisting in layers of volcanic ashes, lapilli, and bombs can be appreciated along the roads leading to the volcano (Fig. 14.13). Some incipient soils developed between sufficiently spaced eruptions. The complete

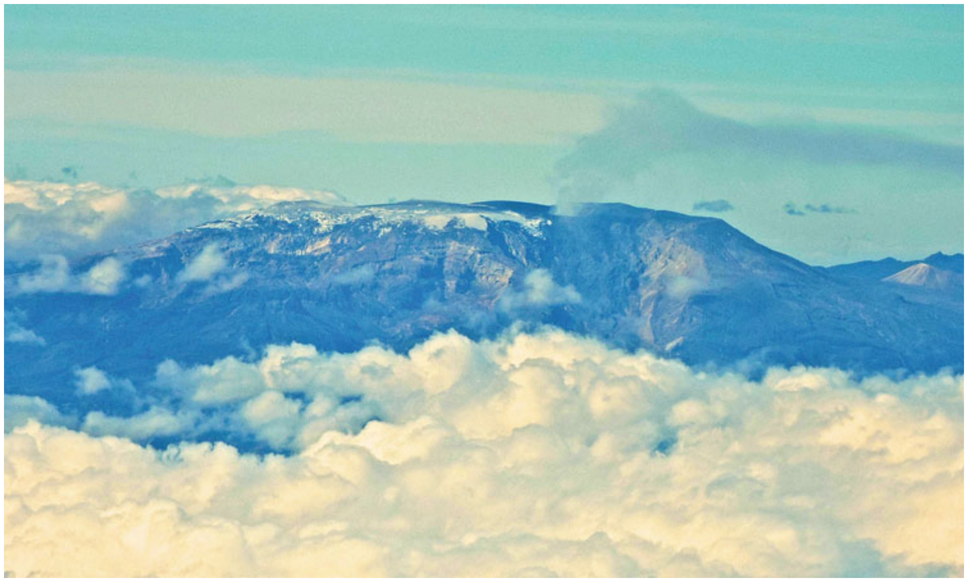


Fig. 14.19 Ruiz volcano and Arenas Crater with fumarole seen from Bogotá, 150 km to tje east. Ice is partially covered by dark ashes. *Photo* Michel Hermelin

Holocene history is present there, as pyroclasts started to accumulate immediately after the last ice retreat.

Glacial landforms

• U-shaped valleys

These valleys, typical of previous fluvial V-shaped valleys which were reshaped by ice during the last glaciation, can be observed in several places of the park. They are now occupied by streams fed by the *páramo* runoff. Figure 14.14 is a photo taken in the surroundings of Cerro Bravo, one of the volcanoes of the northermost part of the massif, at an altitude of more than 3500 m a.s.l.

• Lakes of glacial origin

Several of these lakes can observe. They were formed when the moraines deposited by retreating glaciers closed the valley and forced water to accumulate. Figure 14.15 corresponds to *Laguna Negra* (Black Lake) which can be seen on the right side of the road when ascending to the Ruiz, at an altitude of 3850 m a.s.l. It is now surrounded by *páramo* vegetation.

• Ice-capped Ruiz Volcano

Present glacier melting enables to identify that what was traditionally called Ruiz Snowy Volcano *(Volcán Nevado de Ruiz)* actually corresponds to several volcanic edifices built on lava flow units for which the name of Kumanday Volcanic Chain was proposed, in recognition of the name given to the mountainous massif by the old indigenous inhabitants (Muñoz and Acevedo 2001) (Fig. 14.16).

• Sand dunes

Following the classification adopted by IDEAM (2010) for altitudinal floors, the *superpáramo* is located between the *páramo* and permanent ice cover. Here vegetation is scarce or totally absent and the earth surface is thus exposed to atmospheric agents as frost and wind. Frost is active on a daily basis, as temperatures under 0 °C occur every night. On the other hand, winds are almost permanent due to the presence of the glacier. Immediate temperature changes can be felt when the sun is covered by clouds. As a consequence of these processes, large accumulations of sandy materials can be observed at altitudes around 4300 m a.s.l., resulting in dune-like landforms (Fig. 14.17).

Recommendations

A visit to the Ruiz is an excellent opportunity to look at the different climatic and vegetational vertical distributions in the northern Andes (Fig. 14.18). The road from Manizales, a city located at 2100 m a.s.l., starts in the Andean forest stage, where some natural remnants are still visible, then reaches the *páramo* and the *suprapáramo* and permanent snow and ice. The region is humid and subject to bimodal type of climate, and the best periods to visit it are during the months of December–January or June–July, which use to be relatively dry.

The area is a National Natural Park and visitors are required to obtain permission and to be accompanied by an authorized guide. The trip can be arranged from Manizales. Visits are also limited by the Ruiz volcanic activity. Information can be obtained from the Servicio Geológico Colombiano, Observatorio Vulcanológico de Manizales.

The Ruiz Volcano (Arenas Crater) is presently (February 2015) undergoing moderate pyroclastic activity which can be observed from remote places. Figure 14.19 is a photography taken from te Montserrate Mountain located east of Bogotá at an altitude of 3050 m a.s.l. at a distance of 150 km of the volcano.

References

Acosta J (1846) Relation de l´éruption boueuse sortie du volcán de Ruiz et de la catastrophe de Lagunilla dans la République de la Nouvelle Grenade. Comptes Rendus Académie des Sciences de Paris, tome 22:709–710

Acosta J (1851) Sur les montagnes du Ruiz et du Tolima et les éruptions boueuses de la Madeleine. Lettres à Élie de Beaumont. Bull. Soc. Géol. France, 2eme Série. Tome 8:489–497

Barberi F, Martini M, Rosi M (1990) Nevado de Ruiz Volcano (Colombia): pre-eruption observations and the November 13, 1985 catastrophic event. J Volcanol Geoth Res 42:1–12

Borrero CA, Naranjo JL (1990) Casabianca Formation: a Colombian example of volcanism-induced aggradation in a fluvial basin. In: Williams SN (ed) Nevado del Ruiz Volcano, Colombia I. J Volcanol Geotherm Res, 41:253–267

Borrero C, Hincapié G (2001) Estratigrafía de los depósitos volcánicos, volcaniclásticos y glacigénicos recientes en el volcán Nevado del Ruiz: *VIII Congreso Colombiano de Geología* p 1–13

Borrero C, Toro M, Alvarán M, Castillo H (2009) Geochemistry and tectonic controls of the effusive activity related with Ancentral Nevado del Ruiz volcan. Geofísica Internacional [online]. 48 (1):149–169. ISSN 0016-7169

Boussingault JB (1903) Mémoires, Chamerot et Renouard, Paris Published in Spanish by Biblioteca V Centenario Colcultura Viajeros por Colombia, 2 volúmenes, Bogotá

Calvache MLV (1990) Pyroclastic deposits of the November 13, 1985 eruption of Nevado del Ruiz volcano, Colombia. J Volcanol Geoth Res 41(1–4):67–78

Ceballos JA, Castañeda K Robertson (1994) Análisis geodinámico de la actividad volcánica de Colombia. In: III Conferencia Colombiana de Geología Ambiental, edited, pp 93–105, Armenia, del 27 al 29 de Julio

Ceballos (1998) Volcanes de Colombia. 206 pp, Banco de Occidente

Codazzi A (2005) Geografía física y política de la Confederación Granadina, vol 4, Estado de Antioquia, Antiguas provincias de Medellín, Antioquia y Córdoba. Barona G, Gómez A and Domínguez C, Editors, Universidad Nacional-Universidad EAFIT-Universidad del Cauca

Cuellar J, Ramírez C (1986) Descripción de los volcanes Colombianos.: Revista CIAF 11:189–222

Crandell DR, Booth B Kusumadinata K, Shimozuru D, Walker G, Westercamp D (1984) Source-book for volcanic-hazards zonation. Unesco 97 p, Francia

CHEC (Central Hidroeléctrica de Caldas) (1983) Investigación Geotérmica del Macizo del Ruiz, Fase II Etapa A. Vol III. Geovulcanología. 232 p Manizales

Espinosa (2001) Erupciones históricas de los volcanes colombianos (1500–1995), Academia Colombiana Ciencias Exactas, Físicas y Naturales, Bogotá, 291 p

Fabo, Padre (1926) Historia de la ciudad de Manizales, Tipografía Blanco y Negro, Manizales, Tomo 1, pp 1–412, Tomo 2, pp 413–699

Flórez A (1986) Geomorfología del área de Manizales—Chinchiná. Cordillera Central, Colombia, Análisis Geográficos 9:1–158

Hantke G and Parodi I (1966) Catalogue of the active volcanoes of the world. International Association of Vulcanology, Rome

Herd D (1982) Glacial and volcanic geology of the Ruiz-Tolima volcanic complex Cordillera Central, Colombia: Publicaciones Geológicas Especiales del Ingeominas, vol 8, pp 1–48

Hermelin M, Velásquez A, Bustamante M (1986) Aspectos históricos de erupciones en el Volcán Ruiz Boletín de Vías 13(58):17–38

IDEAM (2010) Sistemas Morfogénicos del Territorio Colombiano. Instituto de Hidrología, Meteorología y Estudios Ambientales. Bogotá DC, 252 p, 2 anexos, 26 planchas en DVD. ISBN–978-958-8067-26-1

INGEOMINAS (1998) Plancha geológica 225 Nevado del Ruiz, cartografía elaborada por Mosquera D, Marin P, Vesga J, Gonzalez H. Ingeominas Bogotá

INGEOMINAS (2000) Atlas de Amenaza Volcánica en Colombia. p 120 INGEOMINAS Bogotá, Colombia

James D, Murcia LA (1984) Crustal contamination in northern Andean volcanics. J Geol Soc 141:823–830

James M, Giraldo M, Schurin E (1990) Relaciones entre lahares y flujos de lodo, la historia glacial de la cuenca del río Otún, CordilleraCentral de Colombia. Climas Cuaternarios de América del Sur. Publicación Especial No. 2, Resúmenes y Contribuciones Científicas. Proyecto 281. IGCP-Unesco. Universidad Eafit. Medellín. pp 1–18

Lescinsky DT (1990) Nevado del Ruiz volcano, Colombia: a comprehensive bibliography. J Volcanol Geoth Res 42(1–2):211–224

Martínez LM, Valencia G, Ceballos JA, Correa AM, Pulgarín BA Narváez BL, Rueda JB (2004)

Mejía EL, Velandia F, Zuluaga C, López JA, Cramer T (2012) Análisis estructural al noreste del Volcán Nevado del Ruíz. Colombia - Aporte a la exploración geotérmica, boletín de Geología 34:27–41

Méndez RA (1989) Catálogo de los volcanes activos de Colombia: Boletin Geológico. INGEOMINAS 30(3):1–75

Méndez R, Patiño JL (1994) El complejo volcánico Cerro Bravo. Cerro Machin. IX Congreso Colombiano de Geología Manizales, abstract 140 p

Méndez R, Valencia H (1995). La erupción del volcán Nevado del Ruiz el primero de septiembre de 1989. Datos geológicos y modelo de la erupción. Boletín Geológico INGEOMINAS, vol 35(2–3), p 21–42. Bogotá. ISSN-0120-1425

Mileti D, Bolton P, Fernández G, Updike R (1991) The eruption of Nevado del Ruiz Volcano Colombia, South America November 13, 1985, 109 pp, National Academy Press, Washington, D.C

Monsalve ML and Méndez R (1997) Geología superficial del área geotérmica de Nereidas (Nevado de Ruiz) Ingeominas, Informe Interno 22p

Mora H, Jordan E, Mohl H (1996). Variaciones observadas en la superficie del volcán Nevado del Ruiz, mediante levantamientos fotogramétricos. 9p INGEOMINAS, Informe interno, Inédito

Muñoz F, Acevedo A (2001) La pequeña edad de hielo en el parque Nacional Natural “Los Nevados”: VIII Congreso Colombiano de Geología, vol VIII, p 1–10

Murcia LA (1982) El volcanismo Plio-Cuaternario de Colombia: Depósitos piroclásticas asociados y mediciones isotópicas de 87Sr/86Sr, 143Nd/144Nd, δ18O en lavas de los volcanes Galeras. Puracé, Nevado del Ruíz: Publicaciones Geológicas Especiales del INGEOMINAS 10:1–17

Naranjo JL, Sigursson H, Carey S, Fritz W (1986) Eruption of Nevado de Ruiz Volcano, Colombia, On 13 November 1985: Tephra fall and lahars. Science 233:961–963

Parra E, Cepeda H (1990) Volcanic hazard maps of the Nevado de Ruiz volcano. Colombia J Volcanol Geotherm Res 42(1–2):117–127

Rayo-Rocha L, Zuluaga C (2011) Procesos magmáticos en el Volcán Nevado del Ruiz: Un análisis cuantitativo textural. Boletín de Geología 33:59–72

Robertson K, Flórez A, Ceballos JL (2002) Geomorfología volcánica, actividad reciente y clasificación en Colombia: *Cuadernos de Geografía*, v. XI 1–2:37–76

Schaefer SJ (1995) Nevado del Ruiz Volcano, Colombia: magmatic system and evolution. D PhD Dissertation, Arizona State University, p 147

Sigurdsson H, Carey S, Palais JM, Devine J (1990) Pre-eruption compositional gradients and mixing of andesite and dacite magma erupted from Nevado del Ruiz Volcano, Colombia in 1985: J Volcanol Geoth Res 41(1–4):127–151

Simón, Fray Pedro de (1625) Noticias historiales de las conquistas de Tierra Firme en la Indias Occidentales. Casa Editorial de Medardo Rivas, Bogotá, (1892), 376 p

Stuebel A (1906) Die Vulkanberge von Colombia, Dresden

Thouret JC (1978) Algunos aspectos y problemas geomorfológicos de la cordillera Central de los Andes colombianos en el área del Parque Nacional de Los Nevados. II Congreso de Geología de Colombia, diciembre 1978, Bogotá. 34 p

Thouret JC (1989) Geomorphology and chrono-stratigraphy of the Ruiz-Tolima volcanic area (Colombian Central Cordillera). In: van der Hammen T, Díaz T, Alvarez E (eds) La Cordillera Central Colombiana: Transecto Parque de los Nevados. Studies on Tropical andean ecosystems, Berlin, pp 257–277

Thouret JC, der Hammenvan T (1983a) La secuencia holocénica y tardiglacial en el Parque Los NevadosECOANDES1262276

Thouret JC, van der Hammen (1983b) Una secuencia holocénica tardi-glacial en la Cordillera Central de Colombia, *Revista CIAF*, 6 (1–3):609–634

Thouret JC, Cantagrel JM, Salinas R, Murcia A (1990) Quaternary eruptive history of Nevado del Ruiz (Colombia). J Volcanol Geoth Res 41:225–251

