World Soils Book Series

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The Soils of Mexico

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Preface

Soils have played an important role in the history of the ancient civilizations that thrived in Mexico. Today as population and pollution pressures mount, it is even more critical to understand soil characteristics, properties, and their distribution so that informed decisions can be made about the soil resource. The purpose of this book is to provide specialists with the most current information about the soils of Mexico. In the past most of Mexico's efforts in soils have centered on management from an agricultural perspective. While this perspective is very important, an understanding of the soil resource is vital to successful building endeavors, erosion and flood control, combating ground water contamination and a host of other management, and ecological concerns. The authors of this volume represent academic scientists with an experience in soil survey and soil surveyors with a strong interest in scientific research. We represent three different soil science schools, that of Mexico, the USA, and Russia. We hope that the combination of our approaches allowed making the picture of the soils of Mexico more complete. This small review by no means claims to be a complete description of the soils of Mexico. It is just an essay on the state-of-the art of the existing knowledge on the subject and represents the work of many research efforts and data form published and unpublished sources.

This book is divided into seven chapters. The first provides an introduction and broad perspective of the subject. The second covers the history of soil mapping and research in Mexico. The third chapter focuses on the factors of soil formation in Mexico and describes the complicated geology and climate of the region and helps to explain the diversity of the soils of Mexico. The fourth chapter discusses classification of the soils and uses the most common systems used in the world. The chapter on soil geography breaks the country into logical sections in order to discuss the geography of soils. This chapter represents one of the first attempts to compile all the information on soil distribution in Mexico. Chapter 6 discusses soil degradation in Mexico, and the final chapter focuses on past civilizations and the soil resource.

The authors are indebted to all soil scientists who have labored to bring an understanding of the soil resources in Mexico.

Contents

1 Introduction

1.1 The Beginning

It is difficult to say how the work on this book started. There were several events that finally have led to the idea to write it. The first and the most important reason was the edition of the book "Soil Geography of Mexico" (Krasilnikov et al. 2011a, b). It showed that there is abundant information on the soils of the country, but an effort is needed to summarize this knowledge. The text on soil geography of Mexico was prepared by a joint effort of 33 authors, and it was intended to be a desk reference for soil scientists of the country. We should note that the book on Mexican soil geography is different from this manuscript for several reasons: the first was made as a collection of mostly scholar texts on soil geography accompanied by an extensive description of the soils of physiographic regions of Mexico. This part has something in common with the Chap. 5, but the extent and the structure of the text is different. A second impulse occurred during the field tour before the International Conference "Soil Geography: New Horizons" (Huatulco Santa Cruz, Oaxaca, Mexico, 16–20 of November 2009). This tour was organized by a joint effort of the National Autonomous University of Mexico (Universidad Nacional Autónoma de México—UNAM) and the National Institute for Statistics and Geography (Instituto Nacional de Estadistica y Geografía—INEGI). It was a unique scientific excursion that crossed about 2,500 km, driving through almost the whole territory of Mexico from the arid lands of the North to the humid tropics of the South. When we completed the tour, we all had the same feeling; "We should write about it." Chapter 4 includes several profiles from this memorable tour.

The last push occurred during the conference devoted to the centenary of the first agrogeological congress in Budapest. Professor Erika Micheli organized the meeting entitled "Bridging the Centuries: 1909–2009", where many outstanding pedologists assisted: it was difficult to miss the event that happens once in 100 years. Professor Alfred Hartenmink attended and was busy thinking about a new book series for Springer. He asked one of the authors of this manuscript for suggestions. The answer was almost knee-jerk—the soils of Mexico (the book on soil geography of the country was almost ready). Professor Hartenmink said, "Excellent, let us start a series of books devoted to the soils of particular countries!" The rest is history.

1.2 INEGI

This book would never appear without INEGI. Without INEGI we would never have all the data that allows characterizing the soils of Mexico. It is noteworthy that almost all the texts available on the web, technical reports and even many scientific publications about the soils of the country as a whole and of particular regions and districts are based on the primary information provided by INEGI. It is incredible that all the soil maps of the country at a scale of 1:250,000 and some at a scale of 1:50,000 have been made by the staff of the Soil Science Department—only 28 persons. The history of making soil maps of Mexico is discussed in detail in the next chapter. Apart from the soil mapping, INEGI was responsible for all the topographic and thematic maps of the country (www.inegi.org.mx).

During the last decade the Soil Science Department of INEGI actively collaborated with the universities all over the country, especially with the UNAM. The latest common initiatives included the organization of the field tour across the country (Sojo-Aldape et al. 2009) and the publication of the book on soil geography of Mexico (Krasilnikov et al. 2011a, b).

The route of the tour in 2009 was planned by a joint organizing committee of the UNAM and INEGI; the latter organization was responsible for preparation of the profiles, their morphological description, sample collection and the major part of the soil chemical analyses. Only some specific properties of the soils were determined in the laboratory of

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Pedology “Nicolás Aguilera” of the Faculty of Sciences of the UNAM, such as the extraction of different forms of iron. Also the laboratory was responsible for X-ray study of the mineralogy of clay fraction of the soil. The micromorphological description and microphotographs were provided by Dr. S. Sedov of the Institute of Geology of the UNAM. An important role of INEGI also included the publication of the field guide (Sojo-Aldape et al. 2009). The tour started in Torreon, Coahuila State, crossed the Sierra Madre Oriental range, then south along the coast of the Gulf of Mexico, and crossed the country in its narrowest place at the Tehuantepec Isthmus. The tour covered five physiographical provinces (Upland and Valleys of the North, Sierra Madre Oriental, Northern and Southern Coastal Plains of the Gulf of Mexico, and Sierra Madre del Sur), numerous geological formations, climates ranging from very dry to extremely humid and from temperate to hot tropical, at least ten different vegetation types, and diverse soil groups.

An important contribution of INEGI to the scientific soil literature in Mexico was its participation of the book on soil geography of the country (Krasilnikov et al. 2011a). The chapter on soil mapping was written by the specialists of INEGI (Guerrero-Eufracio and Cruz-Gaistardo 2011), and all the chapters on soil regions were authored or co-authored by the engineers of INEGI. Initially the editors were slightly anxious about the result, because the experts from INEGI were not accustomed to scientific-style writing. However, the result was encouraging. We hope that this experience will encourage these excellent specialists to share their knowledge with others in the future.

1.3 General Regularities of Spatial Distribution of the Soils of Mexico

Initially we wanted to compose this book as a traditional research monograph—or as a detective story that usually has the same structure. We planned to give a picture of the most abundant soils of Mexico, describe their spatial distribution, and then discuss and finally present our conclusions about the rules that determine the peculiarity of the soils of Mexico. But then we thought that it unrealistic to expect somebody to read this book completely, from beginning to end. Very few people have the time or enthusiasm to finish a thick scientific book. Rather people start reading and then jump from the Introduction to the chapter or even section of most interest. Thus, we decided to start with the conclusions, though it put us in the awkward position of a detective author who conveys the killer’s identity too early. We believe that the result of our observations would provide a frame for better understanding all the material presented in this book.

The abundance and distribution of soils in the territory of Mexico is regulated by many factors and pedogeographic laws. The first block of laws is related to the distribution of climates in the country. The direct influence of actual climate is a driving force for the formation of the majority of the Earth’s soils, though polygenetic history should be also taken into account (Bridges and Davidson 1982). The soils that reflect mainly actual bioclimatic conditions are called “zonal soils” (Glinka 1935). The concept of these soils grows from the seminal works of Dokuchaev (1967, with an original text published in 1899), who postulated that the soils follow the climatic shifts from north to south and from the top of the mountain to the piedmont. Though now we know that a regular latitudinal sequence exists in few places besides the Russian Plain. However, the geographical correspondence between the climate and the soils exists in a broad sense (Arnold 1994). A number of pedogeographic laws exist that characterize the particular soil sequences that follow the climatic gradients. There are gradients of humidity, and temperatures, or both of these parameters. Their combination is complex. For example, in arid climates the temperature gradients commonly do not result in differences in the soils. The relief strongly affects the circulation of air and thus the climates; vertical soil zonality is a classical example. The distribution of climates is commonly complex in the mountains depending on the aspect, altitude, and the prevalent winds (Krasilnikov et al. 2011a).

The most important climatic gradients in Mexico are those related to humidity. There is no use in searching for regular latitudinal zones in this country. The Peninsula of Baja California is stretched in the latitudinal direction, but it is too arid to show any gradient in soil properties, and the situation is complicated by the mountainous topography of the peninsula. The coastal plain of the Gulf of Mexico is long and flat, but the humidity gradient from the sea to the inner areas is stronger than the latitudinal temperature gradient. A latitudinal gradient of humidity exists in the central northern part of Mexico, in the Lowlands and Uplands of the North and in the Central Mesa areas, where the amount of precipitation increases from north to south. The gradients of temperatures and precipitation are much more pronounced in the mountains. At a national scale, the mountainous systems of Mexico all have humid slopes oriented to the sea and arid slopes oriented to the central part of the country due to the rain shadow effect. The distribution of climates on the humid slopes is also complex. The humid air coming from the sea heats over the hot land, and its relative humidity decreases, thus the lowest part of the mountains is dry. The moisture commonly falls as rain at higher elevations, where the air cools. The peculiarities of air circulation in the mountains determine a wide range of vertical sequences of climates, ecosystems, and corresponding soils. Krasilnikov et al. 2011b studied the geographical distribution of soils in Sierra Madre del Sur and found that several laws rule the distribution of soils there. The main factor separating the arid and humid pedogenesis was the rain shadow effect. The vertical zonality was more expressed on the humid slopes oriented towards the sea. Other factors complicate the vertical zonality of soils: if the coastal mountainous chain is low, the extension of each belt might be reduced, or some belts might be absent. The contraction of altitudinal belts in coastal lower mountains is called a biogeography 'Massenerhebung', or 'telescopic' effect (Grubb 1971). The complete reduction of a vertical zone of subdeciduous tropical forests between dry tropical deciduous forest and temperate pine-oak forests resembles the situation described by early workers in Caucases (Zaharov 1914) called "interference of altitudinal zones"—the absence of theoretically predicted zones due to abrupt gradient of climatic factors. In places drier belts are found over humid ones due to the peculiarity of humidity distribution in the mountains; this regularity was described as "inversion of altitudinal zones" (Zaharov 1914). The temperatures decrease regularly with the altitude, but the precipitation has a more complex distribution.

In the dry inland areas the bioclimatic regularities may be expressed shortly as follows. The valleys and plains are dry, and the slopes of the mountains are more humid and covered with arboreal vegetation. However, this general rule may be modified by the scale (many low hills are, on the contrary, completely free of vegetation and even soil) and by local conditions.

Even after taking into account the complex distribution of climates in Mexico due to the complex topography of the country, it is still difficult to predict the exact distribution of soils. The majority of Mexican soils cannot be called "zonal", which means that apart from the actual climate other factors are of major importance. Early studies called these soils intrazonal and zonal (Glinka 1935), which meant that they are somewhat unusual for bioclimatic conditions of a given zone. The concept of "intrazonal" soils says that these soils form under the influence of specific parent material or excessive water supply, or saline water. As a result, these soils have more in common among them when formed under different climatic conditions than between them and "zonal soils". For example, peat soils are similar under a wide range of climates, and have completely different morphology and properties than the mineral soils of the same area. Similar but less pronounced situations are observed for soils formed in pyroclastic sediments, limestone, gypsum, saline environments and for mineral soils affected by excessive moisture. For Mexico specific parent material is of special importance, because extensive areas have limestone and similar calcium carbonate sediments, and volcanic ashes. The presence of these deposits strongly affects the pedogeographical situation in the country. The hydromorphous soils are of minor importance, though in the Southern Coastal Plain of the Gulf of Mexico there are extensive areas of soils affected by excessive moisture, including tropical peatlands. In arid and semiarid condition in endorheic catchments there are saline soils that formed mainly in areas of dried lakes.

The concept of "azonal" soils includes shallow, mostly "young" soils with poor horizon development. The majority of such soils are found in the areas with low pedogenetic potential, for example in deserts. However, some poorly developed soils form under any bioclimatic conditions due to the dynamic nature of the landscape. According to Birkeland (1999), the rate of pedogenesis depends on the rate of erosion or, in contrary, of sediment accumulation. The soils of the stable areas develop in a normal way, but any loss or addition decreases the rate of soil formation. In the case of very intensive loss or additions of sediments the soils stay "forever young", because they do not have the required time for development. Typical examples of "azonal" soils are sand dunes, eroded soils, marsh soils and the soils of flood plains with intensive sedimentation of alluvium.

Complex topography determines broad development of erosional processes in Mexico. Moreover, the intensity of slope processes is intensified by the tectonic uplift of the territory (Krasilnikov et al. 2011b). The origin of the sediments of the valleys in the dry inner areas of the country is mostly alluvial and lacustrine. Though these sediments might be ancient, the surficial layer is commonly made of recent deposits. In dry valleys wind erosion and aeolian accumulations are also of major importance. Thus, Mexico is characterized by wide and continuous refreshments of sediments that results in the abundance of underdeveloped soils in the country. In a more poetic way one can say that the Mexican territory is an eternal battlefield between pedogenesis and sediment transport, and that in most cases the pedogenesis loses the battle.

In Mexico not less than a half of the total area has "intrazonal" and "azonal" soils. It should be taken into account for any land use planning; otherwise serious errors may rise from unjustified extrapolation. Actually spatial modeling including predictive soil mapping is a big new business in soil science (McBratney et al. 2000, 2003), and is based on the old concept of soils corresponding to the soil-forming factors (Hudson 1992), but based on a quantitative mathematical background. It is important to note that in dynamic landscapes this correspondence is very complex, and special geomorphological models should be included in the spatial prediction of soil distribution.

The other feature of the Mexican soils that complicates the situation is the presence of numerous paleosols. As it is widely recognized now, the majority of the world soils are the products of more than one cycle of pedogenesis

(Bronger and Cutt 1989). The evolving environment results in changes in the conditions of pedogenesis. In stable landscapes the same soil profile records the changes in the environment, thus resulting in a polygenetic soil. In the dynamic landscapes the periods of relative stability alternate with the periods of intensive erosion, transport and sedimentation, thus resulting in the formation of buried paleosols. Evidently, in the territory of Mexico the second option is important. Many Mexican soilscapes have buried and exhumed paleosols. This issue is discussed in a special invited chapter of this book, written by excellent specialists in this area, Dr. Elizabeth Solleiro-Rebolledo and Dr. Sergey Sedov from the Institute of Geology of the UNAM.

As one could see from the information listed above, the distribution of soils in Mexico is extremely complex. We are still very far from understanding completely the rules that govern the spatial structure of soils in Mexico. We are often surprised by the unexpected soils we meet. Some soil profiles are so unusual that we can hardly explain the genesis. Much more research is needed in Mexico to have a complete picture of the country's soils.

Acknowledgments There are four authors in this book. However, we cannot say that the whole job has been done only by ourselves. Many people participated at various stages of this work. These are persons who participated in the field work, conducted chemical analyses, helped to interpret the results, assisted in preparing the figures, provided important references and photos, gave valuable comments on the text and supported us at all the stages of the work in any manner. We apologize that we cannot name all the persons who helped us, because there are too many. Just a few names that cannot be forgotten: Norma Eugenia García-Calderón, Abel Ibáñez-Huerta, Elizabeth Fuentes-Romero and Teresa Reyna-Trujillo from the UNAM. Carlos Alberto Ortíz-Solorio, Patricio Sánchez-Guzmán from the Postgraduate College, and Edgar Vladimir Gutiérrez-Castorena from the Metropolitan University of Mexico, Francisco Javier Jiménez-Nava, Arturo Victoria-Hernández, Eliseo Guerrero-Eufracio and deceased Francisco Takaki–Takaki from INEGI. We should also thank our institutions and the financing bodies, such as the National Council for Science and Technology (CONACyT) and the UNAM Program for the Support of the Research and Innovation Projects (PAPIIT) that provided resources for most of the field and laboratory research in Mexico. We are also grateful to our relatives for their patience that permitted completing this work.

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Soil Research and Soil Mapping History

2

2.1 Traditional Soil Knowledge in Mexico

Traditional folk soil knowledge has a long history in Mexico. Archeological research showed that Pre-Hispanic cultures such as the Aztec, Purepechas, Otomies, and Maya civilizations had a developed system of soil classification. Tovar (1986) reported that the cultures in the southeast of the Republic, such as the Olmec and the Maya, had developed practices of fertilization, irrigation, and drainage systems, including a soil classification, which to date are still being used. The Toltecs and Aztecs had a whole nomenclature to describe the physical and chemical characteristics of soils. Other cultures, such as the Zapotec in Oaxaca and Acolhua in Texcoco, used soil conservation practices through the construction of terraces, and the remains are still possible to see at Monte Alban and the Cerro de Tezcutzingo, respectively. Acolman people, Chalco and Xochimilco, among others, developed the systems of irrigation through the construction and use of artificial islands made of lacustrine mud—chinampas (Laird 1989).

The best documented soil and land classification systems that existed and are still partly preserved among indigenous population of the country have been developed by the Aztecs and Mayas. In the Aztec culture, it was common to show in a single document both land ownership relations and soil productivity and properties. Codices of Santa Maria Asunción and the Vergara have been studied thoroughly by Barbara J. Williams since the early 1970s to date (Williams and Jorge y Jorge 2008). These codices showed the plots of the family leaders, and each plot had in its central part a glyph indicating the type of soil; around 132 glyphs were used, built from 14 graphemes, including elements such as stone, points, backpack, thorn hill, eyes, teeth, manure, maiz, water, and so on (Williams 1976) (Fig. 2.1). The Maya civilization left an extensive land classification based on landscape position and soil properties (Bautista-Zuñiga and Zinc 2010).

Fortunately, the indigenous soil knowledge is relatively well-preserved in Mexico (Ortiz-Solorio et al. 1999), and the country is the world leader in ethnopedological research (Barrera-Bassols and Zink 2000). The very term "ethnopedology" was introduced into the scientific literature in a seminal paper from Mexico (Williams and Ortiz-Solorio 1981). In North America, most folk taxonomic research appear in Mexico, which take the first place in ethnopedological studies in the world. More than 70 publications on folk soil classifications and management practices were published on Mexican material, apart from numerous theses of students of various levels. The abundance of ethnopedological research in Mexico is due to high ethnic and linguistic diversity, relatively well-preserved system of ownership and management practices from pre-Hispanic epoch, and to the existence of several research groups of specialists working in ethnopedology in this country.

The local soil knowledge is studied in Mexico not only as a cultural heritage, but also as an important source of pedological information that may be used for complimenting scientific soil surveys (Williams and Ortiz-Solorio 1981; Ortiz-Solorio et al. 2001; Krasilnikov and Tabor 2003). In more detail, these issues are discussed in the Chap.7 of this book.

2.2 Early Soil Research

Several historical reviews on soil science in Mexico exist, as those published by Laird (1989), Ortiz-Solorio (1993), and Núñez-Escobar (2000). These reviews were based mainly on the books "Biografias de Agronómos y Episodios de la vida de la escuela nacional de agricultura" written by Marte Rodolfo Gómez-Segura (1976a, b). Relevant

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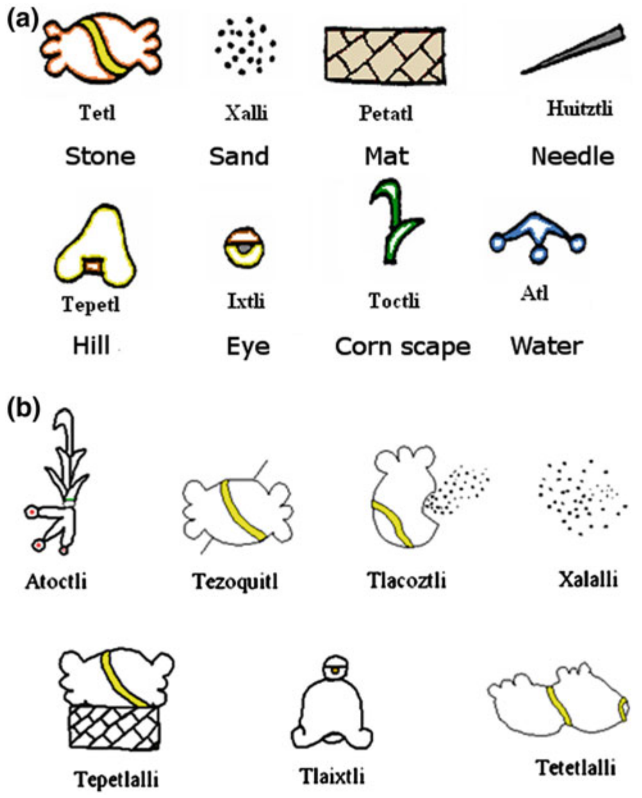


Fig. 2.1 Graphical elements of the glyphs (**a**) and the composite glyphs (**b**) used for soil denomination among Aztecs (glyphs translation after Williams 1976)

Fig. 2.2 Marte Rodolfo Gómez-Segura (1896–1973), the Director of ENA in the epoch of its passage to Chapingo, later the Minister of Agriculture and the Governor of The Tamaulipas State (Gómez-Segura 1976b)

information on the development and evolution of soil studies in Mexico can be found in occasional publications in the Agrociencia and Terra Latinoamericana journals and proceedings of the meetings of the Mexican Society of Soil Science. The historical research of the development of pedology in Mexico was also done with a focus on soil genesis (Gutiérrez-Castorena and Gómez-Diaz 2000) and soil classification (Ortiz-Solorio and Gutiérrez-Castorena 2000). Recently, Palacios-Rangel and Leos-Rodríguez (2011) published a review of the board of the Mexican Society of Soil Science.

The scientific research in the area of agronomy and soil science started its development in the late nineteenth century, when the agronomists extended their interest to the study of chemistry and the geology of soil substrates. One of those was Andres Basurto-Larrainzar who gave the course of agricultural chemistry and was the head of mineralogy section. He wrote a treatise on agriculture that mentioned the importance of physical, chemical, and biological properties of soils, as well as their classification and fertility (Basurto-Larrainzar 1926). The other predecessor of soil science was Alejandro Brambila, who enthusiastically promoted the use of fertilizers since 1892 (Gómez-Segura 1976a). The research activities concentrated mainly in the National School of Agriculture (ENA–Escuela Nacional de Agricultura). The ENA, founded in 1853 in San Jacinto Mexico, D.F, prepared mainly agricultural administrators (*Administradores instruidos* and *Mayordomos inteligentes*) for big land ownerships (*haciendas*). During the early years of the ENA, especially during the government of Porfirio Díaz (1876–1911), the major influence came from France (Cotter and Osborne 1996); one of the most distinguished professors of that period León Fourton taught soils with a focus mainly on agricultural chemistry (Rodríguez-Adame 1984). The first agricultural experimental stations appeared in the country in 1910, and some attention was devoted to soils there.

Fig. 2.3 Charles F. Shaw and Stanley W. Cosby from the University of California at Berkeley, during their travel to the Laguna Salada basin, with Mexican colleagues (the photograph is the courtesy of William Reed; the original provided by Stanley W. Cosby Jr.)

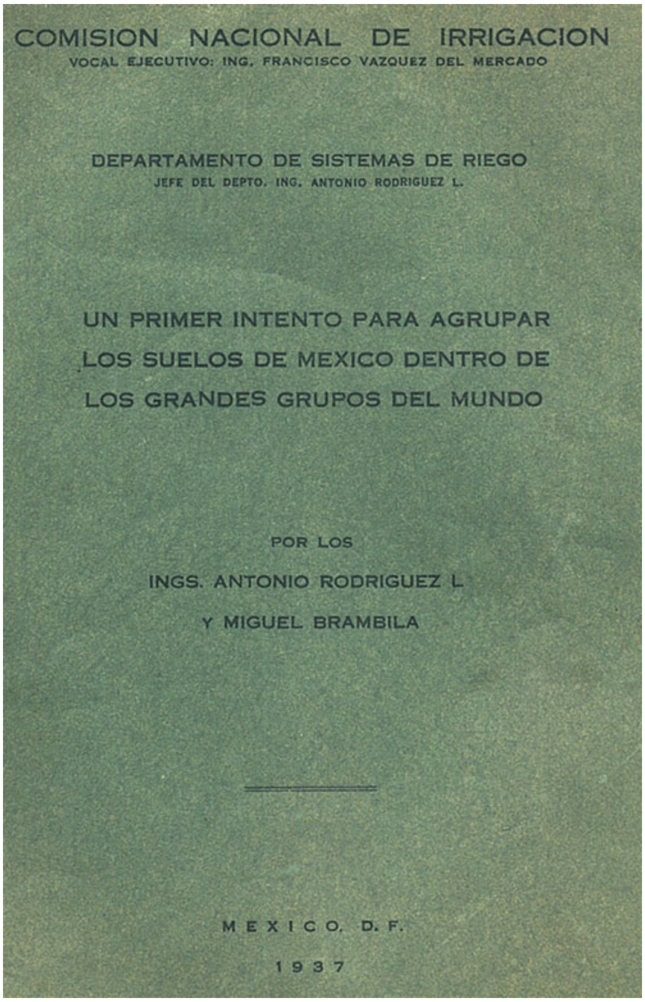
The development of soil research stagnated in the beginning of the twentieth century due to revolutionary events in the country. Only after the revolution did the development of agricultural sciences have a second wind. In 1919, the ENA opened the lines for agricultural engineering and mechanics. The Director of the ENA Marte R. Gómez-Segura (Fig. 2.2) reconstructed the school, and in 1923 invited Alfonso González-Gallardo, who was then recognized as one of the "fathers" of Mexican soil science for the development of agrology. The ENA moved in 1923 to Chapingo, in the State of Mexico, which soon became the center of soil research in the country. In 1929, Jesús Alarcón Moreno presented his bachelor thesis "The study of soils"; this scientist later became the Director of the ENA.