Thouret JC, van der Hammen T Juvigné E Salomons J B (1989a, b) Late Quaternary geology of the volcanic Ruiz- Tolima massif, central cordillera. *Estudio ecosistemas tropandinos*. vol 4. Cramer, Berlin- Stuttgart

van der Hammen T, Díaz Piedrahita S, Alvarez V (eds) (1989a, b) Studies on Tropical Andean Ecosystems, vol 3. J Cramer, Berlin 600 p

van der Hammen T, Dos Santos A (eds) (1995) Studies on Tropical Andean Ecosystems, vol 4. J Cramer, Berlin 613 p

Vargas C Mann P and Borrero C (2011) Field guides for excursions to the Nevado del Ruiz Volcano and to the Romeral Fault System (Colombia), in the frame of the Neotectonics of arc-continent collision concepts: Earth Sci Res J 15:47–74

Vatin-Pérignon N P G Oliver RA Parra E (1990) Evaluation of magmatic processes for the products of the Nevado de Ruiz Volcano, Colombia from geothermical and petrological data: J Volcanol Geoth Res 41:153–1776

Wilson M (1989) Igneous petrogenesis. A global tectonic approack, Chapman & Hall, London, p 466

Young RH (1991) Eruptioñn dynamics and petrology of the most recent eruption of Nevado del Ruiz, Colombia, South America. Msc Thesis, Louisiana State University, Bâton Rouge

The Puracé Region

15

María Patricia Torres, María Luisa Monsalve, and Bernardo Pulgarín

Abstract

Puracé volcanic region is a part of the Puracé National Park, an important area of 83,000 ha dedicated to biological, geological, cultural, and ethnic conservation, located on the top of the Central Cordillera of Colombia. This region owes its origin to effusive and explosive volcanic events that have been going on since the Late Miocene. It consists of lava, ignimbrites, pyroclastic density currents, pyroclastic falls, lahars, and debris avalanche deposits which have been subsequently remolded by glacial and fluvial erosive processes, resulting in the majestic landscape in constant construction. The main landform is the Paletará Caldera within which the Coconucos Volcanic Chain (CVC) occurs, with Puracé and Pan de Azucar volcanoes. Volcanism and glacial activity join in the Puracé region to form a relief of great scenic value. El Buey and San Rafael Lakes situated amidst a vast plain covered with grassland's domain of frailejones (*Espeletia hartwegiana*) and *Calamagrostis sp.* are the source of Bedon River which rushes through a narrow-deep canyon, build on the lava deposits forming the Bedon fall. Also remarkable are the colorful diversity of San Juan, Pozo Azul, and Coconuco hot springs.

Keywords

Volcanic landforms • Glacial landforms

15.1 Introduction

The Puracé volcanic region is located in the Central Cordillera of Colombia, between the Departments of Cauca and Huila and reaches altitudes above 4000 m a.s.l. (Fig. 15.1). The Paletará Caldera, with the diameter of at least 35 km, is the most imposing volcanic structure of the region. It was the source of the voluminous upper Miocene—Pleistocene ignimbrite volcanism that generated deposits which reach 225 km^3 (Torres 2010), within the caldera constituted by the Valley of Paletará which rise the Coconucos Volcanic Chain (CVC), the Chagartón Caldera, the Yerbabuena Maar, San Rafael, and El Buey Lakes.

The historical activity of the Puracé volcano was recorded by several scientists in the past. Humboldt and Bonpland in 1801 described the *Bocas* (small craters) at the flank of the volcano (Academia de Ciencias Exactas, Físicas y Naturales 1982), whereas Boussingault in 1831 was attracted by the Vinegar River, called *Pusambio* by the Indians, which flows from the Puracé volcano. He was interested in this river for its high content of sulfuric acid (Boussingault 1903). Engineer Robert Blake White, in 1869, described an eruption of the Puracé (White 1869). Stübel (1906), Friedlaender (1927), and Oppenheim (1950), among others,

M.P. Torres (✉)
Universidad del Cauca, Popayán, Colombia
e-mail: mptorres@unicauca.edu.co

M.L. Monsalve
Servicio Geológico Colombiano, Bogotá, Colombia
e-mail: mmonsalve@sgc.gov.co

B. Pulgarín
Servicio Geológico Colombiano, Popayán, Colombia
e-mail: bpulgarin@sgc.gov.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_15

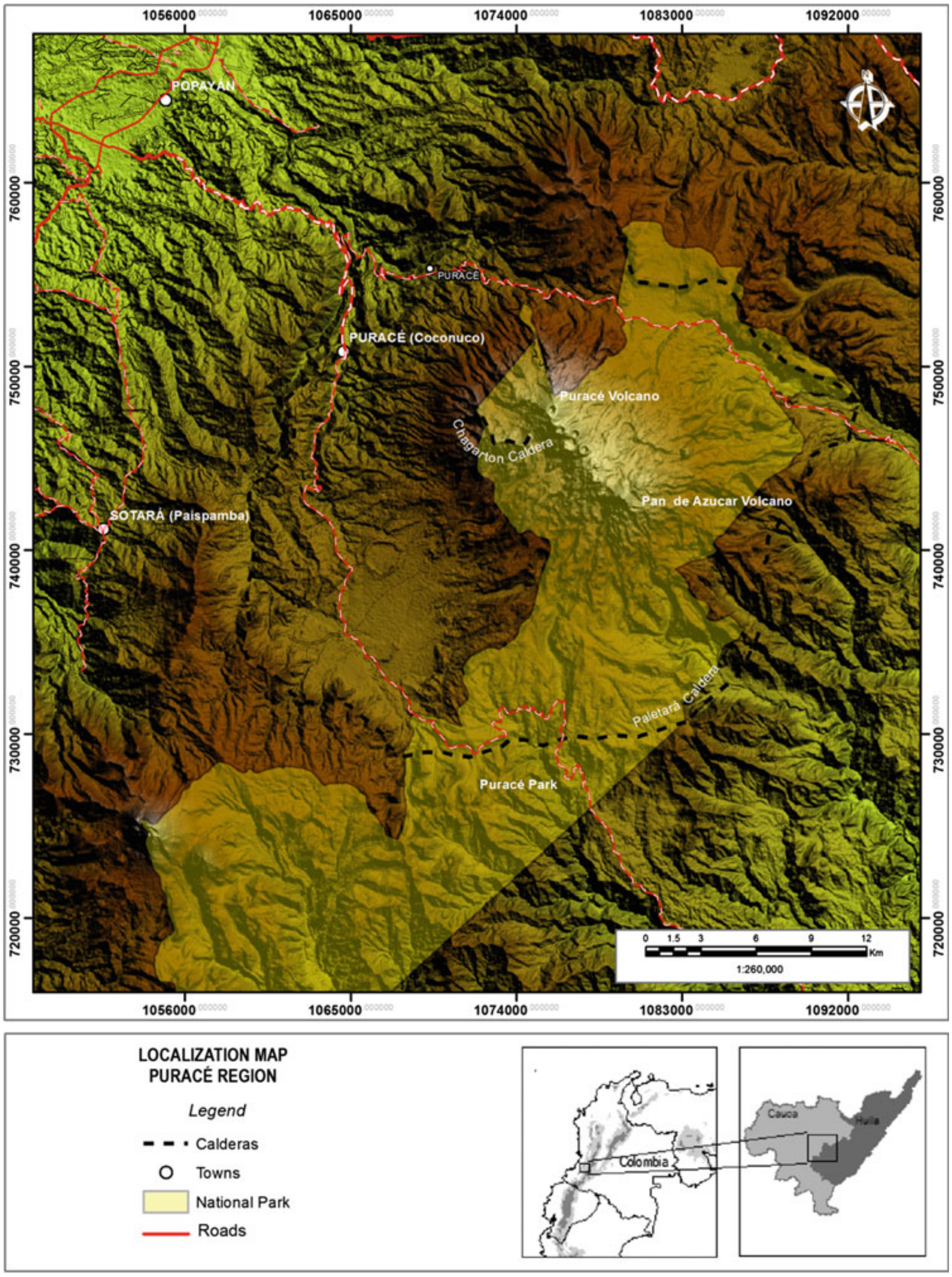


Fig. 15.1 Location of the Puracé volcanic region

provided important documents and drawings, describing geomorphology and activity of the Puracé volcano.

15.2 Structural Setting of the Volcanic Puracé Region

In Colombia, volcanism originates due to the subduction of Nazca oceanic plate under South America continental plate and is a typical example of endogeneous activity associated with an active continental margin (Wilson 1989). The Puracé volcanic structures are part of the volcanic arc, located 200 km east of the oceanic trench.

A close relationship exists between volcanic activity centers and longitudinal and transverse faults systems. In Colombia, this structural pattern is particularly evident, as several volcanic structures emerge at crossing faults of NE and NW trend (Case et al. 1971; Ponce 1979; Murcia and Marin 1981; Hall and Wood 1985) and the Puracé volcano is a perfect example of such a linkage (Fig. 15.2).

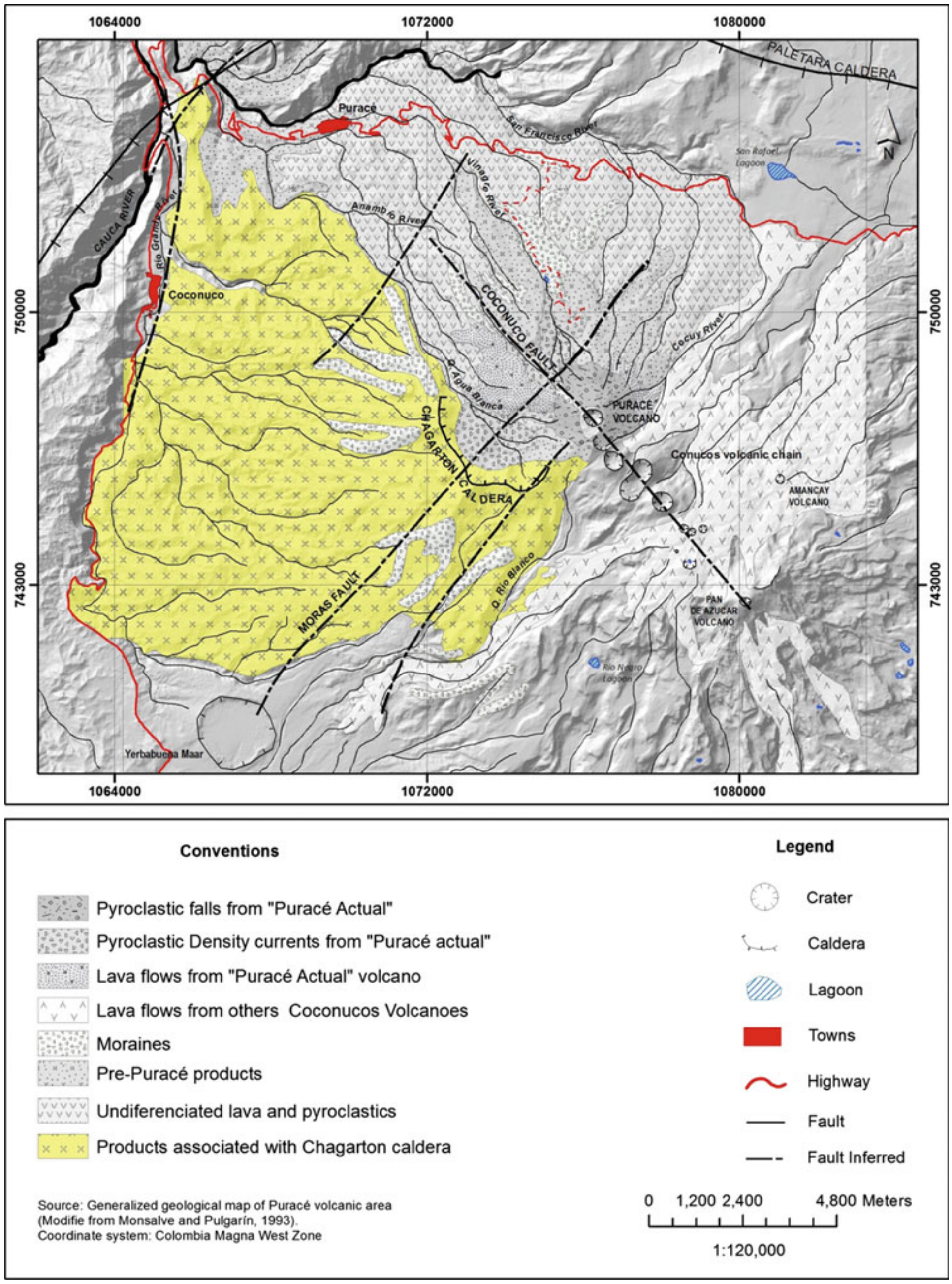


Fig. 15.2 Generalized geologic map of Coconuco Volcanic Chain (after Monsalve and Pulgarín 1993)

15.3 Geological and Geomorphological Aspects of the Puracé Volcanic Region

The Puracé area is build of thick rhyolitic ignimbrites produced from the Paletará Ccldera, covered by andesitic to dacitic lava deposits (Kuroda and Paris 1978; Monsalve and Pulgarín 1993) and extensive pyroclastic deposits of pumice flows, scoria flows, and blocks and ash flows associated with ancient volcanic edifices like the Chagartón Caldera and Pre-Puracé volcano. Deposits of pyroclastic density currents, pyroclastic fall, and debris flows are associated with the recent activity of CVC (Monsalve and Pulgarín 1999). The basement in the region is composed of Paleozoic metamorphic rocks from the Arquía Complex (McCourt et al. 1984) and Cretaceous basic volcanic rocks of the Quebradagrande formation.

Some volcanic landforms show glacial modeling, as the Pre-Puracé volcanic remnants and the Chagartón Caldera, where moraines are arranged radially to the volcanic building; they are currently covered by volcanic ash. There are also areas of pyroclastic deposits covered by elongated lateral moraines displaying sharp peaks and high-angle slopes.

In the San Rafael Lake area, several U-shaped valleys can be seen, some filled with rockfall and fluvioglacial deposits. In some of these valleys, lava flows and debris avalanches indicate a post-glacial volcanic activity.

15.4 Paletara Caldera

The 35-km-diameter Paletará Caldera (Torres et al. 1999) is the most important volcanic structure of the Puracé region. Its morphology is visible on satellite images and on terrain digital elevation models. Toward the SW of the area, low hills bordering the semicircular "Paletará Valley" are remnants of the rim and the valley itself is a plain formed by a volcanic and fluvioglacial fill on the caldera floor, given by the resurgent volcanic activity, represented by Chagartón edifice and Coconucos volcanic Chain, inside of the Paletara Caldera. The other edges have been partially eroded leaving mountains with rounded and elongated summits, as Pusná, the sacred mountain for the Puracé indigenous community, or have been buried by deposits from eruptions of the inner and NE edge volcanism like Uñiñegatuna volcano.

The Paletará Caldera has an important NW structural control defined by Palacé–Mazamorra and Robles–Bedon faults (Acosta 2003) which follow the northern edge of the caldera. Toward the southern edge, an evident NW lineament crosses the Paletará Valley. In the caldera itself, there is a NW fracture that controls the setting of the Coconucos volcanic chain known as Puracé-Coconuco fracture (Murcia 1987) or Coconuco fault (Arcila and Monsalve 1996). These faults are transverse to the main longitudinal NE fault systems of Cauca–Romeral and Moras (Fig. 15.2).

Paletará Caldera volcanism is represented by rhyolitic ignimbrite deposits of the calc-alkaline series with high-potassium content, grouped in the Popayan and Guacacallo Formation (Grosse 1935; Kroonenberg et al. 1981; Torres et al. 1992, 2011; Torres 2010). The ignimbrite flows traveled through the Puracé region following river valleys, sometimes overpassing interfluves and filling the upper basin of Cauca and Magdalena Rivers, reaching distances of 70 and 50 km, respectively (Torres 2010).

Extension of ignimbrites of the Popayán Formation is 1250 km^2 (Torres 2010), and further 1000 km^2 is covered by similar deposits of the Guacacallo Formation (Kroonenberg et al. 1981), with average thicknesses of 100 m and an estimated volume of 225 km^3 (Torres 2010). From K/Ar dating, volcanic activity of Paletará Caldera extended from 7.1 ± 3 to 2.56 ± 0.24 Ma (Kroonenberg et al. 1982; Woodward Clyde Consultants 1983; Murcia and Pichler 1987; Van der Wiel 1991; Bellot-Gurlet et al. 1999, 2008; Torres 2010).

Toward the east of the Central Cordillera mountain range, the ignimbrite deposits form the high plains of Guacacacallo in the Magdalena Valley, while towards westward, in the Cauca valley, they form the Popayán Plateau. Both plateaus are deeply dissected and consist of low hills with rounded summits.

15.5 Coconucos Volcanic Chain

The Coconucos Volcanic Chain, formerly known as "Coconucos Snowy Range," comprises a set of 15 eruptive centers, aligned in N39°W direction (Fig. 15.3) and controlled by the Puracé fracture (Murcia 1987). Most of these volcanoes were active in post-glacial (Holocene) times.

The Puracé and Pan de Azucar volcanoes are located at the extremes of the chain, and the distance between them is 6.5 km. The origin of CVC has been interpreted as resurgent volcanism of Paletará Caldera (Pulgarin et al. 1996). Old volcanic structures, Chagartón caldera, and the Pre-Puracé volcano, located toward NW of the volcanic chain, are the only preserved remnants of the first stage of resurgence of Paletará Caldera (Monsalve and Pulgarín 1993, 1999).

The CVC has two volcanic domains. The NW part contains the Puracé, Piocollo, Curiquinga, and Calambás-Paletará volcanoes, where explosive activity has been dominant (Pulgarín et al. 1996). They are developed as cones with large, circular to slightly oval-shaped craters with diameters of nearly 500 m. In general, deposits associated with these volcanoes are hydrothermal breccias, massive and blocky lavas, and pyroclastic density current deposits, including scoria flows, blocks and ash, surges, pyroclastic fall, and debris flows. The volcanic structures include, from top to the base of the cones, steep slopes, smoothed by pyroclastic fall deposits and dissected by small streams.

The SE domain, with predominance of effusive products, is made of the Shaka with three craters, Killa (a plug), Machangara displaying horseshoe shape, Pan de Azucar, the eroded Pukará volcano, and two adventives volcanoes, Amancay and Piki, slightly displaced toward the east from the main chain axis (Monsalve and Pulgarín 1993; Pulgarín et al. 1996). The main volcanic products of this domain are blocky and macroropy lava flow deposits, which reached distances close to 10 km from the source. The craters of these volcanoes have diameters from 100 to 300 m.

Lavas associated with these volcanoes formed broad summits and irregular and rough surfaces, distributed longitudinally from the emission sources. Rivers have carved narrow and straight valleys in the lava flow deposits.

Fig. 15.3 Aerial photograph of the volcanic chain of Coconucos from the NW; the Puracé Actual volcano active crater is in the foreground, while and Pan de Azúcar volcano is seen in the background (*Picture* by Servicio Geológico Colombiano)

15.5.1 Puracé Volcano: Ancient and Recent Structures

Puracé, which means Mountain of Fire (Puerta 1991), is an active volcano with records of activity since 1540 (Monsalve et al. 2013; Espinosa 2011; Pulgarín et al. 1996). Its construction is related to many eruptive events, which left morphological evidence of its continuous activity. The oldest structure related to the Purace evolution is the Chagartón caldera, followed by Pre-Puracé volcano, into which the "Puracé Actual" is built (Monsalve and Pulgarín 1993).

15.5.2 Chagarton Caldera

The Chagarton Caldera is a 3.5-km-diameter caldera remnant structure located inside the Paletará Caldera. Its former rims are preserved to the west of the NW end of CVC and reached 4310 m.a.s.l. They are known as Chagartón Mount (Cerro Chagarton).

Volcanic deposits associated with the Chagartón Caldera eruptive activity consist mainly of thick lava and pumice flow deposits. From the city of Popayan, in clear days, Cerro Chagartón looks like an imposing fortress constituted by a steep slope mountain with elongated and irregular summits.

Well-preserved evidence of glacial activity in the Chagarton contrasts with the other volcanic structures of CVC, where glacial geomorphological features are scarce, suggesting that its volcanism corresponds to the initial resurgent activity of Paletará Caldera. It includes moraines reaching 2.3 km on the slopes of Chagarton,as well as on Pre-Purace Volcano, which is located between 3400 and 3900 m a.s.l (Fig. 15.4).

15.5.3 Pre-Puracé Volcano

This volcano was built on SE edge of Chagartón caldera. From vestiges of this structure, it is assumed that the crater diameter was about 1.5 km. There are remnants of the volcano to the north and north-west of the Puracé Actual volcano. Deposits of hydrothermal breccias, lava flows, thick mafic ignimbrites forming a high terrace (on which the indigenous town of Puracé is built), pyroclastic density currents, and fall and debris avalanches are products generated by the eruptive activity of Pre-Puracé.

Fig. 15.4 Lateral moraines within both Chagarton and Pre-Puracé volcanic deposits; the larger one is 2 km long. Remnants of Pre-Purace partial collapse and hummocky morphology can be observed in the front of the photo. "Puracé Actual" volcano in the background (*Picture* by Servicio Geológico Colombiano)

On the ruins of this structure, the Puracé Actual volcano was built. The northern remnant represents a collapse structure, probably related to the activity of the Moras fault, which crosses the amphitheater crown. As a result of this partial collapse, a debris avalanche was generated, affecting the headwaters of Vinagre River and creating hummocky morphology (Fig. 15.4), typical of debris avalanches deposits, in this sector of the area.

Pre-Puracé landforms were affected by glacial processes which have left large moraine systems, presumably formed between the last Pleniglacial (before 35,000 years BP) and the Late Glacial (14,000–10,000 years BP) (Van der Hammen 1985).

15.5.4 "Puracé Actual" Volcano

The 4660 m a.s.l. high "Puracé Actual" (which in Spanish means present Puracé) volcano has a truncated pyramidal shape and is constructed at the intersection of the Moras and Coconucos faults, on the ruins of Pre-Puracé volcano. It has a double concentric oval to circular-shaped crater (Figs. 15.3 and 15.5). The Ochacayó outer crater has a diameter of 900 m, whereas the inner one is 500 m in diameter and has a depth of 80 m, with steep inner walls (Monsalve et al. 2012). Inside, there is a 20-m-deep E-W fracture with fumarolic activity (Fig. 15.3). The cone of the active Puracé Actual does not show any glacial evidence. Its slopes are about 30° smoothed by deposition of recent pyroclastic deposits. On its upper northern flank, there is an important fumarolic field, evidencing the current activity of the volcano (Figs. 15.3 and 15.5).

The eruptive activity of this stratovolcano has generated lava flows and pyroclastic density currents, both dilute and concentrated, as well as pyroclastic falls leaving deposits of scoria, and block and ash flows, surges, ash, bomb, and block falls, emitted by Strombolian–Vulcanian eruptions (Monsalve et al. 2012).

The evolutionary history of the "Puracé Actual" volcano is related to the Pre-Puracé volcano and Chagartón Caldera (Fig. 15.5). It represents the most recent period of volcanic activity of the region, which has been reported since the 16th century. The nineteenth century documents describe explosive eruptive events causing human injuries and material losses. The most recent activity of the volcano includes historical deposits from 1816 to 1977 (Monsalve et al. 2012).

The contemporary activity of the Puracé volcano is evidenced by fumaroles inside and outside the crater, hot springs around the volcanic edifice, and by low to intermediate seismicity, which is monitored by the Servicio

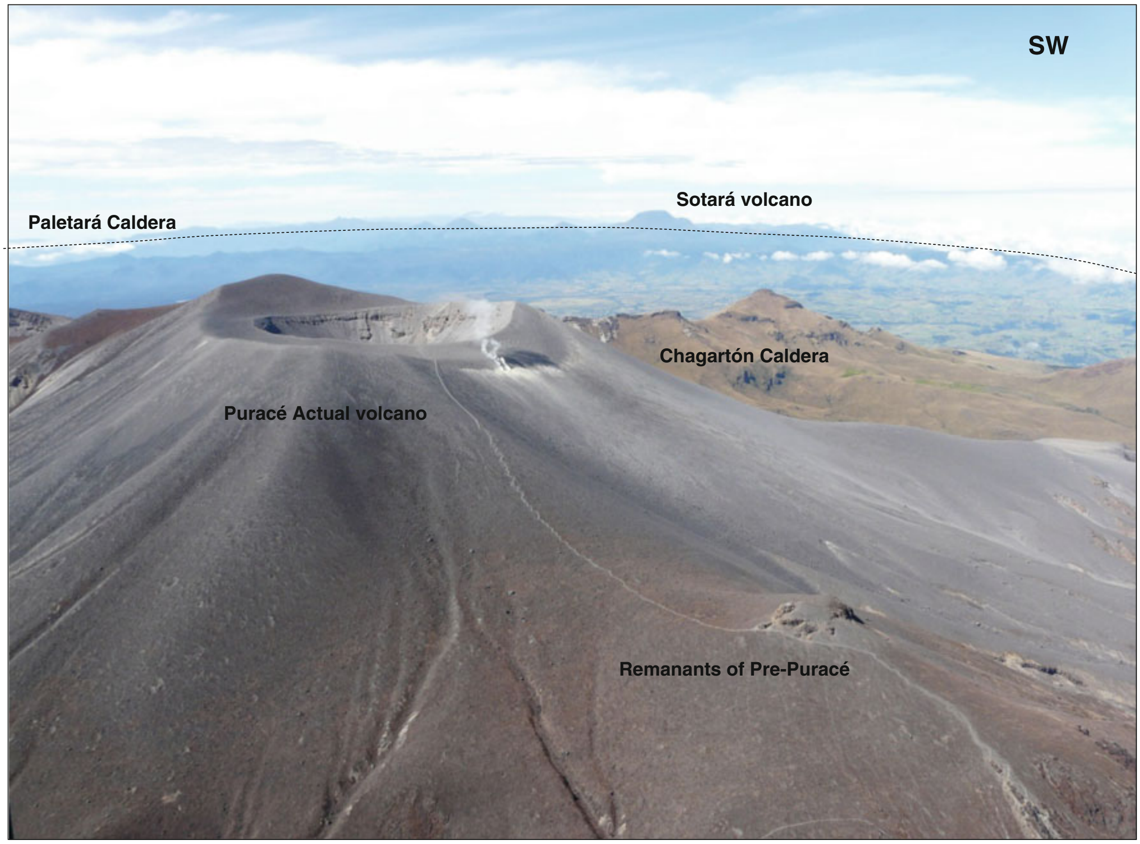


Fig. 15.5 Volcanic structures of Puracé region: remains of the SW Paletará Caldera border and Sotará volcanic complex forming the horizon. "Puracé Actual" Volcano was built on remnants of Pre-Puracé volcano, inside the Chagartón Caldera (*Picture* by Servicio Geológico Colombiano)

Geologico Colombiano (Vulcanological and Seismological Observatory of Popayan).

Limited glacial evidence, as well as a 2110 ± 50 radiocarbon date obtained from a pyroclastic flow deposit, has led to the conclusion that the volcano is a young Holocene structure (Monsalve and Pulgarín 1993; Monsalve et al. 2012).

15.6 Paletará Valley and Other Volcanic Structures in the Puracé Region

The Paletará Valley is located at altitudes between 3000 and 3200 m.a.s.l. and forms the eastern inner sector of the Paletará Caldera. It is an almost flat area, eroded by the Cauca River. Beside CVC, other resurgent volcanic structures exist in the vicinity such as the Yerbabuena Maar, "El Canelo" Tuff Cone, and "Laguna del Buey" (the "ox lagoon") mainly related to phreatic activity inside the caldera (Monsalve and Pulgarín 1992).

The Yerbabuena Maar, located at the western foothills of the CVC, has a circular shape with the diameter of 2 km; the structure has gentle slopes, rising less than 100 m above the valley floor. Its inner walls are almost vertical; the depth of the crater is about 50 m and the inner floor is flat. The morphology of this structure has been softened by pyroclastic deposits from active volcanos of the region. El Canelo is a partially eroded structure exhibiting a semicircular morphology built by pyroclastic products, and rising about 200 m above the Paletara valley floor. Laguna del Buey is a one km wide, almost circular structure, located at the SW of Paletará Valley. The vertical inner walls of the structure rise up to 40 m above the water level of the lagoon. It formed within thick masses of ancient lavas which have been raised by tectonic processes.

Finally, the beauty of the Puracé region is enhanced by the Coconucos landscape (west of CVC), where Cauca and Rio Grande rivers have excavated narrow valleys in old lava and ignimbrite sequences, producing hanging valleys with impressive waterfalls such as the San Bartolo Cascade. At the north-eastern end of CVC, in San Rafael region—a wide plain covered by grassland domain of *Calamagrostis sp* and grasslands dominated by frailejones (*Espeletia hartwegiana*), the San Rafael lagoon and the waterfall of Bedon river (Fig. 15.6) are located. In the same area, overwhelmingly beauty San Juan Hot springs (Fig. 15.7) are a testimony of the continuous volcanic activity in the region.