The first agrology college was inaugurated in Villa de Meoqui, Chihuahua, in 1928. One year before engineer Manuel Meza attended the first International Congress of Soil Science in Washington, and the ideas expressed there led him to propose the creation of Soils Specialty in Meoqui. In 1929, the first Mexican scientific meeting, known as "The First Agrological College", was held in Meoqui. This meeting is considered as the first formal activity in the field of soil science in Mexico (Ortiz-Solorio 1993; González 2006). During this Congress, the term *edaphology* was first mentioned, which was defined as the branch of soil science that dealt with soil as a part of nature. This term, as well as in Spain, was used in Mexico as a synonym of *pedology* in English-speaking countries; the meaning was somewhat different from French understanding that limited *edaphology* to the study of soil–plant interactions.

One of the consequences of the formation of the College was the establishment of the Mexican Society of Agrology to promote and disseminate knowledge of soils in Mexico. The first and the only board of this society consisted of Walter E. Packard of CNI (Chair) and Alejandro Brambila Jr. of the General Directorate for Agriculture (Secretary). The society had an ephemeral existence and disappeared soon after establishment.

Later, Manuel Meza together with the Ing. Norberto Aguirre-Palancares, Jesús Alarcón-Moreno, Ramón Fernández, and Escobar brothers presented to the Union Congress the project "Agricultural Education Act", which was approved in 1946 (Aguirre-Palancares 1984). As a result, researchers, technicians, and specialists were trained in order to implement in the field the results of the agricultural science. Therefore this law included education at the highest level, so they proposed the creation of a postgraduate college to award masters and doctoral degrees.

During the presidency of Plutarco Elías Calles the National Commission on Irrigation (CNI–Comisión Nacional de Irrigación) was founded, and the Law on Irrigation was passed in January of 1926. In the same year, the CNI invited American soil scientists to train the first agronomists on soil surveys required for the implementation of irrigation of lands. Recently discovered negatives and autochrome glass plates give glimpses into two early soil explorations



COMISION NACIONAL DE IRRIGACION
VOCAL EJECUTIVO: ING. FRANCISCO VAZQUEZ DEL MERCADO

DEPARTAMENTO DE SISTEMAS DE RIEGO
JEFE DEL DEPTO. ING. ANTONIO RODRIGUEZ L.

UN PRIMER INTENTO PARA AGRUPAR
LOS SUELOS DE MEXICO DENTRO DE
LOS GRANDES GRUPOS DEL MUNDO

POR LOS
INGS. ANTONIO RODRIGUEZ L.
Y MIGUEL BRAMBILA

MEXICO, D. F.
1937

Fig. 2.4 The seminal work of Rodríguez and Brambila (1937)

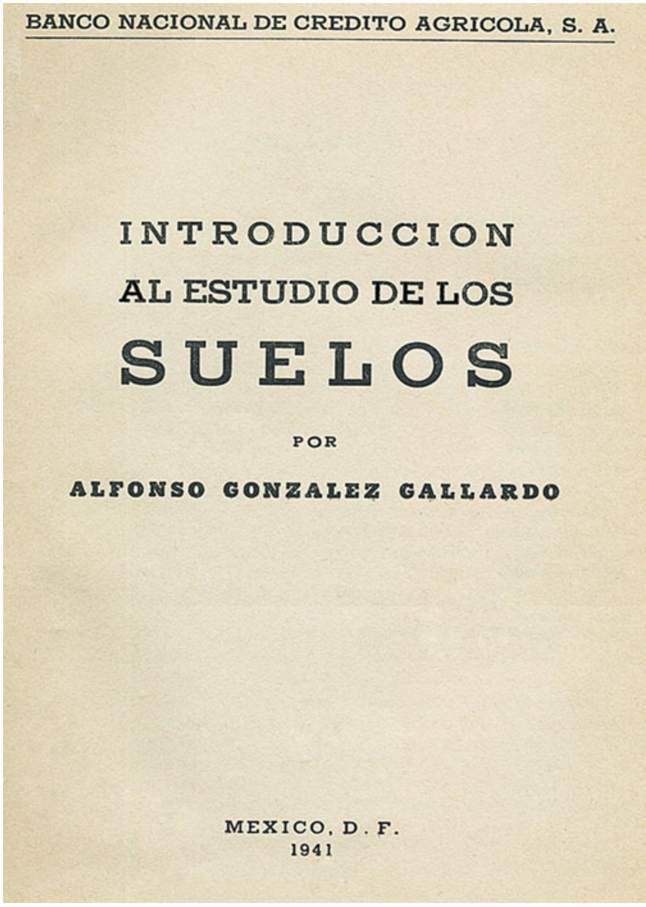
into the Laguna Salada basin in Baja California, Mexico (Reed 2009). Invited by the CNI, two soil science professors from the University of California at Berkeley, Charles F. Shaw and Stanley W. Cosby, traveled to the Laguna Salada basin to conduct preliminary investigations for the potential for irrigated agriculture and to provide soil survey training for Mexican soil scientists (Fig. 2.3). Walter W. Weir, Drainage Engineer at U.C. Berkeley, was also with the exploration party. As many as 25 people were working together from both nations. The other US specialists invited by the CNI were A. E. Kocher and W. E. Packard. As a result, the soil terminology and methodology in Mexico in that epoch were almost completely borrowed from the USA. The CNI also concentrated outstanding specialists in the area of soil management and irrigation. Since May of 1930 it published a monthly journal "Irrigation in Mexico".

In 1937, the CNI published a seminal book by Antonio Rodríguez and Miguel Brambila entitled "A first attempt to group the soils of Mexico into the World Great Groups" (Rodríguez and Brambila 1937). This book also included the first national small-scale soil map (Fig. 2.4). Also in 1937, the CNI published a translation of the Kellog's Manual of Agrological Studies, translated by Miguel Pérez Espinosa (Kellog 1937b).

The soil science of Mexico integrated gradually into the world scientific community. In 1939, Miguel Brambila published an international paper on the "tepetate" soils of Mexico (Brambila 1940).

The Rockefeller Foundation played an important role in the development of soil science in Mexico. Henry Wallace (Vice-President of the USA) promoted and obtained agreements for American scientists to collaborate with Mexican technicians in 1940 (Aguirre-Palancares 1984). In 1943, a collaborative agreement was signed between the Mexican Department of Agriculture (represented by Gómez-Segura, the Secretary of Agriculture and González-Gallardo, senior officer) and the Rockefeller Foundation. One of the most noteworthy impacts of the Rockefeller Foundation on the development of soil science in Mexico was through an academic exchange (González 2006). Approximately, 300 Mexican technicians obtained graduate-level degrees in the USA (Rodríguez-Adame 1984), and later returned to Mexico to conduct research programs (Ortiz-Solorio 1993; González 2006), mainly in crop production. As a result, the use of fertilizers was implemented and soil fertility developed significantly in Mexico (Ortiz-Solorio 1993). Roberto Núñez-Escobar (CP), Leonel Robles-Gutiérrez (ITESEM), Gildardo Carmona-Ruiz (UANL), Nicolás Sánchez-Durón (Oficina de Estudios Especiales), Martínez Medina (ESAAN), and Rodolfo Plinio Peregrina-Robles (Director del INIA) were some of them. Within the US scientists with expertize in soils were Williams Caldwell, Robert F. Chandler, John B. Pitner, and Reggie J. Laird (Rodríguez-Vallejo 1984); the latter stayed in Mexico and worked as a professor in soil science program in CP. Other researchers were Norman E. Borlaug and Edwin J. Wellhausen who remained in the CIMMYT (Hernández-Xolocotzi 1984).

In the beginning of the 1940s serious progress in pedology was achieved. Alfonso González-Gallardo, mentioned above, published a fundamental book "Introduction to the study of soils" (González-Gallardo 1941) (Fig. 2.5). In 1944, Donaciano Ojeda translated the seminal book of Konstantin Glinka "Great Groups of the Soils of the World and their Development" (Glinka 1944). In fact, this monograph appeared in Spanish in a reduced and modified form: initially, it was a



BANCO NACIONAL DE CREDITO AGRICOLA, S. A.

INTRODUCCION
AL ESTUDIO DE LOS
SUELOS

POR
ALFONSO GONZALEZ GALLARDO

MEXICO, D. F.
1941

Fig. 2.5 The first Mexican textbook in soil science by A. González-Gallardo

shortened translation from Russian into German by Herman Stremme of the original Glinka's textbook "Soil Science", followed by its translation from German into English by Curtis Marbut, and then from English into Spanish.

In 1946, the CNI was restructured and transformed into a federal-level department named the Secretary of Water Resources (Secretaría de Recursos Hydráulicos–SRH). As a consequence, reduction of experienced soil surveyors occurred during the period of 1947–1966, from 60 to 15 (Ortiz-Solorio 1993). In 1968, the Commission for the Study of National Territory (Comisión de Estudios del Territorio Nacional—CETENAL), was created under a collaborative project with FAO. The CETENAL, which transformed later into the General Directory of Geography (Dirección General de Geografía—DGG) of the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía—INEGI), was the first institution in Mexico that started a systematic study of the soils of the country.

2.3 The Development of National Soil Science Schools in Mexico

The ENA developed as a national center for preparation of human resources in the area of soil sciences. The line of soil science was opened at graduate and postgraduate levels in 1957 and 1959, respectively. In 1959, a Postgraduate College (Colegio de Postgraduados–CP) branched within the ENA; Soil Science department was also founded there. In 1974, the ENA was transformed into the Autonomous University of Chapingo (Universidad Autónoma de Chapingo–UACH) (Fig. 2.6). Until now it is the most important node for scientific research and human resources training in soil science disciplines. In 1979, CP was separated from the ENA to be an independent research body.

The UACH and CP published the most useable textbook on general soil science (Ortiz-Villanueva 1975a) that outstood seven editions (see Ortiz-Villanueva and Ortiz-Solorio 1990). The other important topics covered by the textbooks published in these institutions were soil chemistry (Gavande 1981), soil physics (Gavande 1972), soil fertility (Ortiz-Villanueva 1975b; Salgado-García and Núñez-Escobar 2010), soil conservation (Oropeza-Mota 2011), and fundamental pedology (Ortiz-Solorio et al. 1999). Also the most popular manual for field soil description was published (Cuanalo de la Cerda 1975). The pedological studies are concentrated mainly in the CP, and the researchers there are known for high-quality papers published in international journals (e.g. Gutiérrez Castorena et al. 2005, 2006, 2007; Etchevers et al. 2006; de León-González et al. 2007; Prado et al. 2007; Cruz-Cárdenas et al. 2010). The UACH was a driving force for the organization of the 15th World Congress of Soil Science in Acapulco, Mexico in 1994; Dr. Andrés Aguilar-Santelises of UACH acted as a president of the IUSS during the period of 1990–1994 and chaired the Congress.

The CP has seven campuses, which form important centers of agricultural research. Some of them play an important role in the inventory of soil recourses, for example, the Campus Tabasco in Lázaro Cárdenas, Tabasco (see Palma-López et al. 1985).

The other important center of soil research formed is the National Autonomous University of Mexico (Universidad Nacional Autónoma de México–UNAM). Nicolás Aguilera-Herrera (Fig. 2.7) was one of the grantees of the Rockfeller foundation; in 1951, he did postgraduate studies in Wisconsin University with Dr. Marion L. Jackson. Returning to Mexico, initially he worked in several institutions of the country, including the CP, where he organized the line of Soil Science. He started the course of soil science at the

Fig. 2.6 The building of the Autonomous University of Chapingo. It is and original photo made by Carmen Gutiérrez especially for this book

Faculty of Sciences of the UNAM in 1958, and in 1965 founded a Laboratory of Pedology there. Later, he also established a Department of Pedology in the Institute of Geology of the UNAM. Nicolás Aguilera-Herrera was one of co-founders of the Mexican Society of Soil Sciences (Sociedad Mexicana de las Ciencias del Suelo–SMCS) in 1962. He organized annual International Courses in Soil Science, currently the most important short-term educational course in pedology for students and specialists in the Spanish-speaking world and published a soil science textbook for graduate students (Aguilera-Herrera 1989). Actually, the pedologists of the UNAM actively publish papers in international journals (e.g. Solleiro-Rebolledo et al. 2003, 2006, 2007; Bocco et al. 2005; García-Calderón et al. 2005, 2006; Méndez-Linares et al. 2007; Peña-Ramírez et al. 2009).