Fig. 15.6 The waterfall of Bedon river emerges from a vast plain built on andesitic lava, covered with grasslands domain of frailejones (*Espeletia hartwegiana*) and *Calamagrostis sp.* The height of the fall is 20 m (*Photography* Sandra López C)

Fig. 15.7 San Juan thermal springs. San Juan and others lakes of the Puracé region constitute a beautiful scenery which testify to the present-day volcanic activity of the area (*Photography* Sandra López C)

15.7 Accessibility

The access to the Puracé region is by paved road that leads to Huila from Popayán, which after crossing the Cauca River leads to the town of La Plata. An unpaved deviation goes to the Puracé volcano, located 27 km from Popayan. The town of San Augustín can be reached through Paletará and Coconuco located 17 and 25 km, respectively, from the city of Popayan. The journey by car from Popayán to the Puracé volcano takes about one hour and a half, to the San Juan Hot springs one hour and a half, to the town of Coconuco half an hour, and to Paletará one hour.

To visit the Puracé volcano, it is advisable to start early in the morning from Popayán or to sleep at the indigenous villa of Puracé at the *Pilimbalá* Cabin, located at the base of the volcano. If the atmospheric conditions are good, the Puracé volcano and the Coconucos Volcanic Chain (CVC), the Paletará valley, and the snowcapped volcano Huila can be seen. Another day can be spent visiting the San Juan Hot springs, the San Francisco River canyon, and the Bedón River waterfall. West and Southwest part of the Puracé region are the indigenous town Coconuco where "Pozo Azul," "Aguas tibias," and "Aguas calientes" Hot springs are tourist attractions and the Paletará Valley, which is located inside the Paletará Caldera. On a clear day, the Sotará Volcano is visible.

Acknowledgement This chapter was written with support from the University of Cauca and Servicio Geológico Colombiano.

References

Academia de Ciencias Exactas, Físicas y Naturales (1982) Alexander von Humboldt en Colombia. Extractos de sus diarios. Flota Mercante Gran Colombiana. Publicismo y Ediciones, Bogotá, 142 p

Acosta ACE (2003) La Cordillera de los Andes. Ingeominas, Publicaciones Especiales, No.26, Bogotá, 290 p

Arcila MM, Monsalve ML (1996) Aspectos estructurales a partir de una evaluación dinámica del proceso de réplicas del Sismo de Páez (06. 06. 1994). Memorias VII Congreso Colombiano de Geología, Tomo III. INGEOMINAS, Bogotá, pp 504–516

Bellot-Gurlet L, Dorighel O, Poupeau G (2008) Obsidian provenance studies in Colombia and Ecuador: obsidian sources revisited. J Archaeol Sci 35:272–289

Bellot-Gurlet L, Poupeau G, Dorighel O (1999) A pixe/fission-track dating approach to sourcing studies of obsidian artefacts in Colombia and Ecuador. J Archaeol Sci 26:855–860

Boussingault JB (1903) Memorias. Chamerot et Renouard, Paris. Ed. Banco de la Republica, Bogotá, 1985, 5 vol

Case JE, Duran SL, López G, A Moore WR (1971) Tectonic investigations on western Colombia and eastern Panamá. Geol Soc Am Bull 82:2685–2712

Espinosa A (2011) Enciclopedia de Desastres naturales Históricos de Colombia. Erupciones históricas de los volcanes colombianos 1550 – 2000. Segunda edición. Academia Colombiana de Ciencias Exactas, Físicas y Naturales. Universidad del Quindío, vol. 6, Bogotá. 453 p

Friedlaender I (1927) Ueber einige Vulkane Columbiens Teil II. Zeitschr. F- Vulkanologie No.4: 223 p

Grosse E (1935) Acerca de la geología del sur de Colombia II. Compilación de los estudios oficiales en Colombia. Bogotá. Tomo III. pp 139–231

Hall M, Wood CA (1985) Volcano-tectonic segmentation of the northen Andes. Geology 13(3):203–207

Kroonenberg S, Pichler H, Diederix H (1982) Cenozoic alkalibasaltic to ultrabasic volcanism in the uppermost Magdelena Valley, Southern Huila Department, Colombia: Geologia Norandina, vol 5, pp 19–26

Kroonenberg S, León LA, Pastana JM do N, Pessoa MR (1981) Ignimbritas pilo-pleistocenícas en el suroeste del Huila, Colombia y su influencia en el desarrollo morfológico. Rev CIAF 6(1–3):293–314

Kuroda N, Paris G (1978) Petrographical notes of some dacites and andesites of Purace Volcano, Cauca Colombia. Report of Andean Studies, Shiziukoa University (Japan), Special Volume: pp 21–32

McCourt W, Apsden J, Brook M (1984) New geological and geochronological date from the colombian andes: continental growth by multiple accretion. J Geol Soc London 141:831–845

Monsalve ML, Pulgarín B, Narváez BL, Aguirre LP, Laverde C (2012) Geología y estratigrafía del volcán Puracé Actual. Colombia. Informe interno Servicio Geológico colombiano, Bogotá

Monsalve ML, Pulgarín B (1999) Cadena volcánica de los Coconucos (Colombia), centros eruptivos y productos recientes. INGEOMINAS. Boletín Geológico, Bogotá 37(1–3):17–51

Monsalve ML, Pulgarín B (1993) Mapa preliminar de amenaza volcánica potencial del volcán Puracé. Revista INGEOMINAS, Bogotá 1(2):3–27

Monsalve ML, Pulgarín B (1992) Mapa geológico preliminar de los productos proximales de la Cadena Volcánica de los Coconucos. Informe interno, INGEOMINAS, Bogotá

Murcia A, Pichler H (1987) Geoquímica y dataciones radiométricas de las ignimbritas cenozoicas del Sw de Colombia. Revista CIAF, Bogotá, Tomo II (1–3), 11:346–363

Murcia LA (1987) Volcanismo activo y terremotos asociados a Megafallamiento en el SW de Colombia. Simp. Internac. Neotectónica y Riesgos Volcánicos, 1986. Rev CIAF, Bogotá 11(2):161–178

Murcia LA, Marín PA (1981) Petrología y petroquímica en lavas recientes de algunos volcanes de Colombia. Revista CIAF, Bogotá 6(1–3):349–363

Ponce A (1979) Anotaciones sobre geología de la parte SE del departamento de Nariño. Ingeominas, Informe 1769, Bogotá. 53 p

Pulgarín B, Monsalve ML, Torres P, Cepeda H (1996) La Cadena Volcánica de los Coconucos, producto de vulcanismo resurgente? VII Congreso Colombiano de Geología, Proceedings, Tomo III, Bogotá. pp 367–377

Oppenheim V (1950) The volcano Puracé. Am J Sci 248:171–179

Puerta G (1991) Historias y leyendas del volcán Puracé. 1a edición. Impresión Canal Ramírez & Antares Ltda. Popayán. 103 p

Stübel A (1906) Die Vulkanberge von Colombia. Verlag von Wilhem Baensch, Dresden 252 p

Torres MP, Monsalve ML, Pulgarín B, Toro G (2011) Caldera de Paletará: Fuente de un voluminoso vulcanismo riolítico en la Cordillera Central de Colombia. XIV Congreso Latinoamericano de Geología y XIII Congreso Colombiano de Geología, Medellín

Torres MP (2010) Petrografía, geocronología y geoquímica de las ignimbritas de la Formación Popayán, en el contexto del vulcanismo del SW de Colombia. Universidad EAFIT, Tesis de Maestría, Departamento de Geología, Medellín 105 p

Torres MP, Monsalve ML, Pulgarín B, Cepeda H (1999) Caldera de Paletará: aproximación a la fuente de las ignimbritas del Cauca y del Huila (Colombia). Boletín Geológico. Ingeominas. Bogotá 37(1–3):1–15

Torres P, Ibáñez D, Vásquez E (1992) Geología y estratigrafía de la Formación Popayán. Informe Interno, Ingeominas, Popayán 85 p
Van Der Hammen T (1985) The Plio-Pleistocene climatic record of the tropical Andes. J Geol Soc London 142:561–580
Van der Wiel AM (1991) Uplift and volcanism of the SE Colombian Andes in relation to Neogene sedimentation in the upper Magdalena valley. The Quaternary of Colombia 18:139–167
White RB (1869) Informe del ingeniero Robert B. White sobre la observación hecha de los efectos de la explosión del volcán Puracé, que tuvo lugar el día 4 de octubre de 1869. Revista Anales de la Universidad, Popayán, pp 163–173
Wilson M (1989) Igneous petrogenesis. Unwin Hyman, A global tectonic approach 466 p
Woodward Clyde Consultants (1983) Seismic hazard evaluation Calima III project: Consorcio Integral-Planes, Ltda., Corporación Autónoma Regional del Cauca (CVC), Cali, 116 p. No 69

Geomorphological Features of the Galeras Volcanic Complex

16

Marta Lucia Calvache and José Fernando Duque-Trujillo

Abstract

The Galeras volcanic complex, near the city of Pasto, was formed in several steps. At ~560 ka, BP a major caldera (the *Coba Negra* Caldera) appeared with its center ~5 km west of the present-day active volcano top. This caldera was 5 km in diameter and elongated in the E–W direction. The wall of the subsequent Jenoy caldera is covered by glacial morphology indicating a pre-glacial (<ca. 20 ka) age. These data suggest that the location of the eruptive main centers changed several times, moving eastward. Another 4-km-diameter caldera was formed during the Jenoy stage. The E–W migration trend of the volcanic centers can be seen in the Coba Negra caldera. Between 12.8 and 5 ka, the summit portion of the cone collapsed toward WSW and formed the youngest avalanche debris deposits. The collapse scar has a horseshoe shape and the sliding surface almost certainly cut across the main magma conduit. The presence of other, older avalanche debris deposits suggests previous lateral collapses, the scars of which can be recognized on the upper southern slope of the volcano. The active cone lies in the uppermost part of the sector collapse depression. Most of the surroundings are covered by pyroclastic deposits from the Galeras and neighboring volcanoes. The Galeras volcano is still active and constitutes a real hazard for the surrounding inhabitants.

Keywords

Active volcanism • Volcanic landforms • Glacial landforms

16.1 Introduction

The Galeras volcano, the most active volcano in Colombia (Stix et al. 1997) is located in the southwestern part of the country, near the city of San Juan de Pasto, the capital of the Department of Nariño (Fig. 16.1). Pasto is a city of 430,000 inhabitants, located 9 km east from the active volcano summit. Pasto lies within the Galeras volcanic complex (GVC) influence area, which covers an area of approximately 220 km^2, including several other localities such as Nariño, Yacuanquer, Consacá, Sandoná, and La Florida, with a total of more than 90,000 inhabitants. All those localities are communicated by the *Circunvalar* road, which surrounds the volcanic complex (Fig. 16.2) and constitutes the best way to see ancient and recent GVC volcanic deposits. The Galeras volcano itself rises to 4276 m a.s.l. and 1600 m above the so-called "Knot of the Pastos" or Huaca Massif, a geographic place where the Andes Cordillera divides itself into two different branches (eastern and central-western).

The GVC has always been an attractive site, visited during the last two centuries by foreign naturalists, such as

M.L. Calvache (✉)
Servicio Geológico Colombiano, Bogotá, Colombia
e-mail: mcalvache@sgc.gov.co

J.F. Duque-Trujillo
Grupo de Geología Ambiental e Ingeniería Sísmica,
Universidad EAFIT, Medellín, Colombia
e-mail: jduquetr@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_16

Fig. 16.1 Galeras volcano seen from city of Pasto, (*Photo* Michel Hermelin)

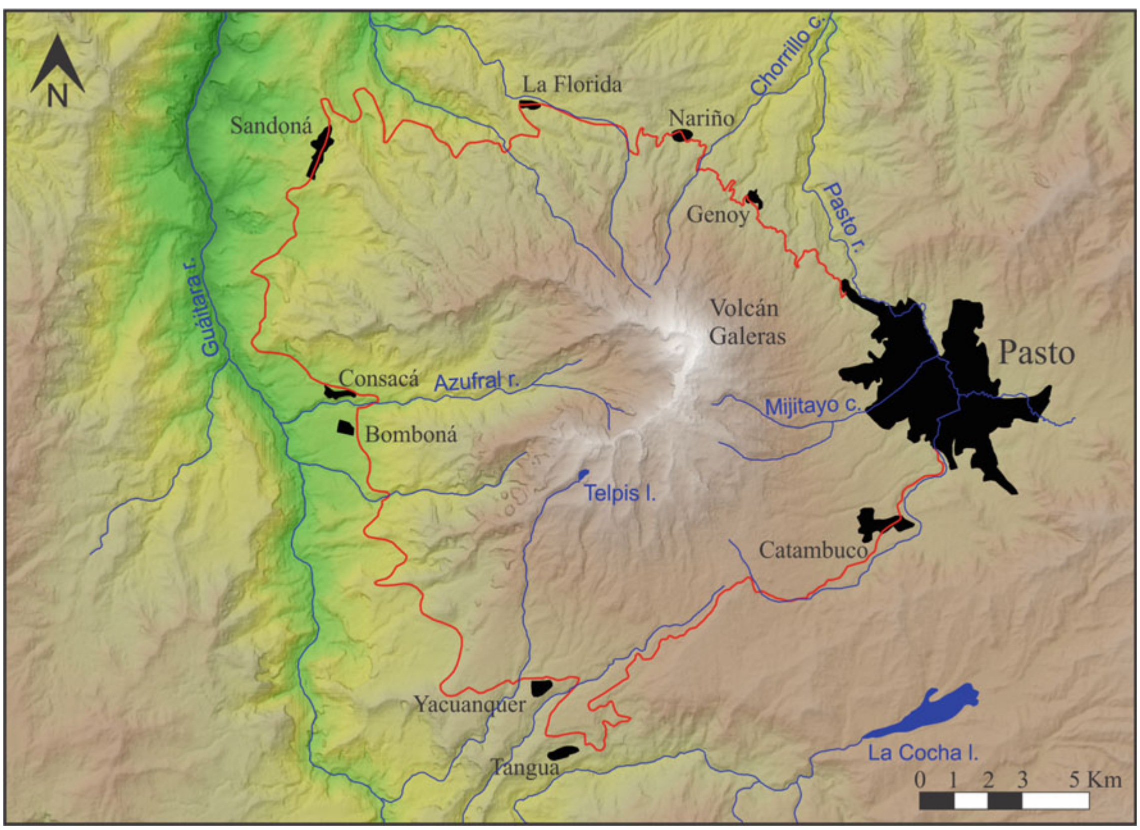


Fig. 16.2 Road itinerary around the Galeras volcano. Notes. *l* lake, *c* creek, *r* river

Pierre Bouguer in 1743, Alexander von Humboldt in 1801, J.B. Boussingault in 1831, Wilheim Reiss and Alphons Stuebel in 1868 (Stuebel 1906), and E. Friedlaender in 1925.

For several years, government agencies have taken on the task of raising awareness among the inhabitants of Pasto and surrounding villages of the risks represented by the volcano, and have carried out much work on the prevention measures that the population should take. But the idea that "the volcano is our best friend, and never would never do us harm" is a deeply rooted idea in the collective imagination and people feel that the volcano is more likely an old family friend than a dangerous neighbor.

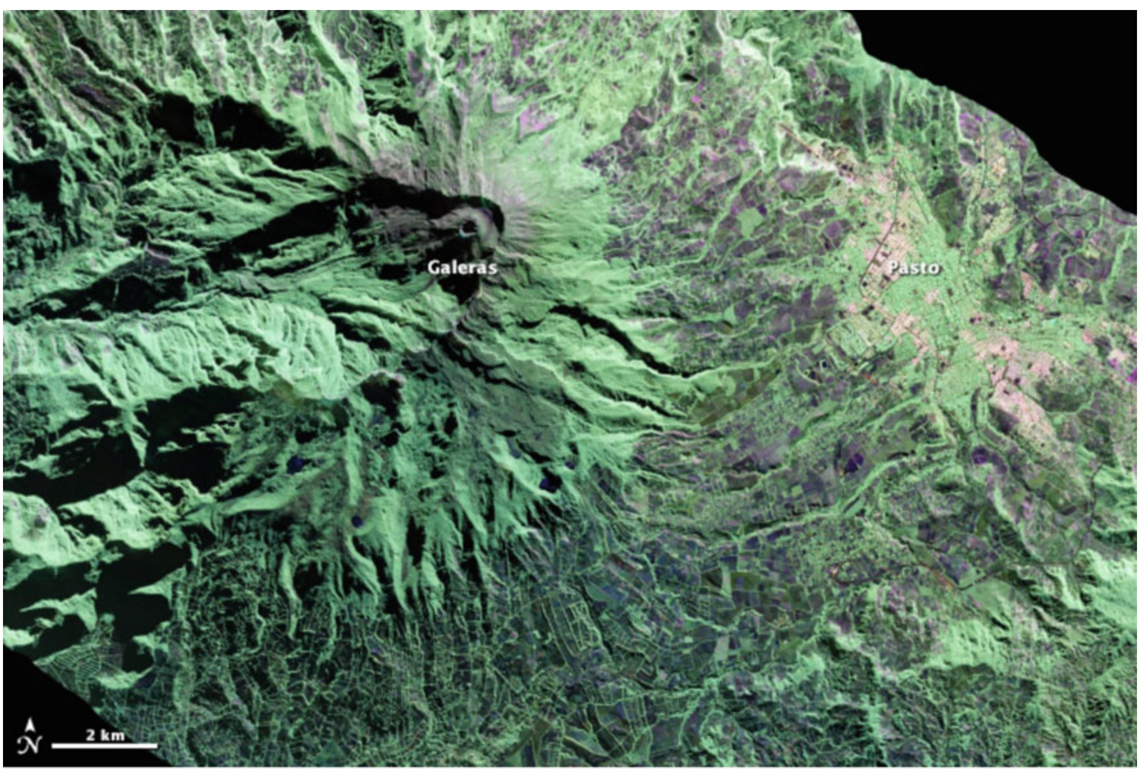
The volcano dominates the Atriz Valley, where the city of Pasto is located and its majestic presence, often capped by fumarolic smoke, can be perceived from far away. Its name was given by the first Spaniards who visited the place, due to its remote resemblance to a galley hull (Figs. 16.1 and 16.3).

16.2 Geological Background

The actual tectonic configuration of the Colombian Andes is characterized by an intimate relationship between the orogenic chains and large reverse and strike-slip fault systems with a regional N–S to NE–SW trend, kinematically compatible with a stress field (E–W oriented σ_1, and N–S σ_3), controlled by the convergence between the Nazca and South American plates and the Chocó Block. The convergence between the Nazca and South American plates (Fig. 16.4) is distributed between the subduction under South America and stresses along some of the continental fault systems subparallel to the Cordilleras (Taboada et al. 2000; Trenkamp et al. 2002).

The Romeral fault zone (RFZ) is one of the main structural elements in the Northern Andes. It extends from the Gulf of Guayaquil in Ecuador to Barranquilla in Colombia (Fig. 16.5) (Chicangana 2005; Tibaldi and Romero 2000). In Colombia, this fault is associated with an important change in basement composition, putting together the Precambrian–Paleozoic poly-metamorphic continental basement intruded by the Mezosoic–Cenozoic plutons of the Central Cordillera and Mesozoic to Cenozoic accreted terrains of oceanic affinity of the Western Cordillera from the west, which constitute the GVC basement (Nelson 1962; Botero 1963; Barrero 1979). This basement is covered by a thick volcanic and volcaniclastic sequence of Tertiary age, produced by ancient volcanic activity along the inter-Andean valley between the Central and Western Cordillera (Barrero and Vesga 1976; Alvarez et al. 1983; Restrepo et al. 1981).

The GVC is located over the Romeral fault zone, where its main trace is intersected by a minor scale Buesaco Fault



download large image (4 MB, JPEG, 4802x4133) acquired March 13, 2013

Fig. 16.3 Satellite image of the Galeras volcano. INGEOMINAS

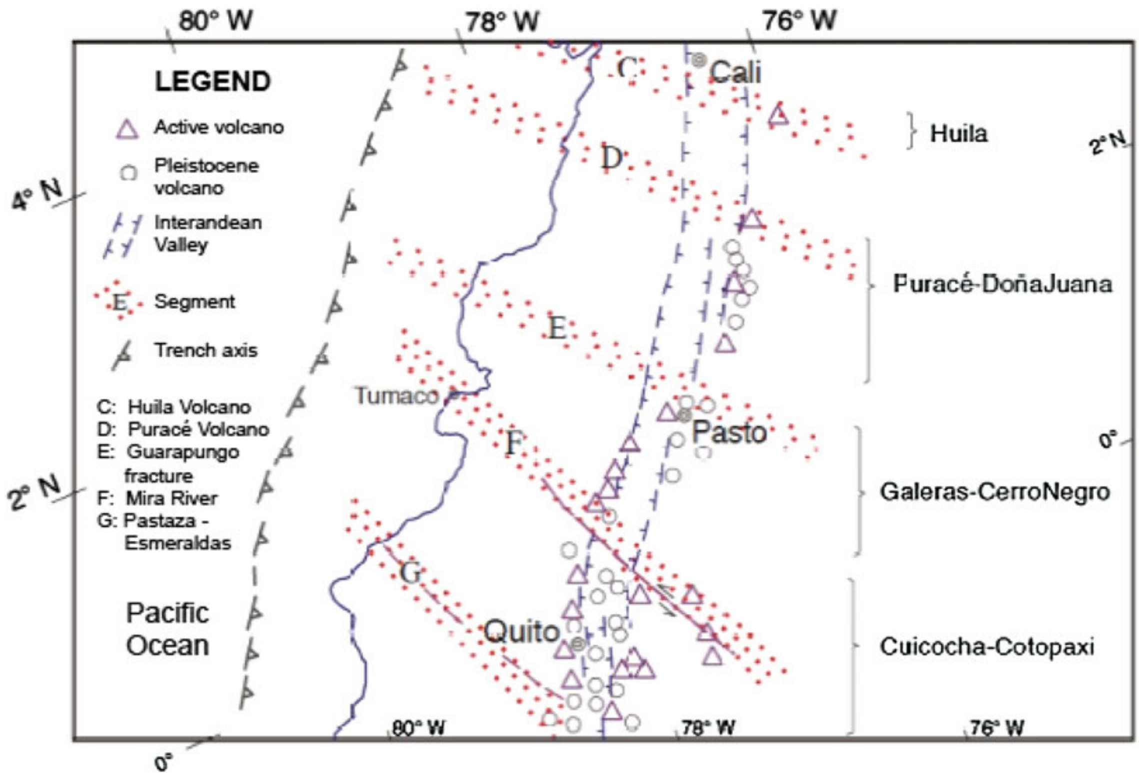


Fig. 16.4 Tectonic setting of the Galeras volcanic complex (after Hall and Wood 1985)

belonging to the same system, which has the same sense of movement as the Romeral Fault and shows a similar degree of recent tectonic (Tibaldi et al. 2005; Tibaldi and Romero 2000).

16.3 The Galeras Volcanic Complex

The Galeras volcanic complex (GVC) consists of ancient and recent volcanic deposits from previous volcanic stages and from the contemporary active cone of Galeras (Calvache 1995). Several stages of its evolution have been identified on the basis of geological and geochronological studies performed by Calvache (1995), Calvache and Cortés (1996) and Calvache et al. (1997).

Detailed studies allowed Calvache et al. (1997) to define six different stages in the evolution of the GVC. Each of these eruption stages is the result of numerous eruption episodes, which occurred during long periods of time. Some of the older eruptive stages are difficult to trace, due to subsequent weathering, erosion, and burial by later deposits, especially by thick ash falls erupted from various volcanic centers located around the GVC (Figs. 16.5 and 16.6).

16.3.1 Pre-Galeras History

The pre-Galeras history is divided into five stages. The oldest of them is the Cariaco stage, whose only remnant is a pinnacle in three directions re-shaped by glacial activity at three sides, suggesting that it was a topographic high during the Pleistocene glaciation (Calvache et al. 1997). This was followed by the Pamba Stage, which left deposits around the town of Sandoná, where the best exposure of the edifice can be seen (Fig. 16.2). Lava flow deposits are by far the major volcanic products of the next Coba Negra eruptive stage. These are mainly composed by two pyroxene-high silica andesites, with few dacites and basaltic andesites, whose eruptions began around 793 ka (Calvache et al. 1997). Around the end of this stage and before the activity of the Jenoy stage, a small monogenetic cinder cone (0.2 km^3) named La Guaca was formed on the southwestern side of the GVC. La Guaca is dated at 166 ± 34 ka and it is characterized by eruption of lapilli to block-sized scoria clasts, and

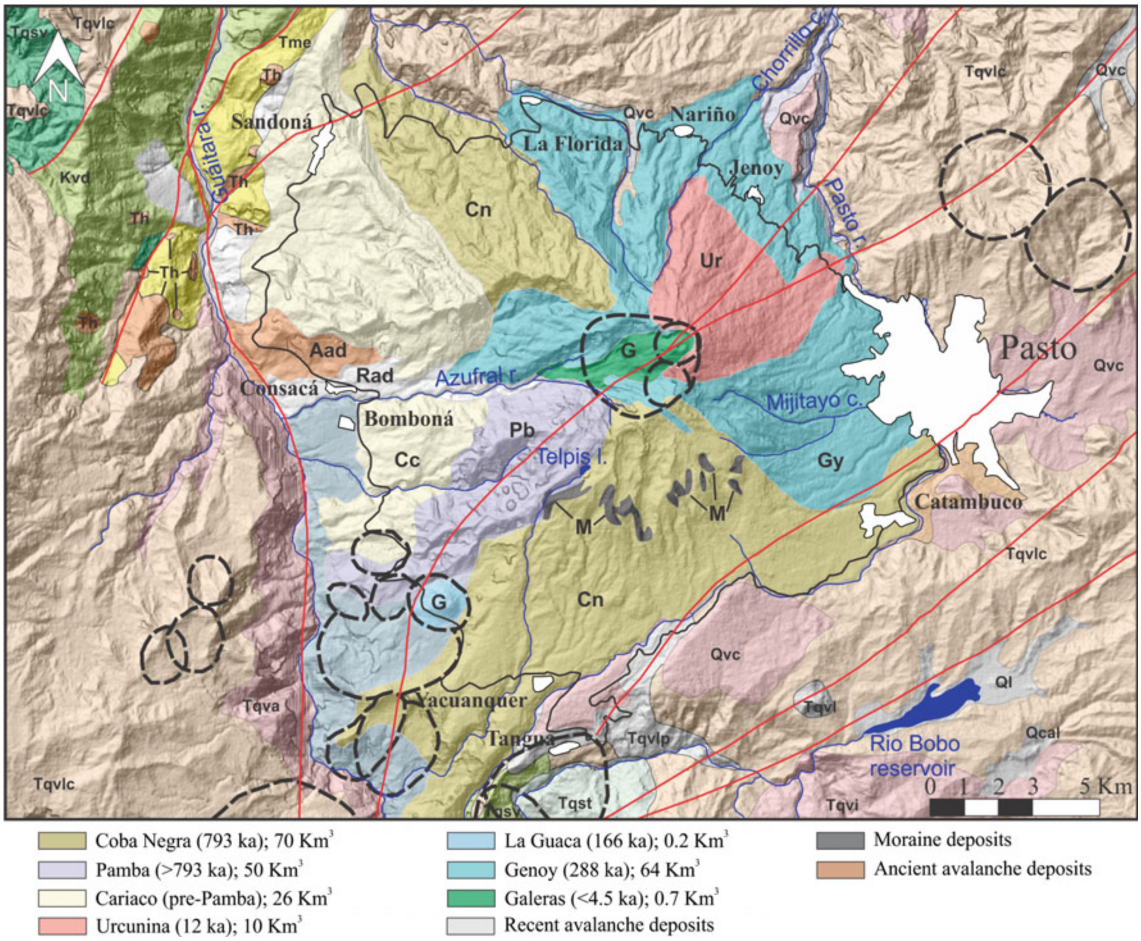


Fig. 16.5 Geological map of the Galeras volcanic complex, modified from Calvache et al. (1997). Abreviations: *Cn* Coba Negra stage; *Pb* Pamba stage; *Cc* Cariaco stage; *Ur* Urcunina stage; *G* La Guaca stage; *Gy* Genoy stage; *Rad* Recent avalanche deposits; *M* Moraine deposits; *G* Galeras stage; *Kvd* Diabase group; *Tqsv* La Macarena sediments; *Tqvlc* Tertiary ashes and lavas; *Th* Hypabyssal rocks; *Tme* Esmita formation; *Tqva* Pyroclastic and debrie flow deposits; *Tqst* Tapialquer sediments; *Tqvlp* Lahar and pyroclasts; *Qvc* Ash fall deposits; *Tqvi* Eutaxitic ignimbrites; *Tqvl* Tertiary Lavas; *Ql* Lacustrine deposits. Regional geology from Murcia A, Cepeda H (1991); detailed geology from GVC from Calvache et al. (1997)

some small lava flows at the end of its activity. The volcanic materials erupted by La Guaca are composed exclusively of olivine-bearing basaltic andesites (Calvache et al. 1997) (Fig. 16.7).

The source of the ensuing Jenoy-stage activity has been located east of the Coba Negra caldera, or along the eastern border of this caldera. The caldera-forming event at the Jenoy stage has been dated to be as old as 40 ka (Calvache et al. 1997). Explosive activity continued during the Jenoy stage with minor eruptions that formed valley-controlled pyroclastic deposits and dated for 41–31 ka (Calvache et al. 1997). The evidence of the next Urcunina Stage is one among the best preserved old GVC stages (Fig. 16.2). Actually, it is the tallest edifice, which can be seen directly from the city of Pasto (it is commonly called “The Galeras Volcano”). The major part of Urcunina is formed by a two pyroxene-andesite lava flows with some associated lava flow collapse pyroclastic flows (Calvache et al. 1997).