Regional research developed in many states of Mexico. One of the most important centers of soil-related research in the tropical areas of the country is the College of the Southern Frontier (Colegio Frontera Sur), with five campuses in the states of Chiapas, Quintana Roo, Campeche, and Tabasco. Generally, this research center is focused on the issues of sustainable development, but also has strong research groups of pedologists (Mendoza-Vega et al. 2003; Mendoza-Vega

Fig. 2.7 Maestro Nicolás Aguilera-Herrera, the founder of soil science in the National Autonomous University of Mexico (portrait provided by N.E. García-Calderón)

and Messing 2005; Geissen et al. 2006, 2007, 2009). Important regional settings were described in an extensive monograph about the soils of the Yucatan (Bautista-Zuñiga and Palacio-Álvaro 2005). Some interesting publications were prepared by the researchers in Veracruz State together with Cuban colleagues (Hernández-Jiménez 1991; Ascanio-García and Hernández-Jiménez 2005).

Some recent research activities have been developed in Mexico in collaboration with the US and Canadian colleagues, mostly in the northern part of the country. The majority of these cooperative studies were related to the issues of soil fertility, remediation, and erosion (e.g. Martínez-Gamiño and Walthall 2000; Hudson 2003; Kuhn et al. 2003; Bravo-Garza and Bryan 2005), but several important pedological papers have been also published on the organic matter of volcanic soils (Drijber and Lowe 1990, 1991), the effect of lithology on soil genesis in arid regions (Graham and Franco-Vizcaino 1992), and the formation of calcium carbonate coatings on gravel in extreme arid areas of Baja California (Amundson et al. 1997).

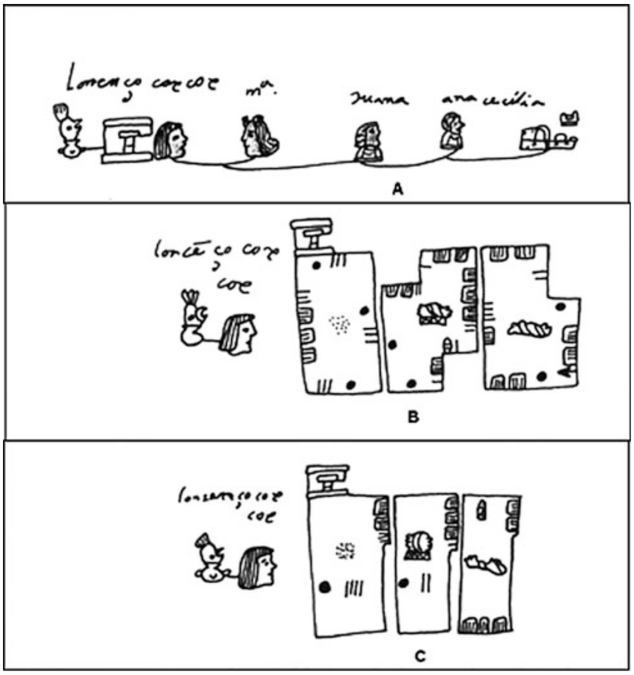


Fig. 2.8 An element of Códice Vergara with representation of the quality of each plot

The French scientific school of pedology also actively collaborated with Mexican researchers. The most interesting recent papers include the research of Dubroeucq et al. (1992b) of the dune soil complexes on the coast of the Mexican Gulf, the investigation of the genesis of volcanic soils (Dubroeucq et al. 1992a, 2002; Barois et al. 1998), and the study of the pedogenesis and mineralogy of soils in the Chihuahua desert (Ducloux et al. 1995). A large group headed by Christian Prat conducts a long-term study of the properties and remediation of volcanic soils with cemented layer (tepetate) (Servenay and Prat 2003; Prado et al. 2007).

Currently, many papers are published in international scientific journals by Mexican pedologists alone or together with the colleagues from abroad. However, still a significant part of soil research in Mexico is unavailable for

Fig. 2.9 The first map of the soil Great Groups of Mexico from the book by Rodríguez and Brambila (1937)

international readers: many data are published in "grey" literature or left unpublished in the form of the thesis of various levels. The situation is brightened by the presence of a national scientific journal with free full-text on-line access. The most important journal in the area of soil science was launched in 1983 by the SMCS under the name *Terra*. In 2004 it was renamed into *Terra Latinoamericana*. It is published quarterly in the UACH, Texcoco in Spanish with occasional papers in English. About one-fourth of the volume of the journal is dedicated to pedology and related issues. The other journal that publishes a limited number of papers on soil science is *Agrociencia*. Geological journals, such as *Revista Mexicana de Ciencias Geológicas* and *Boletín de la Sociedad Geológica Mexicana*, also sporadically publish papers on soil science, including special issues.

The Mexican Society of Soil Science (SMCS), founded in 1962, served as a strong organizing force for national soil studies (Palacios-Rangel 2011). Since its foundation, 34 annual and biennial meetings have been organized, and full papers or extended abstracts have been published in a book series « The pedological research in Mexico » . The SMSC has organized several internationals congresses, including VI and XVII Latin American Congresses of Soil Sciences and 15th World Congress of Soil Science in Acapulco (1994). The SMCS has four divisions, namely "Diagnostics,

Fig. 2.10 The soil map of Mexico, showing the distribution of “zonal”, “intrazonal”, and “azonal” soils

methodology and evaluation of soil resources”, “Relations between soils, climate and biota”, “Use of soil resources”, and “Education and technical support” (Palacios-Rangel 2011).

2.4 Soil Mapping in Mexico

According to Hernán Cortés, Mexican indigenous leaders had geographical maps drawn on different materials. These maps reproduced routes and specific areas. Some codices were very similar to cadastral maps; for example, the Codex Santa María Asunción and the Codex Vergara (Gibson 1978; Williams 1976; Williams and Harvey 1988). These codices prepared for Tepetlaoztoc and surrounding communities in the Valley of Mexico, consisted of three parts: one was the census of population housing and household head and the other two were representations of their plots (Fig. 2.8). The striking feature of these codices was that in the middle of each plot there was a glyph, which represented the class of land/soil. Although they were not formally soil maps, they possessed all the elements for soil mapping.

Since colonial times, with the exception of the Tepetlaoztoc Codices, until the completion of the Mexican Revolution, no soil maps of Mexico have been produced.

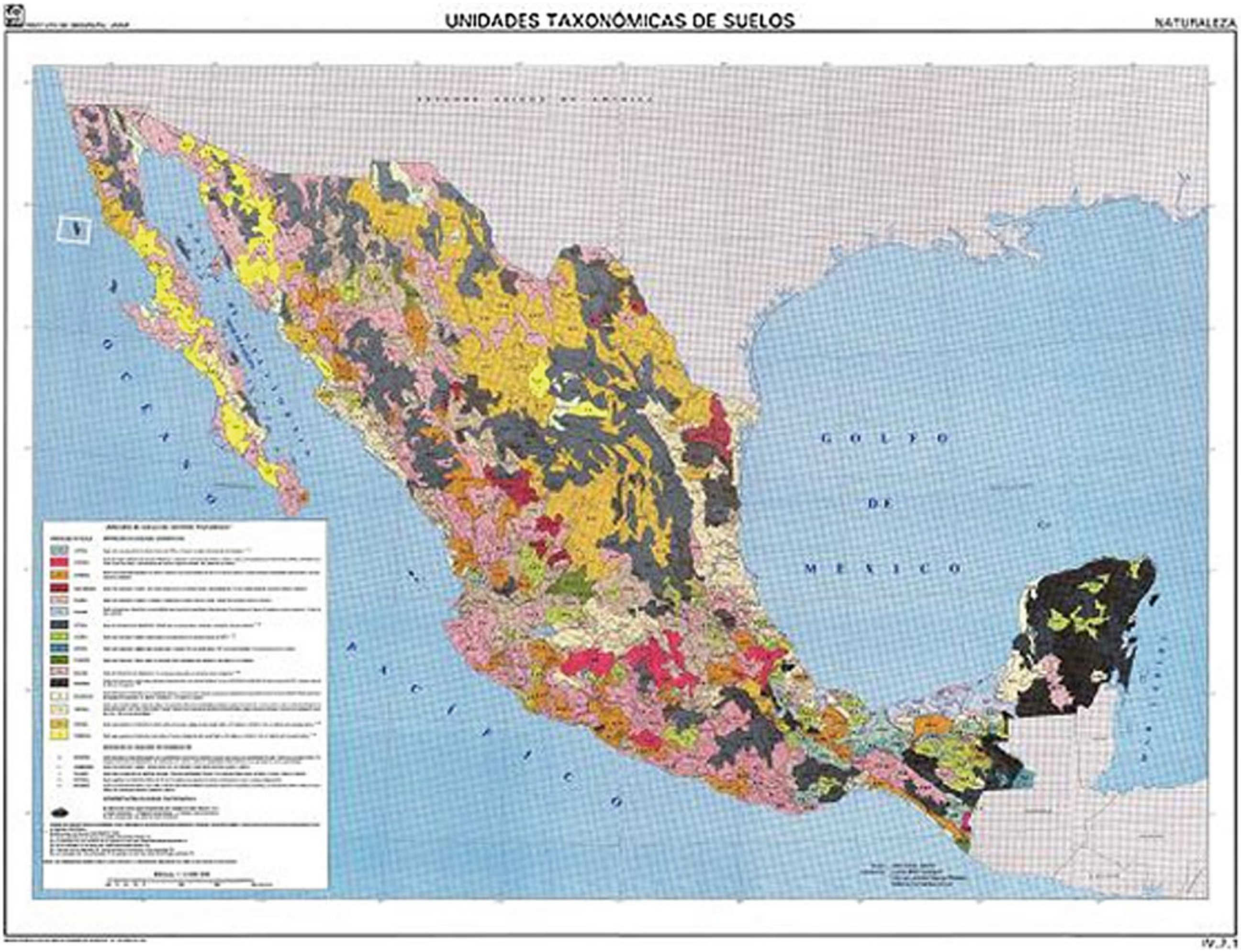


Fig. 2.11 Soil map of Mexico of the scale 1:1,000,000, prepared by the CETENAL using the legend modified after FAO

As mentioned above, the National Irrigation Commission (CNI) was created in 1926, mainly for the construction of large dams in the country. Agriculture Department was established in CNI the same year, and the first Head of the Department from 1926 to 1929 was Walter E. Packard (Baum 1970). The US specialist was hired for that position, because, as President Calles explained, there was a lack of technical experience among Mexicans (Aboites 1998). Agronomy department became the official government agency for conducting soil surveys, a procedure unknown in the country at the time. For unknown reason, the soil surveys were given the name of Agrology. Macías-Villada (1963) indicated that the term ‘agrology’ was used to characterize the applied part of soil science, mainly in regard to soil mapping and agrologic surveying. Basurto-Larrainzar (1926), in Volume 2 of his Treatise of Agronomy and Agrology, stated that the study of soils belongs to the field of geology, which means that in that epoch pedology was still not considered an independent science in Mexico.

It was the suggestion of the Chief of Agriculture Department to establish the first agrological College in the town of Meoqui in 1928, in order to enlighten young agronomists on developing soil surveys. Meoqui was chosen because of its proximity to the Conchos River, where a big project developed; it seemed convenient to use it as a base for field training (Comisión Nacional de Irrigación 1929).

At that time no aerial photographs were available, soil mapping was done together with topographic survey using a plotting board, and all the maps appeared at the same scale (Ortiz-Solorio 1993). In 1929, Alejandro Brambila Jr. led

Fig. 2.12 Soil map prepared on the basis of the Revised legend of the FAO-UNESCO Soil Map of the World INEGI-SEMARNAP (1999)

the squad that made the agrological map of the State of Morelos, the first federal entity fully studied (Ortiz-Solorio 1993). In 1937, CNI published the first soil map of Mexico as an Annex to the book of Rodríguez and Brambila "First attempt to group the soils of Mexico within the Great Soil Groups of the World" (1937). The map reflected mainly the general concepts of global soil distribution rather than real soil cover of the country (Fig. 2.9). The legend included the Great Groups of soils following the system developed by the USDA Soil Survey (e.g. see Baldwin et al. 1938).

Charles Kellogg published the Soil Survey Manual in the USA (Kellogg 1937a), which was translated into Spanish by Manuel Pérez Espinosa of the CNI with a somewhat erroneous title "Manual de Levantamientos Agrológicos" (Manual for Agrologic Surveys). This document was considered as the standard to follow in soil studies.

The US technical support came to an end in 1930. The CNI was renamed into the Secretary of Water Resources (Secretaría de Recursos Hidráulicos–SRH) in 1946. The staff of Agrology, previously estimated at about 60 technicians, for budgetary problems was reduced to 15 persons. The situation required employment of new methods to achieve speed, accuracy, and economy in agrologic studies, which was implemented by national experts, giving birth in 1958 to the Office of Photogrammetry and Photointerpretation. During the period from 1927 to 1962, the Department of

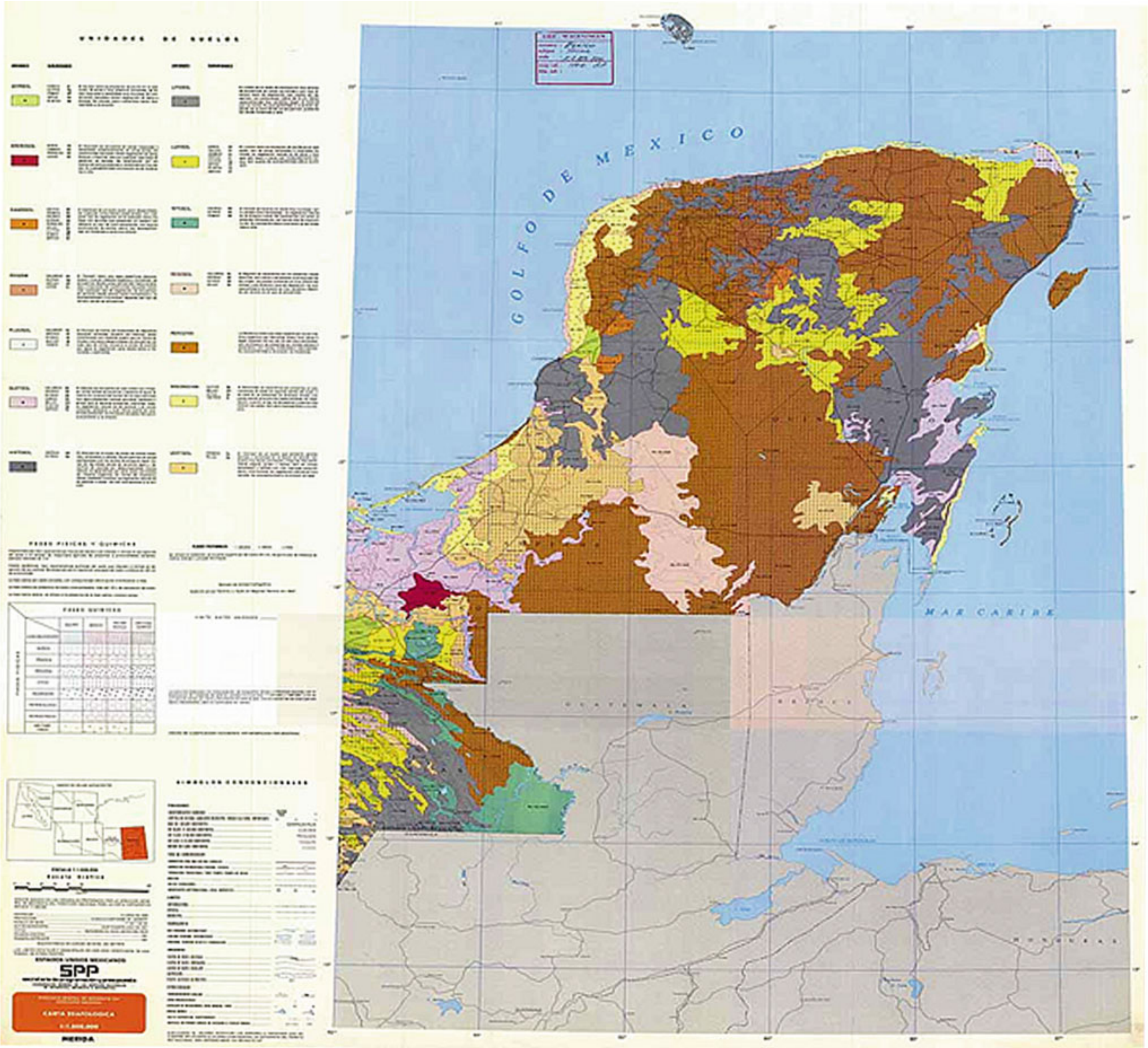


Fig. 2.13 An example of the map of the scale 1:250,000 developed by INEGI

Agrology studied soils at different levels for 17 % of the territory of Mexico, i.e., at 36 million ha (Macías-Villada 1963). As a part of these activities, the SRH published a soil map, stressing the distribution of "zonal", "intrazonal", and "azonal" soils in the country (Fig. 2.10).

The soils mapping in Mexico have been detonated by the project of the World Soil Map of the scale 1:5,000,000 by the Food and Agricultural Organization of the United Nations (FAO). This project has been developed during the period of 1961–1978, and implied close cooperation of the national experts with the international soil science community. In the decade of the 1970s, the Department of Agrology under the leadership of Gaudencio Flores Mata and in collaboration with experts from FAO integrated the available information on the soils of Mexico to World Soil Map of the FAO (1974). The information about the soils of the country was not very precise in that epoch, and the FAO soil map for Mexico had numerous errors. Generally, the

Fig. 2.14 The distribution of reference soil profiles used by INEGI for developing the soil map of the country

map had the same mistakes as the map prepared by the Secretary of Hydraulics: the systematic study of the soils of Mexico had not yet started, and large gaps in the knowledge existed, especially for arduous areas.

Apart from these efforts, some Mexican pedologists developed their own soil maps. A schematic map of soil Great Groups was published by Aguilera-Herrera (1969); it was one of the early attempts to use the American soil taxonomy for mapping Mexican soils.

The other early product of national-scale soil mapping in Mexico was the soil map of the scale 1:1,000,000, prepared during 1978–1980 by the CETENAL, which transformed later into INEGI (see Fig. 2.11). This institution, founded in 1968, later played a major role in the development of soil mapping in the country. There was a discussion on soil classification to be used for the map. Finally, the legend was based on the legend of the FAO-UNESCO Soil Map of the World (FAO-UNESCO 1968), modified by CETENAL (1970). The main reason for the selection of classification was that it could be used with minimal data on soil chemistry, while the classification used in the USA (Soil Survey Staff 1960) required extensive analytical support.

The other example of small-scale soil map was the map of dominant soils of the Mexican republic developed by the National Commission for the Study and Use of Biodiversity (CONABIO–Comisión Nacional para el Conocimiento y Uso de la Biodiversidad) of the scale 1:1,000,000 by generalization of the soil maps of INEGI and updating the legend using the new version of classification proposed by FAO (FAO-UNESCO-ISRIC 1988).

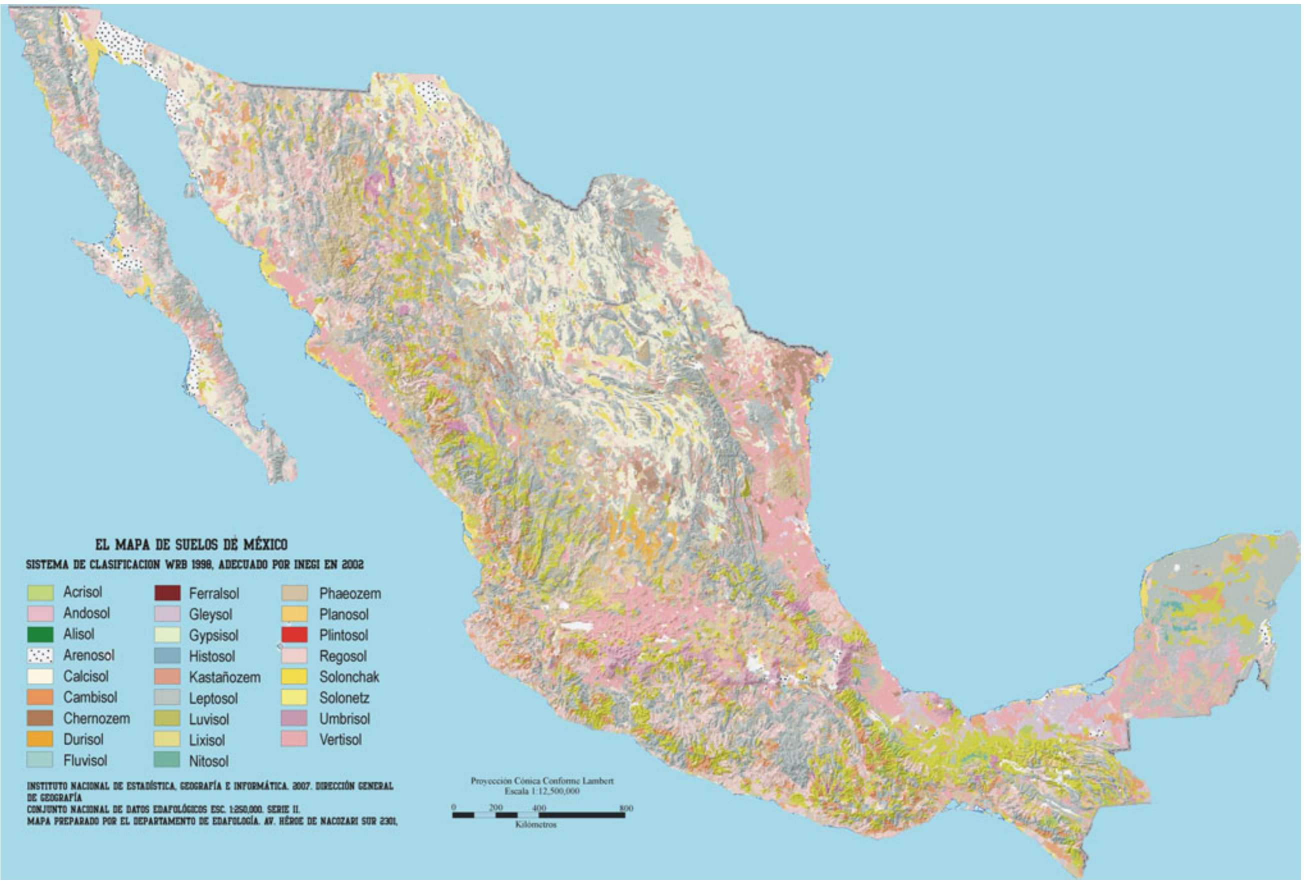


Fig. 2.15 The soil map of Mexico prepared by INEGI in 2006 using the WRB classification as a legend (FAO-ISRIC-ISSS, 1998)

The second version of this map was developed by three Mexican institutions: the Secretary of Environment, Natural Resources and Fishery (Secretaría del Medio Ambiente, Recursos Naturales y Pesca–SEMARNAP), the CP, and the INEGI. One of the aims of this map was to update the nomenclature of the soil maps, using the Revised Legend of the World Soil Map of FAO/UNESCO/ISRIC (1988). The process of updating the information consisted of a translation of names, and where possible keep to the original boundaries of soils, taking into account that such abundant in Mexico units as Xerosols and Yermosols have been deleted from the legend (Ortiz-Solorio et al. 1994). The map also included a general description of the main soil groups of the country (Fig. 2.12).

The development of medium- and large-scale soil mapping started in 1980s in Mexico. In 1968, the INEGI started work on preparation of soil maps of the scale 1:50,000. Each sheet of these maps had a size of 15 min of latitude per 20 min of longitude, thus covering an area of about 1,000 km^2. The total coverage of these maps, elaborated during the period of 1968–1982, was 762 sheets, or about 30 % of the whole territory of the country. The maps used Mercator Universal Transversal Projection (UTM) and Datum NAD27 as cartographic bases. The maps have been prepared both by field surveys and by interpreting stereoscopic pairs of black-and-white aerial photographs of the scale 1:50,000 and 1:75,000. The disadvantage of these maps was that the density of the survey was insufficient for the declared scale, and real resolution of the maps corresponded to a smaller scale.