16.3.2 The Galeras volcano

The Galeras volcano (Cepéda 1985) is the present focus of volcanic activity in the GVC. It is localized at the center of the complex, inside the scar left by the summit collapse of the Urcunina edifice (Fig. 16.8). The Galeras active cone is 800 m wide and 150 m high and contains the main crater which is ∼350 m wide, representing only a volume of 0.7 km^3 (Ordóñez and Cepeda 1997).

The Galeras activity apparently began at 4500 years BP and was characterized by vulcanian-type eruptions (Banks et al. 1997) that basically consisted of a dense cloud of ash and gas exploding from the volcano crater in repetitive, but

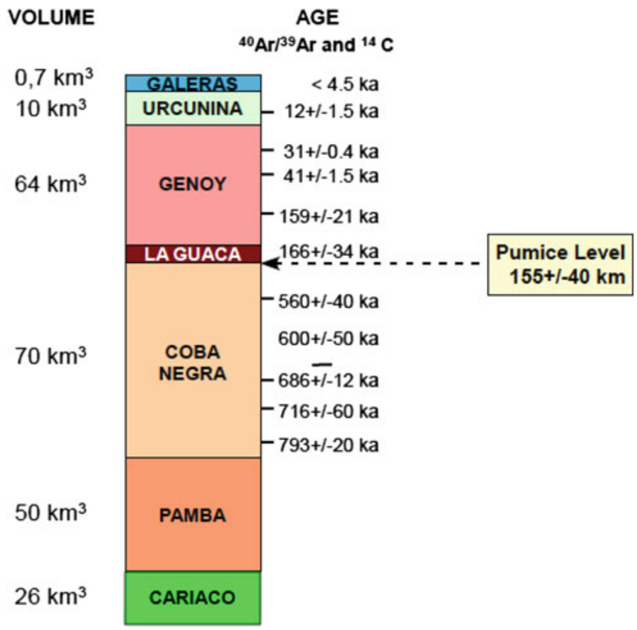


Fig. 16.6 Generalized stratigraphic column of the Galeras volcanic complex. Modified from Calvache et al. (1997)

irregular intervals. Several periods of activity have been identified and associated with pyroclastic flows, pyroclastic falls, mud, and/or debris flow deposits (Cortes and Calvache 2002). Nevertheless, the most characteristic product of Galeras explosive activity is the gravitational column collapse, which usually produces lithic-rich pyroclastic flows due to vent-cleaning processes; later, the column is enriched with juvenile material. This material does not represent an important volume on the GVC and is restricted to the active cone. Debris and/or mudflows can be seen in the north and northwestern areas of the GVC and also along the Azufral River, together with some small Andesitic lava flows (Calvache et al. 1997).

16.4 Main Geomorphologic Features

The diverse volcanic products generated during the volcanic activity on the GVC, the wandering of the emission centers, and the intrinsic instability associated with volcanic

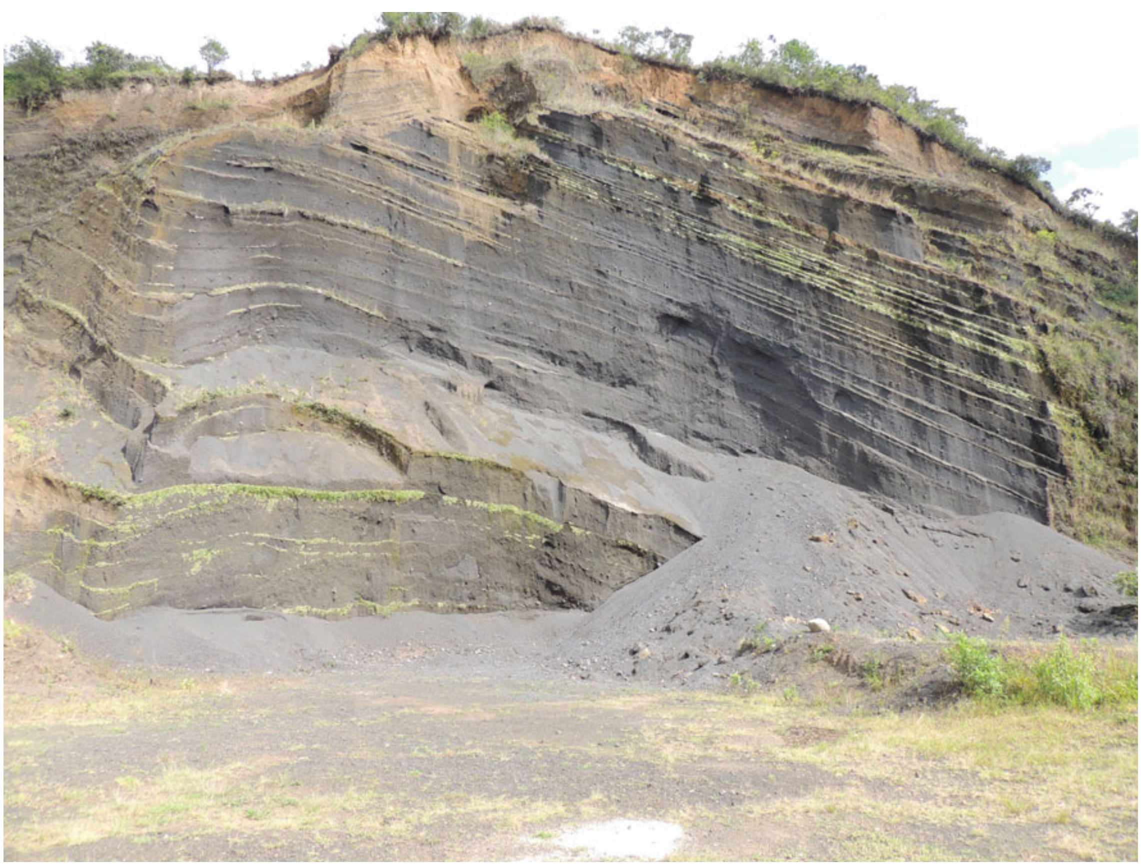


Fig. 16.7 La Guaca pyroclastic deposit (outcrop is about 30 m high), (*Photo* Michel Hermelin)

Fig. 16.8 Aerial view of the Galeras calderas and crater, Ingeominas

complexes have been the main contributors to the GVC landscape.

16.4.1 Glacial Erosion

Although there is no clear evidence of the existence of moraine deposits older than those formed during pre-Late Pleistocene glaciation, some descriptions of subdued moraines and weathered till are given by Schubert and Clapperton (1990). On the other hand, the maximum of the last Pleistocene glaciation in the Northern Andes occurred around 20–18 ka BP, when the glaciers reached 3000–3900 m a.s.l. (Schubert and Clapperton 1990). This glacial timing implies that most of the GVC stages occurred before the last glaciation, and thus, respective landscapes should have been influenced by glacial processes.

Calvache et al. (1997) described evidence of glacial action on remnants of the early stages of the GVC, Cariaco, Coba Negra, and Jenoy. The primary evidence of glacial action on the GVC is found on the volcanic products of the Coba Negra stage. In the southern part, landforms related to glacial erosion, such as amphitheaters, U-shaped valleys, and lakes can be found. Landforms related to glacial deposition in the form of lateral and frontal moraines are found up to 3400 m a.s.l. along the Cubijan, La Magdalena, La Aguada, and Telpis Rivers (Calvache et al. 1997), indicating that the glacial front reached at least 3400 m a.s.l., probably during the glacial maximum, between 20 and 18 ka.

The effects of glacial erosion are evident, especially due to the reduction of the slope angle and the notorious contrast between the U-shaped valleys with gentle slopes and the steep slopes (30°–40°) of the unaffected flanks, characterized by craggy stacking of lavas. The same effect of slope angle reduction can also be observed in the eastern and southeastern part of the Cariaco edifice, which, according to Calvache et al. (1997), also presents evidence of glacial erosion. In fact, the present highest point of this edifice is a glacial horn, flanked by three glacial cirques directed toward the north, the southeast, and the southwest, suggesting that this was also a topographic high during Pleistocene glaciation.

Jenoy-stage remnants, similar to Cariaco and Coba Negra, also include deep valleys and glacial deposition morphology; however, these are not as notable as glacial morphology observed within the extent of the older stages. This may confirm the Pleistocene age of the Jenoy stage (Calvache et al. 1997).

16.4.2 The Caldera Walls

Some of the most distinctive features in the GVC are its caldera walls, located in the upper part of the complex. These caldera-forming eruptions are notorious due to its explosiveness, large volume of material involved, and the spectacular walls which remain until nowadays (Figs. 16.5 and 16.8).

At present, only the northern and southern caldera walls remain. Both walls are nearly 4 km long. The southern wall is ~600 m high, while the northern wall is ~400 m high. The eastern caldera rim was buried and destroyed by Urcunina constructional and collapse processes, and the western rim was completely destroyed by flank collapse and eroded by the Azufral River due to its strong gradient.

16.4.3 The Active Crater

The currently active crater of the Galeras volcano belongs to the last eruptive stage of the GVC, named as the Galeras volcano, which has been active for at least the last 4500 years (Banks et al. 1997). It measures ~350 m in diameter and ~80 m in depth, and contains a cone inside which is 100 m tall and 500 m across (Fig. 16.8). The first direct description of the main crater was made by Boussingaultin in 1903, based on his visit on May 15, 1831. He observed a lava dome, several tens of meters in diameter, in the crater with a major NE–SW fracture, and many fractures, fissures, and fumarolic activities. Boussingault also described recent explosive activity with ash emission. Later, in 1832, an important eruption occurred, which ejected a significant volume of ash, possibly blowing out a part of the dome, cleaning the conduit, and forming a new crater (Espinosa 1989).

The first sketched description of the crater was made by Stübel (1906), who visited the volcano between July 1869 and January 1870, observing the growth of a small scoria cone inside the crater. Many other historical descriptions were compiled by Espinosa (1989) and Ordóñez and Cepeda (1997). These descriptions basically point out the main crater with many fissures and parasite craters located within it, from which gases were released.

By 1982, the main crater had markedly enlarged, and two new secondary craters named El Pinta and El Paisita appeared, which showed considerable activity until 1991 (Ordóñez and Cepeda 1997).

By the end of October 1991, a dome of 400,000 m^3 was detected inside the crater. The dome was partially destroyed by an explosive eruption on July 16, 1992; the rest of the dome was blown by the January 14, 1993 eruption, which resulted in the deaths of 6 scientists and 3 tourists who were attending a workshop on Galeras, declared as the "Decade Volcano" (Ordóñez and Cepeda 1997; Cortés and Raigosa 1997; Stix et al. 1997). After destruction of the dome, the crater suffered minor changes, with the activity concentrated on the western side and the same centers of eruption as

Fig. 16.9 Pyroclastic materials quarried south of Pasto, (*Photo* Michel Hermelin)

Fig. 16.10 Collapsed tunnels signify the site of underground exploitation of pyroclastic materials south of Pasto, (*Photo* Michel Hermelin)

during earlier episodes of activity (Ordóñez and Cepeda 1997).

16.4.4 Ash Fall Deposits

Ash cover tends to smooth the landscape around southern Pasto, Catambuco, and Yacuanquer; this zone has very gentle slopes due to the thick pyroclastic fall out coverage (Banks et al. 1997), consisting of a series of ash fall layers alternating with paleosoils, which indicate periods of volcanic quiescence. The ash fall cover is usually more than 25–30 m thick. Murcia and Cepeda (1991), Calvache (1995), and Cortés and Calvache (2002) mapped these deposits as non-differentiated ash falls. Banks et al. (1997) and Cortés and Calvache (2002) described and dated the ash fall sequence around the city of Pasto, identifying many ash fall events and defining the Los Pastos Formation, which includes the sequence of fall off deposits (Fig. 16.9).

Several layers of these ash fall deposits are targets of artisanal exploitation for building materials. The main quarries are located near Pasto and along the *Circunvalar* road, near Catambuco and Yacuanquer. These exploitations are done by means of long tunnels inside the deposits, where laborers and trucks extract the material. This has generated major subsidence problems at the surface immediately above locations where this material has been extracted (Fig. 16.10).

16.4.5 Structural Landforms

The GVC and its surroundings present an important influence from the Romeral fault system. In fact, the location of the actual Galeras active cone and its wandering along the GVC evolution may respond to sustained tectonic control, which allowed the magmatic ascent along cortical weakness zones. Like the GVC activity centers, other volcanic features are or have been controlled by the tectonic regime present in the area. The La Guaca cinder cone is aligned in NE–SW, within the Telpis Lake fault swarm. This swarm is also affecting the active cone and the southern scarp of the Urcunina sector collapse (Tibaldi et al. 2005). The tectonic regime since the Late Pliocene has been dominated by a right-lateral strike-slip motions along the NE striking vertical to subvertical faults. These faults also control minor uplift of the northwestern block (Tibaldi and Romero 2000). This tectonic setting could respond to a regional compressional stress regime characterized by a horizontal E–W trending major vector, and a minor stress vector located in N–S (Tibaldi and Romero 2000).

16.4.6 The La Guaca Cinder Cone

La Guaca is known as a small cinder cone located on the southwestern flank of the GVC near the town of Yacuanquer. The La Guaca cone is slightly elongated along E–W, 200 m tall and has a diameter of 1800 m in E–W direction and 1500 m in N–S direction (Figs. 16.5 and 16.7). It is totally composed of layers of black scoria clasts, which vary from lapilli to block size. Layer thickness ranges between 1.2 and 40 m. Only one lava unit has been described; it crops out on the western flank and exhibits the same composition as the scoria clasts. Composition of this cinder cone is totally different from the rest of the GVC volcanic products because it is exclusively composed by olivine-bearing basaltic andesites.

16.5 Visiting Galeras

Although the volcanic behavior of the Galeras volcano is well known, and the Colombian Geological Service is continuously monitoring its activity level through its telemetric surveillance station (Seidl 2003; http://www.sgc.gov.co/Pasto/Volcanes/Volcan–Galeras/Generalidades.aspx), the area near the Galeras summit is a high-risk area and access is generally forbidden. The best way to observe the volcanic deposits that compose the different volcanic stages of the GVC (except for most of the current Galeras deposits) is the *Circunvalar* road, which runs through different towns around the volcano, including Pasto, La Florida, Sandoná, Consacá, and Yacuanquer, allowing visitors to observe different landscapes, climate zones, and touristic attractions, such as coffee-producing farms, artisanal products, and sugarcane plantations. The complete circuit by car takes approximately 5 h.