The next stage was to make soil maps of the scale 1:250,000 for the whole national territory (Fig. 2.13). Each sheet had an extension of 1° of latitude per 2° of longitude; the cartographic bases were UTM and Datum NAD27. Field soil survey was strengthened by the use of remote sensing data, mainly Landsat MSS satellite images of the bands 4, 5, 6, and 7. During the period of 1980–1998, the mapping plan for the whole territory of Mexico, excepting isles, have been completed in the scale 1:250,000. The legends of the maps of the scales 1:50,000 and 1:250,000 were based on the

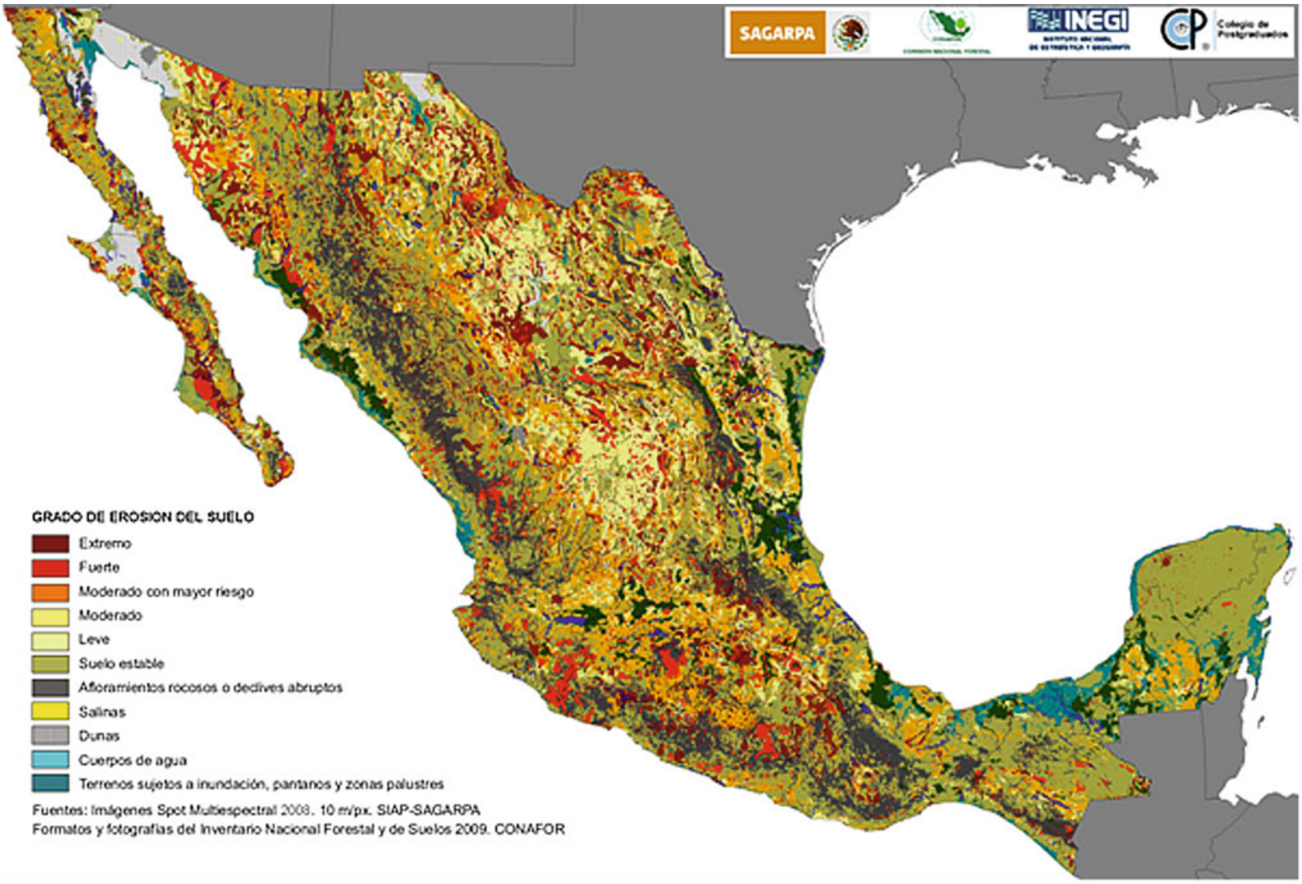


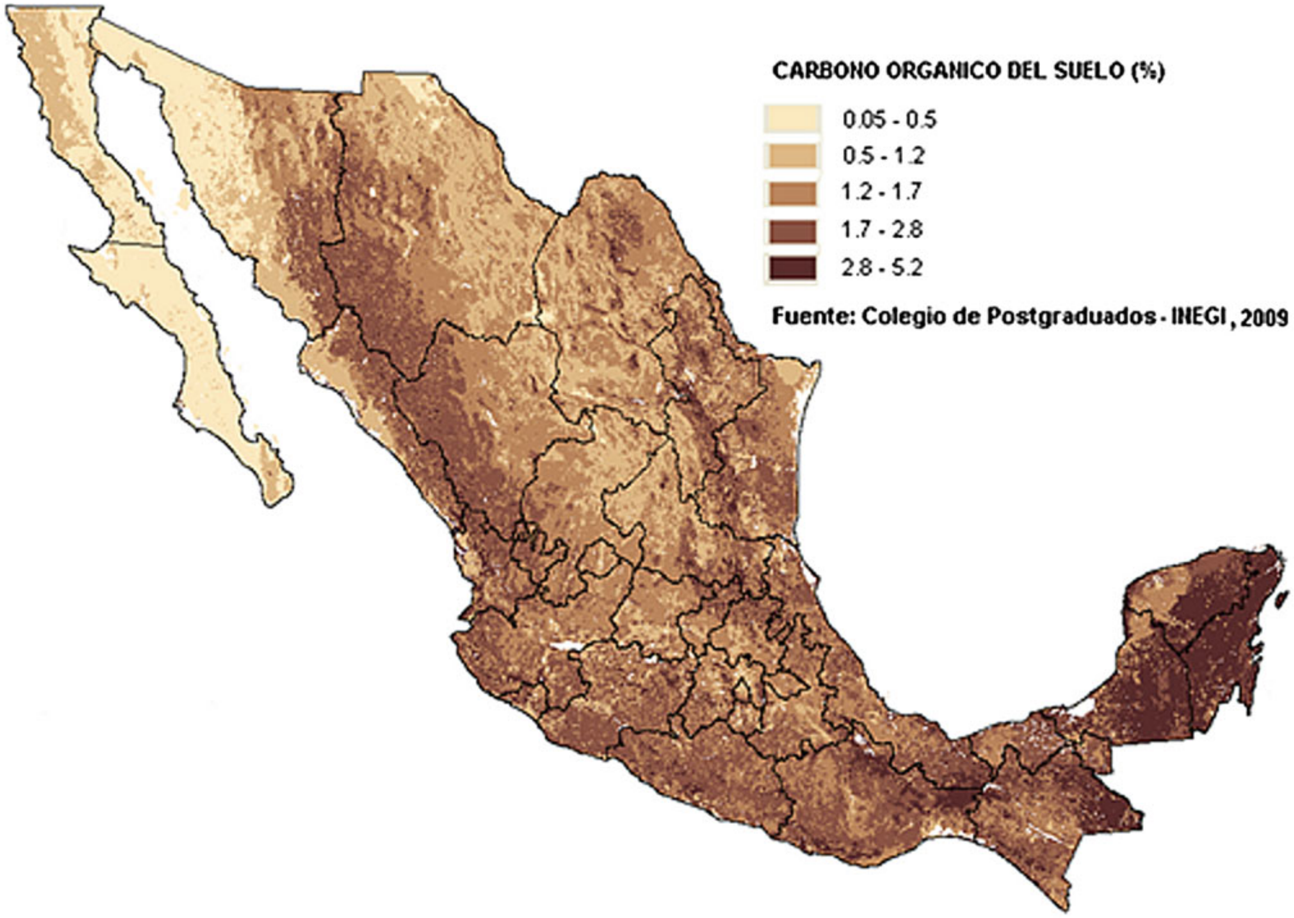
Fig. 2.16 The map of the development of soil erosional processes in Mexico, prepared by SAGARPA

classification system of FAO World soil map, modified by CETENAL (1970).

In 2001, it was decided that the maps at the scale 1:250,000 for the first round of soil survey needed certain improvement (Guerrero-Eufracio and Cruz-Gaistardo 2011). During the period of 2002–2007, the INEGI conducted the second round of soil survey that included excavation of new profiles, the revision of legacy data, and reshaping the polygons using available remote sensing data. The legend was based on the World Reference Base for Soil Resources–WRB (FAO-ISRIC-ISSS 1998). The advantage of the improved maps was that the classification was much more detailed than in the previous version, and that the staff of the Pedology Department had more professional skill than during the previous inventory (Cruz-Gaistardo et al. 2006). The maps exist in GIS format and are linked with a database that includes 9,549 soil profiles (in fact, more than 30,000 profiles are potentially available for including in the database). The distribution of soil profiles is shown at Fig. 2.14. The second round allowed developing a new small-scale soil map of Mexico with strikingly higher detail than the previous versions (Fig. 2.15).

The maps produced by INEGI received certain criticism, mostly because many users had unjustified expectations that small-scaled soil maps (1:250,000 and 1:1,000,000) might give precise information for development site-specific practical recommendations. Also the methodology applied by INEGI overstated the use of interpretation of aerial photographs and satellite images; the number of observations in the field was low '(about 1 observation per 50 cm^2 map), and the state of soil information should be still regarded as insufficient.

A number of maps have been developed on the basis of the data recently obtained by INEGI and other institutions of Mexico. A map for estimating soil erosion was developed by the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA–Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentacion) mainly on the basis of interpretation of satellite images (Fig. 2.16). A set of auxiliary data, the use



Fuente: Colegio de Postgraduados - INEGI, 2009

Fig. 2.17 The map of the reserves of soil organic carbon in Mexico prepared by C.O Cruz-Gaistardo

of conventional and nonparametric methods for modeling, and certain field verification makes the map a reliable tool for assessing soil degradation. The interpretation of the map showed that most of the heavily eroded soils (24.6 million ha) were erodible soils subjected to intense changes in land use, specifically deforestation, overgrazing, or poorly planned agriculture.

The soil organic carbon map provides data estimates of the C content in the soil, and serves as background for recording the C loss or acquisition in the future. The information will enable management to formulate policies that positively impact the reserves of CO_2 in ecosystems (Fig. 2.17).

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Factors of Soil Formation

3

3.1 Introduction

The United States of Mexico is an extensive country with a total area of 1,964,375 km^2, which exceeds the total area of France, Spain, Germany, Italy, and the UK. The high diversity of environments in Mexico results from its extent and complex topography. The relief of most of the country is mountainous due to high tectonic activity, both past and present. There is a well-known historical anecdote about the Spanish King Carlos V, who asked Hernán Cortés to describe the characteristics of the new possession of the Spanish crown. Cortés answered simply by crumpling a piece of paper (Carballo and Pluchahn 2007).

On the west and south the country is washed by the Pacific Ocean, and the Baja California Peninsula is separated from the mainland by the Californian Bay (or Cortes Sea). The Mexican Gulf washes the eastern coast, and the eastern part of the Yucatan Peninsula jets out to the Caribbean Sea.

3.2 Orography

Most of the Mexican territory is mountainous. The mountainous systems are represented by Mexican uplands, Sierra Madre ridges, and the Transmexican Volcanic Belt (Fig. 3.1). On the very north-west of the country is the mountainous Peninsula of Baja California with ridges of 800–1,000 m above sea level (asl). On the southeast of Mexico is the nearly level lowland of the Yucatan Peninsula.

The Transmexican Volcanic Belt is a tectonically active area with more than 350 volcanoes, including the highest peaks of the country Pico de Orizaba (5,610 m asl), Popocatepetl (5,465 m asl), Iztaccihuatl (5,286 m asl), La Malinche (4,461 m asl), Nevado de Toluca (4,392 m asl), and many others. Volcanic eruptions and earthquakes are common phenomena in this region (López-Ramos 1985).

Two mountainous ridges in the west and east of the country, the Sierra Madre Occidental and the Sierra Madre Oriental, correspondingly, encase a group of extensive tablelands of the central part of Mexico that are known as the Altiplano Central or Mexican Upland. The internal part of the Mexican Upland includes two regions: the Northern Mesa and the Central Mesa. The Northern Mesa consists of a system of relatively flat bolsons separated by short ridges at elevations of 900–1,200 m asl. The Central Mesa includes ancient volcanic tablelands at the elevations between 2,000 and 2,400 m asl, divided by mountainous culminations and kettles.

The maximum altitude of the Sierra Madre Occidental reach 3,150 m asl, and that of the Sierra Madre Oriental—4,054 m asl. The southern part of the country is separated from the Mexican Upland by the bowl of the Balsas River with the mountainous region Sierra Madre del Sur south of the river. The Sierra Madre del Sur mountains have medium elevations of about 2,000 m asl with a maximum of 3,750 m asl. This mountainous system stretches from the Nayarit to the Oaxaca state, to the Tehuantepec Isthmus, where the mountains descend to 300 m asl. On the Pacific coast, a narrow line of coastal plain follows the mountains of the Sierra Madre del Sur, and then goes further to the south reaching Guatemala. Behind this plain there are the Chiapas highlands, belonging to two different physiographic regions: the Central Cordillera and the Ridges of Chiapas and Guatemala.

Between the Sierra Madre Oriental and the Gulf of Mexico, there is an extensive coastal plain that stretches from USA to the Peninsula of Yucatan.

In more detail, the topography and other natural conditions of Mexico are described in Chap. 5 by physiographical regions.

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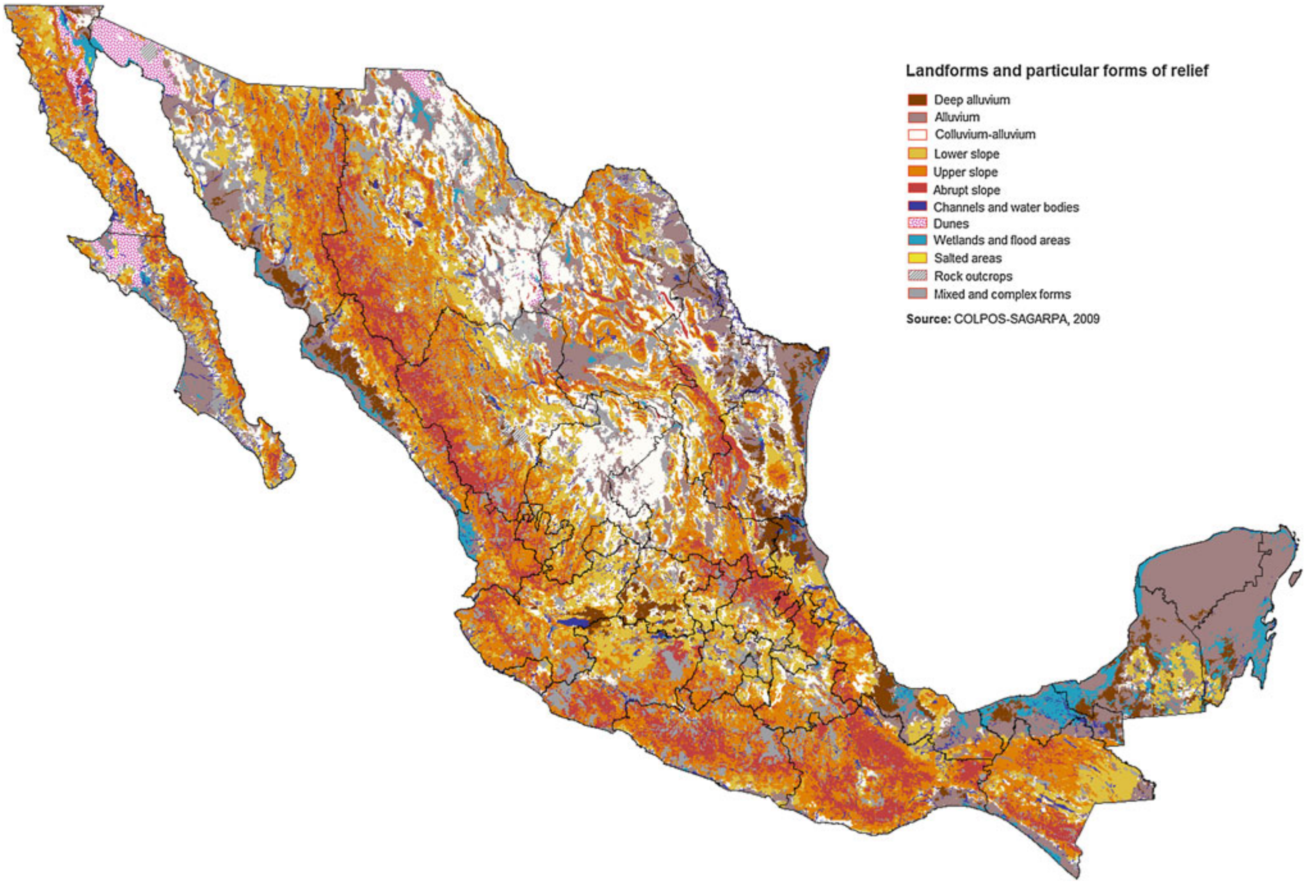


Fig. 3.1 The topographic/geomorphologic map of Mexico. Reproduced with a permission of SAGARPA

3.3 Geology and Geomorphology

Most of the Mexican territory belongs to the infolded belt of the Cordilleras of North America (Fig. 3.2). The eastern coast and Yucatan Peninsula represent fragments of a young platform with Paleozoic infolded basis, covered with a mantle of Mesozoic, Palaeogene, and Neogene–Anthropogene sediments that form gentle bowls and lifted blocks. In the structure of the Sierra Madre Occidental, the main constituents are igneous and metamorphic rocks of Upper Pre-Cambrian and Paleozoic age that form extensive massifs, and some sedimentary and pyroclastic sediments of Jurassic and Cretaceous age. All these rocks are strongly folded. Granite intrusions of Cretaceous and Palaeogene epochs are widespread. The Sierra Madre Oriental is formed mainly by a system of wrinkles of Jurassic and Cretaceous limestones with minor volcanic impact. There are also some outcrops of igneous Paleozoic rocks, surrounded by younger sedimentary rocks. The extensive plateaus of Central Mexico are formed mainly by sedimentary rocks and Oligocene and Miocene lavas and tephras. The Sierra Madre del Sur consists mainly of Pre-Cambrian metamorphic rocks with abundant later intrusions of granites, diorites, and gabbros, with extensive sedimentary mantles in the intermontane valleys. There is the general concept that the Sierra Madre Occidental is constituted with igneous rocks, the Sierra Madre Oriental—with sedimentary ones, and the Sierra Madre del Sur—with metamorphic ones. Though this concept is true in general, it is important to remember that all these mountainous systems are extensive and complex, thus each of these includes a wide variety of rocks.

Along the Transmexican Volcanic Belt that limits the Mexican Uplands in the south, there is a longitudinal zone of large snaps, where most of the active volcanoes are located, including the famous Paricutin volcano that rose in 1943. The infolded structures of the Cordillera Mountains are formed in the Alpine epoch of revolution in upper Cretaceous and lower Paleogene. Numerous neoteric bowls and sunken blocks are filled with Neogene–Anthropogene molasses. The southern part of the Baja California Peninsula formed by Paleogene and Neogene sediments, is referred to as the region of young (Neogene) infolded framing of the Pacific Ocean.

Fig. 3.2 Geological map of Mexico. Reproduced with a permission of INEGI

Practically, all the territory of Mexico is characterized by high volcanic activity. The Transmexican Volcanic Belt is one of the most active volcanic regions in the world, with dozens of active volcanoes and regular destructive earthquakes. The rest of Mexican territory that would seem stable, composed of ancient Pre-Cambrian, Paleozoic, and Mesozoic rocks, are also affected by tectonic movements, both slow and catastrophic ones (earthquakes). The slow movements of tectonic blocks are also of major importance for the geomorphology of the region, because they activate the processes of geologic erosion and sediment accumulation. The whole territory of Mexico may be characterized as a zone of active geomorphological processes.

3.4 Climate

The flat areas of Mexico show a distinct latitudinal gradient of temperatures: the northern part of the country is classified as having subtropical climates, and the southern part, roughly to the south of the Tropic of Cancer, as having tropical climates (Fig. 3.3). However, level areas are not very abundant in Mexico, and they are located on the sea coast, thus being strongly affected by the ocean that masks the latitudinal gradient of temperatures.

Humid tropical air masses enter the Mexican territory from the eastern and southern coasts, and torrentially shower the windward escarpments of the mountains. The north-west of the country is affected by the winds blowing from the central parts of the North American continent, and has a dry continental climate. The Mexican Upland has a cooler climate than the coastal areas: the mean temperatures in winter are about +2 °C and in summer about +15 °C, while at the coast even in the winter the temperature does not drop below +20 °C.

The mean annual temperature ranges between 10 °C at the north-west of the country and 25 °C at the south. The coolest period corresponds to the calendarian winter and lasts from December to February. The penetration of cold air masses from the north sometimes lead to drastic decreases in winter temperatures in the North Mesa: the extreme temperatures of −20 °C have been recorded in Chihuahua State. In the northern part of the country and in high mountains, winter snowfalls are abundant.

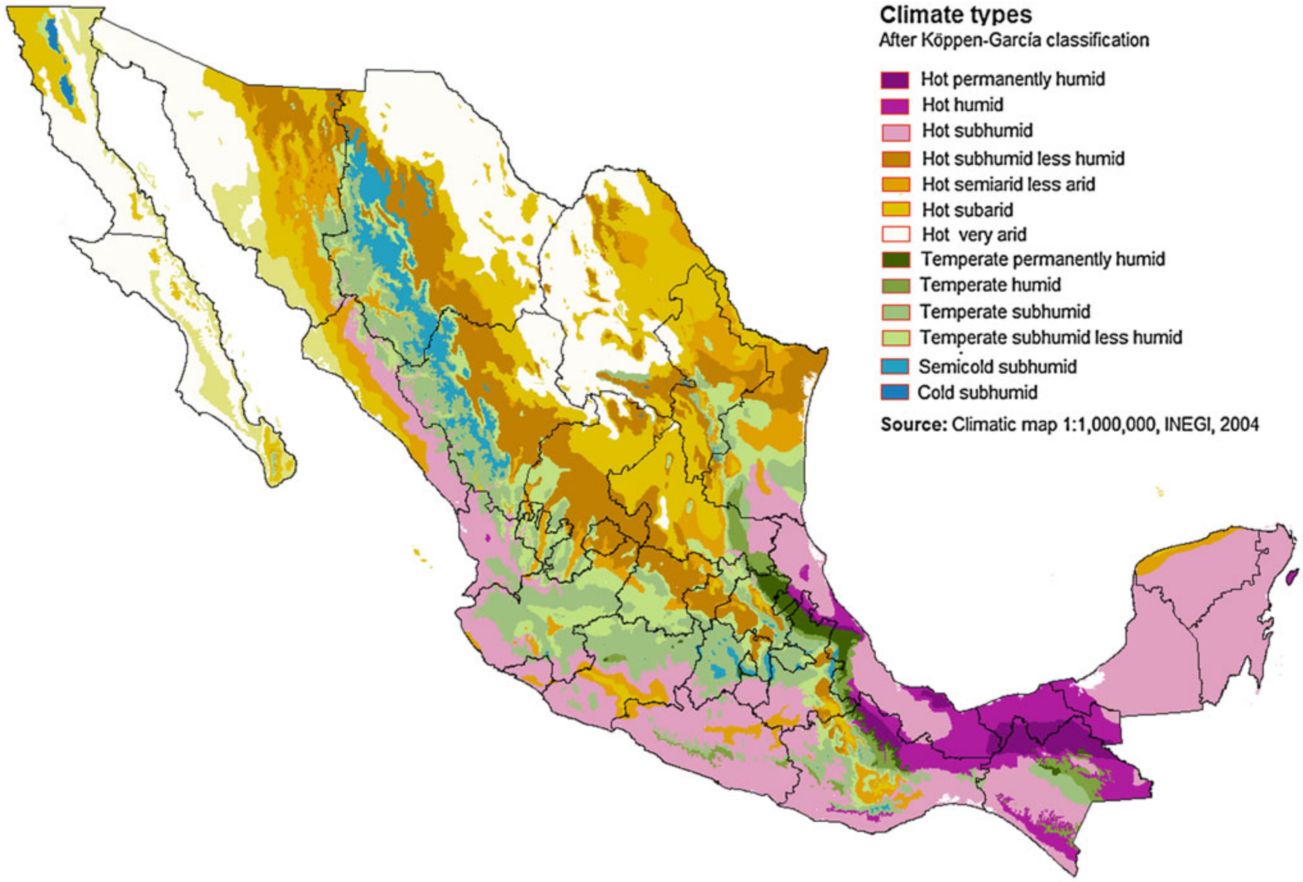


Fig. 3.3 The types of climates in Mexico (after García 1973). Reproduced with a permission of INEGI

The mountainous relief determines vertical climatic zonality. The climate varies according to the relief: it is hot and wet at the coast, and dry and cooler in the inland territory that is situated in the shadow of the mountainous systems of the Sierra Madre. For most part of the territory, the dynamics of precipitation is typical for a tropical (monsoon) climate: the driest period corresponds to the winter, and the summer is rainy. The exact dates of rainy period, its length, and the quantity of precipitation vary widely depending on the location of each region. In few places, like in Baja California, the climate is Mediterranean, i.e., the relation of climate and temperature is reverse to that in monsoon climates: the winter is rainy, and the summer is dry.

The range of annual precipitation is wide in Mexico, varying from 100 to 3,000 mm, with local extremes of up to 5,000 mm. The coast of the Gulf of Mexico receives much more precipitation than the Pacific coast. On both coasts, tropical cyclones and hurricanes are abundant. The quantity of precipitation clearly divides the national territory into two major parts. The first one has arid and semiarid climates and includes the northern part of the country, the Mexican Uplands, the Baja California Peninsula, and the inner parts of the Transmexican Volcanic Belt and Sierra Madre del Sur. The second part has subhumid, humid, and extrahumid climates and includes most parts of the coastal areas on both coasts, the extreme south of the country and the Yucatan Peninsula. It is important to note that the extent of the aridity of climate depends also on real evapotranspiration. For example, in the Mexican Uplands in spite of low precipitation, the climate is not very arid because of low temperatures. Scarce vegetation results in lower transpiration rates.