References

Álvarez A (1983) Geología de la Cordillera Central y el Occidente colombiano y petroquímica de los intrusivos granitoides Mesocenozóicos. Instituto Nacional de Investigaciones Geológico–Mineras

Banks NG, Calvache M, Williams S (1997) ^{14}C ages and activity for the past 50 ka at Volcán Galeras, Colombia. J Volcanol Geoth Res 77(1):39–55

Barrero D (1979) Geology of the Central Western Cordillera west of Buga and Roldanillo, Colombia. INGEOMINAS, Colombia Special Publication. 4, 75 p

Barrero D, Vesga C (1976) Mapa geológico del Cuadrángulo K–9 Armero y mitad sur del Cuadrángulo J–9 La Dorada. Scale 1:100.000. INGEOMINAS. Bogotá 1, no. 400.000

Botero G (1963) Contribución al conocimiento de la geología de la Zona Central de Antioquia. Annals, Faculty of Mines, National University of Colombia, Medellín, Colombia, 57, 101 pp

Calvache M (1995) The geological evolution of Galeras Volcanic Complex. Ph.D. Dissertation, Arizona State University, Tempe, AZ, 180 p

Calvache M, Cortés G (1996) Estratigrafía del Complejo Volcánico del Galeras. VII Congreso Colombiano de Geología, Bogotá

Calvache M, Cortés G, Williams S (1997) Stratigraphy and chronology of the Galeras volcanic complex, Colombia. J Volcanol Geoth Res 77(1):5–19

Cepeda H (1985) Anotaciones acerca de la geología del volcán Galeras, Colombia, S.A. 6th Latin American Geology Congress, Bogotá, Book 1, pp 339–383

Chicangana G (2005) The Romeral Fault System: a shear and deformed extinct subduction zone between oceanic and continental lithospheres in northwestern south America. Earth Sci Res J 9(1):50–64

Cortés G, Calvache M (2002) Formación Los Pastos: Catálogo de las unidades litoestratigráficas de Colombia. INGEOMINAS. 41 p

Cortés JG, Raigosa J (1997) A synthesis of the recent activity of Galeras volcano, Colombia: seven years of continuous surveillance, 1989–1995. J Volcanol Geoth Res 77(1):101–114

Espinosa A (1989) Actividad del volcán Galeras en épocas históricas. INGEOMINAS, Popayán, Preliminary Report, 80 p

Hall M, Wood C (1985) Volcano-tectonic segmentation of the northern Andes. Geology 13:203–207

Murcia A, Cepeda H (1991) Plancha 429–Pasto (Departamento de Nariño) Escala 1:100.000. INGEOMINAS, Intern. Rep., 18 p

Nelson W (1962) Contribución al conocimiento de la Cordillera Central de Colombia. Sección entre Ibagué y Armenia, Bol Geol X (1–3):161–202

Ordóñez VM, Cepeda VH (1997) Morphological changes of the active cone of Galeras Volcano, Colombia, during the last century. In: Stix J, Calvache ML, Calvache V, Williams SN (eds) Galeras Volcano, Colombia: Interdisclipinary Study of a Decade Volcano. J Volcanol Geotherm. Res 77:71–87

Restrepo JJ, Toussaint J, González H (1981) Edades Mio–Pliocenas del magmatismo asociado a la Formación Combia. Departamentos de Antioquia y Caldas, Colombia: Geología Norandina 3:21

Schubert C, Clapperton CM (1990) Quaternary glaciations in the northern Andes (Venezuela, Colombia and Ecuador). Quat Sci Rev 9:123–135

Seidl D, Hellweg M, Calvache M, Gomez D, Ortega A, Torres R, Böker F, Buttkus B, Faber E, Greinwald S (2003) The multiparameter station at Galeras Volcano (Colombia): concept and realization. J Volcanol Geoth Res 125(1):1–12

Stix J, Calvache M, Williams S (1997) Galeras volcano, Colombia. Interdisciplinary study of a Decade Volcano. J Volcanol Geoth Res 77:1–4

Stuebel A (1906) Die Vulkanberge von Colombia. Dresden, W. Baensch

Taboada A, Rivera L, Fuenzalida A, Cisternas A, Philip H, Bijwaard H, Olaya J, Rivera C (2000) Geodynamics of the northern Andes: subductions and intracontinental deformation (Colombia). Tectonics 19(5):787–813

Tibaldi A, Lagmay A, Ponomareva V (2005) Effects of basement structural and stratigraphic heritages on volcano behaviour and implications for human activities (the UNESCO/IUGS/IGCP project 455). Episodes J Int Geosci 28(3):1–13

Tibaldi A, Romero-Leon J (2000) Morphometry of late Pleistocene-Holocene faulting and volcanotectonic relationship in the southern Andes of Colombia. Tectonics 19:358–377

Trenkamp R, Kellogg J, Freymueller J, Mora H (2002) Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. J S Am Earth Sci 15 (2):157–171

The Guamuéz (La Cocha) Lake

17

José Fernando Duque-Trujillo, Michel Hermelin, and Gloria Elena Toro

Abstract

The Guamuéz Lake (also called La Cocha) lies at 2765 m a.s.l. southeast of Pasto. La Corota, its main island, houses a wildlife sanctuary of endemic species protected by the Ministry of the Environment. The La Cocha valley and its neighbor the Sibundoy valley (similar, but completely drained lake) are both seated along one of the main strike-slip faults, the Algeciras fault. This fault system borders the Northern Andes in southwestern Colombia, forming valleys along its trace due to local pull-apart stress associated to its movements. Several small volcanic structures are aligned over the main fault traces which limit the tectonic valleys, making La Cocha a unique landscape. The vegetation that could be found around La Cocha is also unique, because it represents one of the altitudinal lowest páramo ecosystems in the world.

Keywords

High altitude lakes • Volcanic landforms • Transtensional tectonics

17.1 Location and General Setting

The Guamuéz lake, better known as La Cocha lake (in the Quechua language *cocha* means lake), is a beautiful Andean lake located about 10 km (a 40-min car ride) southeast of the city of Pasto (01°06′N, 77°09′W), the capital of the Department of Nariño, which borders with Ecuador (Fig. 17.1). Its altitude is 2765 m a.s.l., between mountains which reach elevations between 2800 and 3600 m a.s.l. La Cocha Lake is among the largest lakes in northern Andes and is surrounded by wetlands (González–Carranza et al. 2012). The lake is 16-km long and has a maximum width of 6 km and a maximum depth of 75 m. The surface area is 42 km^2, water volume is 1.55×10^9 m^3, and it discharges into the Guamuéz River (Matabanchoy and López 1999). The lake receives 26 tributaries in a watershed of 225.9 km^2 which lies between 2780 and 3650 m.a.s.l. (Figs. 17.1 and 17.2). The average temperature near La Cocha Lake is ~11.6 C and has a mean annual precipitation between 1300 and 2000 mm (depending on the location), with most of it falling between April and August, and the lowest precipitation in December (González–Carranza et al. 2012). The lower temperatures, compared with other locations at similar elevations, are associated with the permanent flow of moist air masses coming from the Amazonian lowlands (González–Carranza et al. 2012 and references therein).

The Guamuéz River, an affluent of the Amazonian Putumayo River, evacuates the water surplus of the lake. The highest point on the road between Pasto and La Cocha

J.F. Duque-Trujillo (✉) · M. Hermelin · G.E. Toro
Grupo Geología Ambiental e Ingeniería Sísmica, Universidad EAFIT, Medellín, Colombia
e-mail: jduquetr@eafit.edu.co

M. Hermelin
e-mail: hermelin@eafit.edu.co

G.E. Toro
e-mail: gtoro@eafit.edu.co

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0_17

is, thus, the continental divide between the Amazonian Basin and the Pacific Ocean. Since 2000, the Guamuéz Lake belongs to the Ramsar Convention.

The village of El Encano is situated near the road from Pasto (Fig. 17.1). The name El Encano is an evolution of the original name El Incano, the Inca man. It is worth

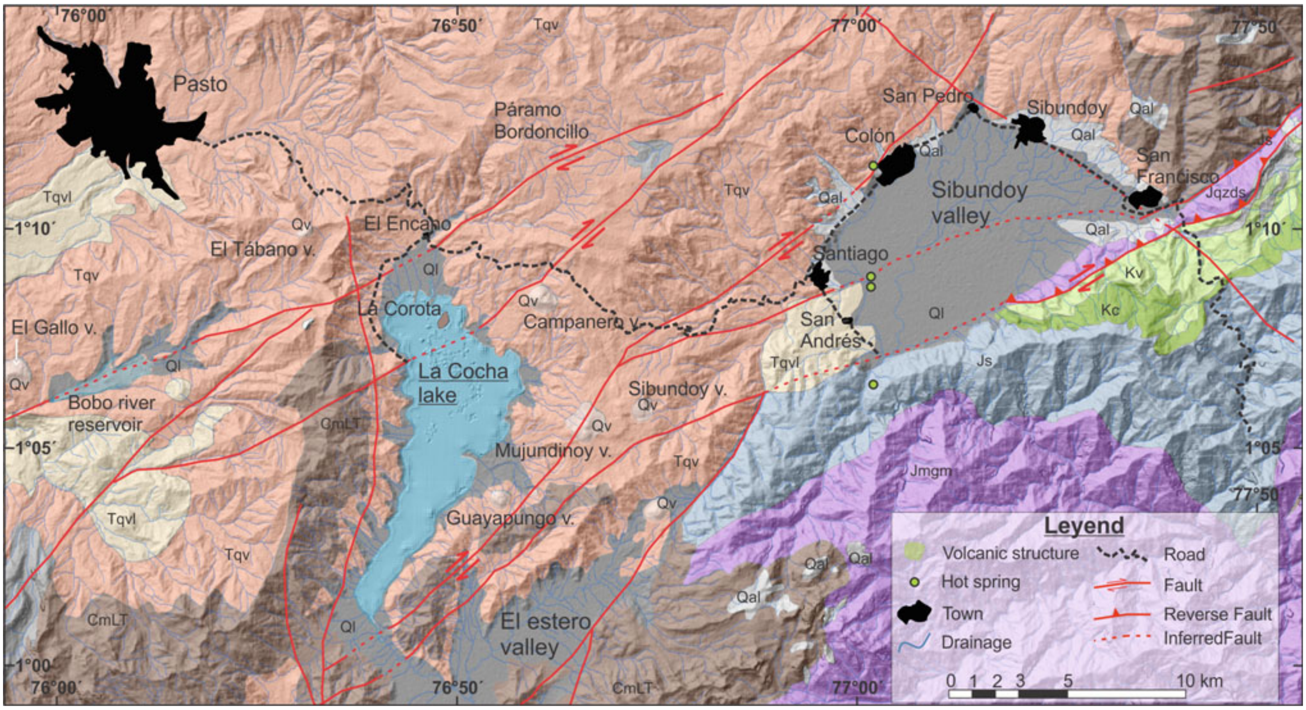


Fig. 17.1 Geologic map of La Cocha and Sibundoy valleys área. Showing the main tectonic and geographic features. The road from Pasto city to La Cocha and Sibundoy is also shown. Abbreviations: *CMLT* La Cocha—Rio Tellez Migmatitic Complex; *Jmgm* Mocoa Monzogranite; *Jqzds* Sombrerillos Quartz-monzonite; *Js* Saldaña Fm; *Kv* Villeta Fm.; *Kc* Caballos Fm.; *Tqv* Tertiary Quaternary volcanic deposits; *Tqvl* Tertiary Quaternary lavas; *Ql* Lagoonal deposits; *Qal* Aluvial deposits (Ingeominas 1991)

Fig. 17.2 La Cocha Lake from the north. La Corota Island is visible to the left. *Photography* Michel Hermelin

Fig. 17.3 La Corota Island wildlife sanctuary. *Photography* Michel Hermelin

remembering that the influence of the Inca Empire reached the region of Pasto shortly before the Spanish conquest. Some isolated houses are found around the lake. The island of La Corota (12 ha) is the site of a protected sanctuary for Fauna and Flora, recognized as such by the Ministry of the Environment. It is also considered a sacred place in the tradition of the Quillasingas Indians, who live in the surroundings. It also contains a catholic chapel where Our Lady of Lourdes is venerated by pilgrims coming every Sunday and also for an annual celebration in February (Figs. 17.1 and 17.3).

17.2 Historical Aspects

The lake was probably seen by Europeans for the first time around 1535, when Spanish soldiers coming from the recently submitted Peru went north under the leadership of Benalcazar. It was mentioned by Pedro Cieza de León in his chronicles as "the great lake of the Mocoas," where "the water is so cold that, though the lake is eight leagues long and more than four broad, no fish nor bird can live in it…" A comment which, as many of those made by chroniclers, proved to be completely erroneous.

Neither Humboldt nor Boussingault, who stopped at Pasto on their way to Quito at the beginning of nineteenth century, visited La Cocha Lake. The first modern descriptions come from the French traveler André (1876–1878), who left a vivid description of an exhausting 7-h trip from Pasto to the lake and from the German vulcanologist Stuebel (1906) (Fig. 17.4).

17.3 Vegetation

The lower strip of land surrounding the lake belongs to Holdridge's life zone of Lower Montane wet forest and the more external fringe to the Montane rain forest (Espinal 1977). Under present climatic conditions, the Andean forest reaches up to the ~3550 m a.s.l., above which the subpáramo and páramo vegetations are present. Deforestation for agriculture and grazing unfortunately has been very active during recent decades, causing erosion and other environmental damage.

The pollen record of La Cocha Lake shows important climatic and environmental changes during the Holocene (González–Carranza 2012; Flantua et al. 2014). During the Last Glacial Maximum (LGM), permanent snow covered more than 20 % (~24 km^2) of the highest lands around La Cocha, the páramo covered around 47 % and the Andean forest were relegated to the lower lands which represented less than 20 % of the area (Flantua et al. 2014). After the LGM (21,000 year BP) the temperature raised, leading to the melting of the permanent snow and forcing the vegetation to migrate upwards, exceeding in some cases its migration capacity. Therefore, the páramo and subpáramo ecosystems disappeared for several short intervals of time (González–Carranza 2012), restricting nowadays the páramo vegetation

Fig. 17.4 La Cocha Lake (to the left) from Páramo de Bordoncillo (looking NW). On the central-right part is the Galeras volcano. Drawn by A. Stübel in 1876

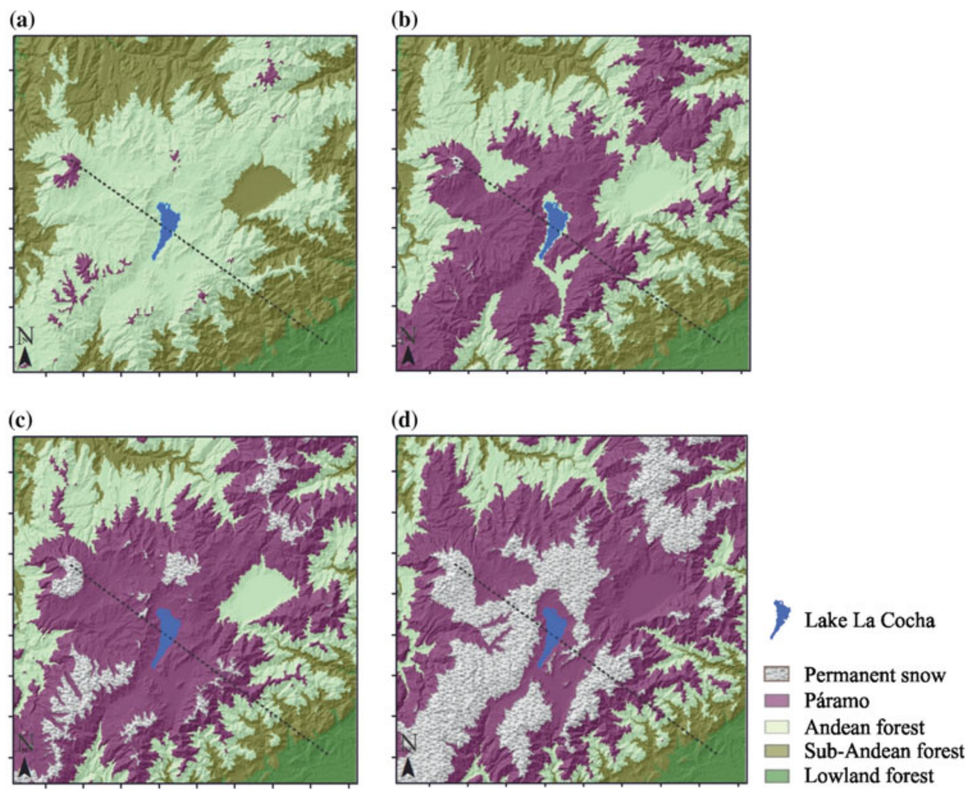


Fig. 17.5 Distribution of lowland forest, Sub-Andean forest, Andean forest, Páramo and permanent snow, during four different altitudinal positions of the Upper Forest Line (*UFL*) at **a** present-day conditions, **b** 8060-2860 cal year BP, **c** 14085-8060 cal year BP, **d** 21000 cal year BP. (Flantua et al. 2014) **a** UFL ~3500 m: Modern, **b** UFL ~2800 m:8060–2860 cal year BP, **c** UFL ~2400 m:14,085–8060 cal year BP, **d** UFL ~2000 m:21,000 cal year BP (LGM)

to the 3600–4200 m a.s.l. with a loss of 95 % of its surface, which corresponds up to 2 % of the area (Flantua et al. 2014). The area left by the páramo and subpáramo was gained by the Andean and Sub-Andean forest, which shifted from 2800 to 3600 m a.s.l., now representing the most widespread ecosystem around La Cocha lake with more than 60 % of the area (Fig. 17.5) (Flantua et al. 2014). The pollen record of La Cocha Lake also shows sudden and significant deforestation starting at 1405 BP (545 AD) evidenced by charcoal which is clearly related to the fire used in anthropogenic activities (González–Carranza 2012).

17.4 Geology

The geological basement of the La Cocha region is composed by the Precambrian La Cocha–Río Téllez Migmatitic Complex, consisting of gneisses, amphibolites, schists, and anatexis granitoids, where migmatitic structures and textures have developed. Along both margins of the lake, the La Cocha gneiss, a quartzofeldspathic gneiss of possible Paleozoic age crops out (Ingeominas 1991) (Fig. 17.1).

This metamorphic basement was covered by volcanic rocks produced by the intense volcanism which took place

Fig. 17.6 El Campanero volcanic cone, with slopes dissected with erosional ravines. The hill is approximately 255-m high. *Photography* Michel Hermelin

since Tertiary. La Cocha Lake is surrounded by several recent volcanoes (Fig. 17.1) which stand out over the landscape. These volcanic structures are evidence of the active tectonic setting of the area, as many are located over the trace of active faults. The main dormant volcanoes located around La Cocha include Bordoncillo to the north, Campanero to the northeast (Fig. 17.6), Motilón to the northwest, and Mujundinoy to the east.

The age of this volcanic coverage varies between Upper Miocene and present, and is mainly composed by massive, scoriaceous, or blocky lavas. Their composition is quartz–lati–andesitic, quartz andesitic, latiandesitic, andesitic, and dacitic of the calc–alkaline series (Ingeominas 1991). Nevertheless, near Santiago (inside Sibundoy Valley), some alkaline basaltic flows have been reported and associated with mantle derived magmas which reached the surface via deep regional structures (Rodriguez and González 2004). These volcanic structures seem to be very young, because these are deposited over the alluvial plain which fill the valley (Nuñez and Gómez 2003), and are only covered by a plinian fall deposit, indicating a very young Holocene age (Nuñez and Gómez 2003).

Recent deposits around La Cocha are mainly alluvial and terrace deposits which have covered most of the lake surroundings.

17.5 Tectonics

Southwestern Colombia is a very complex tectonic zone, because there, in the “knot of the Pastos” or Huaca Masif is where the Andes divide forming two different branches, Central and Eastern Cordilleras. In the sense of Hall and Wood (1985), the “knot of Pastos” is limited by two tectonic boundaries, the Guairapungo and Rio Mira boundaries (north and south, respectively). These two limits also constrain the Galeras-Cerro Negro volcanic segment.

The Guairapungo Boundary is one of the most striking tectonic boundaries from the Northern Andes, marked by the physiographic break where the Patia, Juanambu and Mocoa rivers cut through the Andes. This boundary is evidenced by NW–SE trending structures.

Nevertheless the regional importance of the Guariapungo boundary, the most evident structures along this area are the NE–SW striking structures, which bound the La Cocha Lake, and Sibundoy valleys by the east. Locally, these structures are known by the name of Algeciras fault system (AFS), a right-lateral wrench structure with vertical component (Velandia et al. 2005). This structure is part of the Afiladores-Cayambe-Sibundoy fault system (CASF) (Tibaldi et al. 2007), which constitutes the present boundary of the transpresive regime caused by the NE tectonic “escape” of

Fig. 17.7 The Sibundoy Valley with the town of Santiago. *Photography* Michel Hermelin

the northern Andes which begins at the Gulf of Guayaquil and continues to Colombia and Venezuela. In the southern Andes of Colombia, this tectonic transport is partitioned into a swarm of transcurrent, relatively slow slip rate faults and one structure with higher slip rate, the AFS. Velandia et al. (2005) identify a series of folds, faults, and pull-apart basins, formed along the AFS, and associated with its right-lateral displacement.

Along the Sibundoy-La Cocha sector (in the sense of Velandia et al. 2005), two main valleys are found, Sibundoy and La Cocha. Both have been interpreted as pull-apart basins formed along the AFS. La Cocha valley is interpreted by Ceballos and Pérez (1996) as a pull-apart basin, generated by the right-lateral stike-slip displacement of the subsidiary faults of the main AFS (Fig. 17.1). It has an inverted "L" shape, which evidences not only the influence of the NE–SW trending of the AFS, but also activity along the NW–SE structures in the northern part of the lake. These structures are poorly defined, and only mentioned as transverse basement faults (north from the described area) by Ingeominas (2001).

North-East of La Cocha valley, these structures are parallel to and runs along the Guairapungo Boundary, supporting the hypothesis that they are basement related structures. These structures not only represent the topographic limit between La Cocha and Sibundoy valleys (Fig. 17.1), they also seem to control the location of some recent volcanic cones in the northern part of the La Cocha lake, as the El Bordoncillo, El Campanero, and the Mujundinoy (located NE), which also lie over the trace of the AFS (Fig. 17.1).

Besides La Cocha, two other tectonic depressions are present in the area. The Sibundoy (Fig. 17.7) and El Estero valleys, which are located north and east of La Cocha, respectively. The first one constitutes the main tectonic depression in this area, and has a rhomboid-shaped pull-apart basin with a 100 km^2 area and a length of 18 km. Meanwhile, El Estero has an elongated (NE trending), 20-km long shape. Both seem to have formed as pull-apart basins developed by relay step-over inside the right-lateral AFS (Velandia et al. 2005). Neotectonic activity along this fault system is suggested by the well-preserved structures and recent volcanic structures aligned along the fault trace; furthermore, Tibaldi and Romero (2000) calculate a cumulative displacement rate of $\sim 9.4 \pm 3$ mm/year during Holocene for this structure. The recent activity of the fault is proved by the 1834 earthquake, located within the Sibundoy area, which completely destroyed the surrounding houses. This event had a magnitude of Ms > 7 and a Modified Mercalli Intensity of XI (Ingeominas 1999).

Several geothermal water sources are located near La Cocha Lake, and also indicate the high tectonic activity of the AFS. All those features are located within the Sibundoy valley, near Santiago, Colón and Sibundoy towns (Fig. 17.1).

Fig. 17.8 Hummocky field. Volcanic rock mounds left by a flank eruption, near the village of San Andrés, Sibundoy valley. *Photography* Michel Hermelin

17.6 The Indigenous Legend

Before the La Cocha Lake existed, an Indian chief called Pucara (Fortitude) lived there with his wife Tamia (Star Rain) and their three children (Bright Star, Star, and Wind). The valley was the site of seven important cities. But during a festivity, in honor to the God Sun, Tamia fell in love with Munami, the main dancer and ran away with him. Pucara went with his sons to a mountain and started breeding insects. Tamia and Munami became an object of scandal for the inhabitants of the seven cities, who refused to give them food. One day, they went door-to-door asking for water, and they finally convinced a boy to give them a jar of water. Then they rested nearby and Munami inadvertently kicked the jar, which became a fountain. In this particular moment, a "tábano," one of the insects which Pucara breeded, bite Munami, turning him into a water fountain which flooded the entire valley, along with the seven cities. At the end, a bell sound, coming from the Cerro Campanero (The Bell Tower Mount) was heard all along the valley. The legend tells that Pucara was petrified forever in the mountain called "El Tábano," and sometimes, when he remembers the history, he sadly cries his misfortune and his tears raise the level of La Cocha Lake. This legend apparently contains both Indian and Spanish traditions.

17.7 The Sibundoy Valley

A 40-min drive leads to the Sibundoy "Valley," which is really an old lake filled with sediments at an altitude of about 2000 m a.s.l., located eastward from La Cocha (Fig. 17.7). Several towns have been built in this area, including Santiago, Colón, Sibundoy, San Francisco, and San Andrés. The divide is also the geographical limit between the Departments of Nariño (Pasto) and Putumayo (Mocoa).

Sibundoy was a swampy place until the middle of the twentieth century, when it was drained. It is now used for agriculture and intensive cattle raising. It is crossed by the road that leads to the Amazonian region through Mocoa. West of this city, an oil field discovered in the 1960's is still in operation. A pipeline has been constructed to carry oil to the harbor of Tumaco, in the Pacific coast.

In the vicinity of the village of San Andrés (Fig. 17.1), a volcanic activity form an interesting geomorphic site, where the main feature is a hummocky terrain, formed by several small mounts (up to 10–15 m high) resulted from a volcanic debris avalanche, apparently produced by a flank eruption (Figs. 17.8 and 17.9). Explosion breccias and volcanic bombs of different sizes could be also found all around the area west of San Andres. This volcanic event has not been dated, but it seems to be very young. Ramirez (1975) in

Fig. 17.9 Volcanic rock mounds (Hummocky field) left by a flank eruption, near the village of San Andrés, Sibundoy valley. The foreground hills constitute the south-western flank of the Sibundoy valley formed by the action of the Algeciras Fault System (AFS). *Photography* Michel Hermelin

Nuñez and Gómez (2003) mentions a violent earthquake on January 20 of 1834, and report that a volcano near Santiago de Sibundoy "blew-out at 6:00 am" covering the landscape with "rocks and sand." This report could correspond with the last eruption of the Sibundoy volcano.

References

André EF (1876–1878) La América Equinoccial, in Colombia en Le Tour de Monde. In: Navas P (ed) Villegas Editores, Bogotá, pp 189–198

Ceballos J, Pérez S (1996) Rasgos geomorfológicos de la vertiente oriental andina y del piedemonte amazónico de Colombia, 7 Congreso Colombiano de Geología, Memória

Espinal LS (1977) Zonas de vida o formaciones vegetales de Colombia. Mapa geológico. Memoria explicativa. Bogotá. Instituto Geográfico Agustín Codazzi (IGAC)

Flantua S, Hoogimstra H, Van Boxel J, Cabrera M, González-Carranza, González-Arango C (2014) Connectivity dynamics since the last glacial Maximun in the northeasthern Andes: a pollen-driven framework to assess potential migration. In: Stevens WD, Montiel OM, Raven PH (eds) Paleobotany and Biogeography: A Festschrift for Alan Graham in His 80th Year, Chapter: 6, Publisher: Missouri Botanical Garden Press, St. Louis

González–Carranza Z, Hooghiemstra H, Velez MI (2012) Major altitudinal shifts in Andean vegetation on the Amazonian flank show temporary loss of biota in the Holocene. The Holocene 22 (11):1227–1241

Hall M, Wood C (1985) Volcano-tectonic segmentation of the northern Andes. Geology 13:203–207

INGEOMINAS (1991) Geología de la Plancha 429, Pasto (A Murcia, H. Cepeda)

INGEOMINAS (1999) Mapa de grandes sismos en Colombia 1566–1999. Escala 1:2'000.000. Santafé de Bogotá

INGEOMINAS (2001) Mapa Geológico del Departamento del Huila (F., Velandia, A. Nuñez and G. Marquinez), scale 1:300000. Bogotá. 151 p

Matabanchoy JC, López OD (1999) Pasto entre la sed y el agua. Asociación para el Desarrollo Campesino, Medellín, Colombia

Núñez A, Gómez J (2003) Geología del Departamento del Putumayo. Ingeominas 241 p. Bogotá

Rodríguez G, González H (2004) Caracterización geoquímica y marco tectónico de los basaltos alcalinos del sur de Colombia. Boletín de Ciencias de la Tierra, v. 16, p 9–22

Stuebel A (1906) Die Vulkanberge von Colombia. Dresden, W. Baensch

Tibaldi A, Rovida A, Corazzato C (2007) Late Quaternary kinematics, slip-rat and segmentation of a major Cordillera-parallel transcurrent fault: the Cayambe-Afiladores-Sibundoy system, NW South America. J Struct Geol 29:664–680

Tibaldi A, Romero L (2000) Morphometry of late Plehistocene-Holocene faulting and volcanotectonic relationship in the southern Andes of Colombia. Tectonics 19(2):358–377

Velandia F, Acosta J, Terraza R, Villegas H (2005) The current tectonic motion of the Northern Andes along the Algeciras Fault System in SW Colombia. Tectonophysics 399:313–329

Index

M. Hermelin (ed.), *Landscapes and Landforms of Colombia*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-11800-0