The system used for the characterization of climate in Mexico is the system of Köppen, modified by García (1973). It is based on the division of climates on the highest level by mean annual temperatures and annual amounts of precipitation. According to these principles, the climates of mountainous areas of Mexico are mostly classified as temperate ones; though the dynamics of temperatures and precipitation resemble that of monsoon tropical regions, the difference between the summer and winter temperatures is not very large and there is a distinct rainy season corresponding to the warmest summer period. The system uses the dynamics of the temperatures and precipitation and

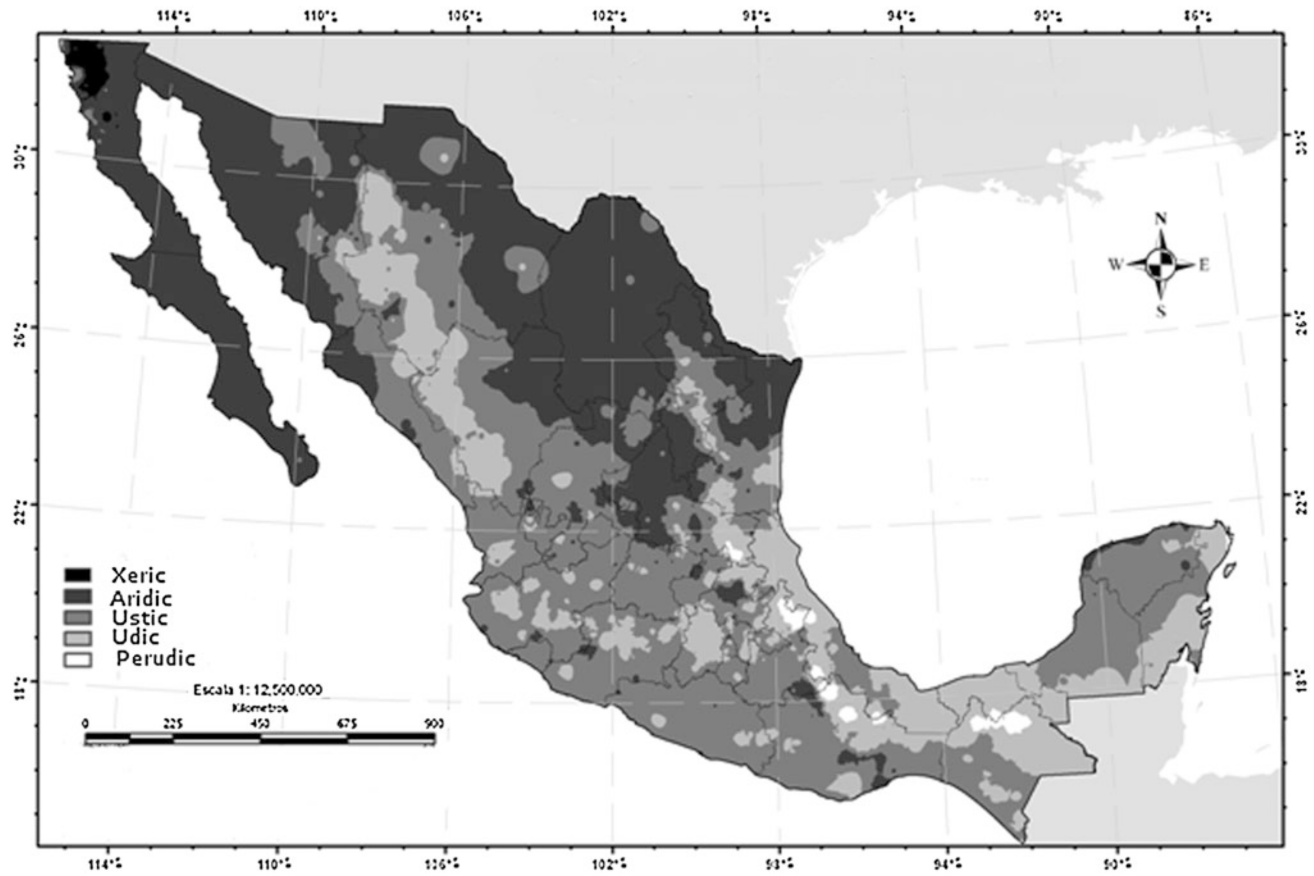


Fig. 3.4 Soil moisture regimes of Mexico (after Sánchez-Guzmán et al. 2009)

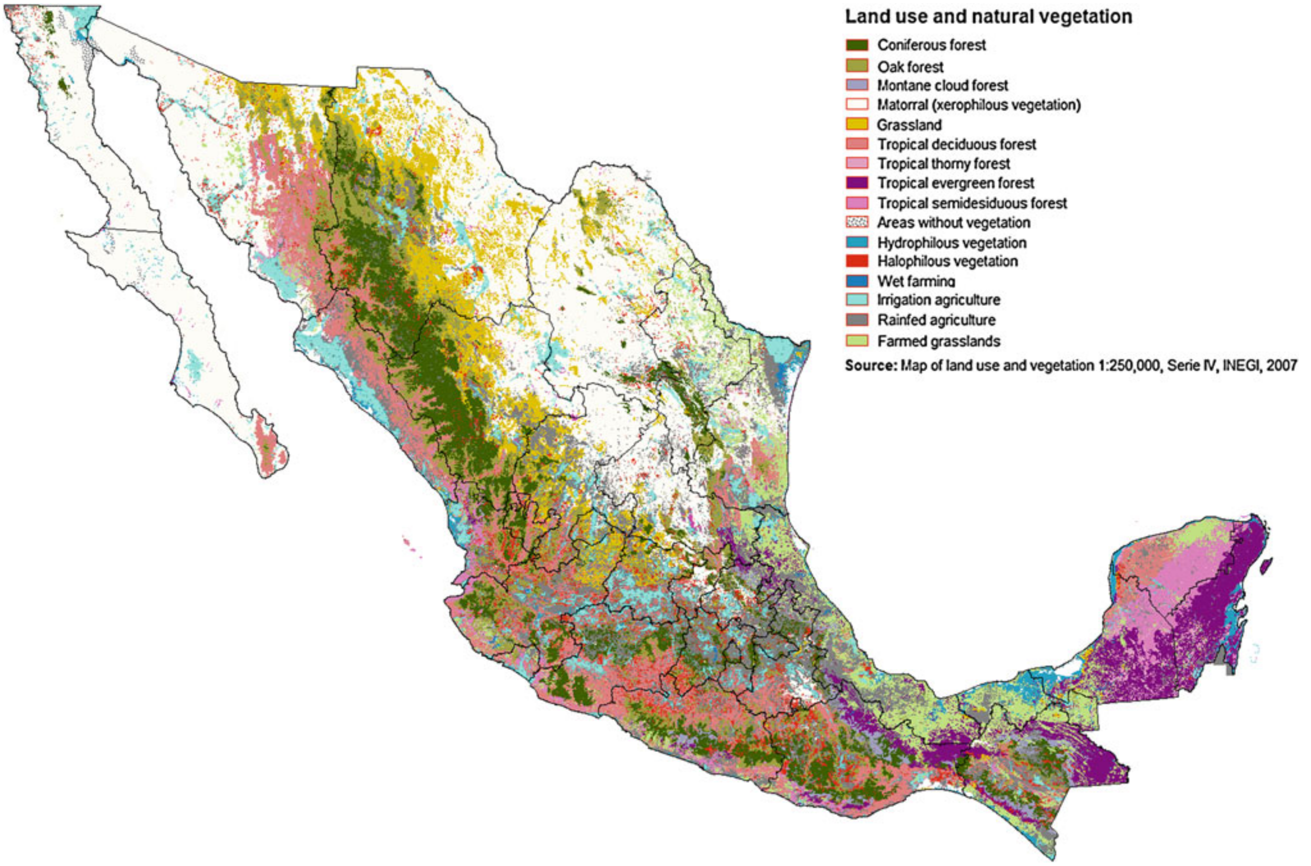
potential vegetation on the lower levels of classification of climates. Though discussable from the point of view of climatology, the system provides a good guideline for the land use in the country.

A better insight into the climate as a soil-forming factor and an important condition for land-use planning used the system of soil temperature and moisture regimes used by the USDA (Soil Survey Staff 1999). The Fig. 3.4 shows a map of the soil moisture regimes of Mexican soils prepared by Sánchez et al. (2009), who used the Newall model based on the data from 2,703 normal meteorological stations of the National Meteorological Service of Mexico (CNA-SMN, 2010).

The results of Sánchez-Guzmán et al. (2009) show that the most abundant moisture regime in Mexico is ustic (41 % of the national territory), followed by the aridic moisture regime with 39 %, and the udic moisture regime with 19 %. The least abundant regimes are perudic, which occurs in less than 1 % of the territory of the country, and xeric in 0.56 % of the territory. Seven of the nine soil temperature regimes occur in Mexico, mostly the warmest ones. In order of extension, the thermal regimes of soils in Mexico are: isohypethermic covering 37 % of the territory, hyperthermic—26 %, thermic—23 %, and isothermic—12 %. Minor areas correspond to mesic—1.4 % and isomesic regimes—less than 1 %. The only meteorological station in Nevado de Toluca, located at 4,000 m asl, reports the cryic temperature regime; this regime should be extended to all the highest peaks of Mexico.

3.5 Hydrography

The climates of Mexico are influenced to a great extent by the circumferential seas. The Gulf of Mexico is one of the biggest gulfs in the world with a total area of 1,555,000 km^2. Though the Gulf of Mexico has deep zones (as deep as 3,822 m), approximately 38 % of the Gulf is comprised by shallow and intertidal areas of less than 20 m deep, thus the water constantly heats there. Both the Caribbean Sea and the Gulf of Mexico are included in the global circulation of ocean water. A big oceanic North Equatorial Current crosses the Caribbean Sea along the coast of Yucatan, and enters the Gulf of Mexico to form the Loop Current which melts into the Florida Current which, in turn, contributes to the Gulf Stream. Generally, the whole



Source: Map of land use and vegetation 1:250,000, Serie IV, INEGI, 2007

Fig. 3.5 Biogeographic division of Mexico. Reproduced with a permission of INEGI

Eastern coast of Mexico is affected by the hot humid air both from the Gulf of Mexico and the Caribbean Sea. The Pacific coast of Mexico is somewhat different. The southernmost part of the Western coast of the country is affected by warm the concurrent North Equatorial Current. The northern part of this coast suffers the influence of the cold Californian Current. It means that cool air from the sea heats over the land and its relative humidity decreases. The phenomenon results in much drier climates on the northwestern coast of Mexico; in Baja California, the climate is characterized as Mediterranean, which means that the maximum of precipitation corresponds to winter period, when the difference in the temperatures of the water and the land is not very strong.

The river net is dense in the southeastern part of the country and very scarce in the northwestern part. In the Yucatan Peninsula, which is composed of limestones, and in some inner parts of the Mexican tableland, surface discharge is absent. In the latter region, most of the rivers flow into dry estuarian valleys. These valleys have thick packages of alluvial sediments and suffer intensive salinization. The rivers of the south-east are short, with intensive stream and high water content and have a good potential for energy development. The rivers of the northwestern part of the country are longer, but shallow, especially at the mouth, because of evaporation and use of water for irrigation. The regime of these rivers coincides with the irregular precipitations. The biggest rivers in Mexico are: Rio Grande situated on the border with the USA (this river is called Río Bravo del Norte in Mexico) with its biggest tributary Conchos, Rio Lerma, Rio Balsas, and a river system Grijalva—Usumacinta. Lakes are not very common; the biggest one is Chapala, which is located along the flow of the Rio Lerma in the Jalisco State. Its dimensions are about 80 km from east to west and 18 km from north to south, and it covers a total area of 1,100 km^2. The other important, but much smaller lakes are Cuitzeo (300–400 km^2), Patzcuaro (126 km^2), Catemaco (72.5 km^2), and Miguel Aleman reservoir (47.8 km^2). All these lakes are shallow with a medium depth of a few meters. Also there are several big water reservoirs at the Rio Grande on the border with the USA, some dry salted lakes in the north of the country (e.g. Laguna Salada), and the almost completely drained system of lakes in Mexico City and its surroundings, which includes the brackish lakes Texcoco, Zumpango, and Xaltocan and the fresh water lakes Xochimilco and Chalco.

3.6 Flora and Fauna

Complex physiographic conditions of Mexico impart a tremendous diversity of bioclimatic conditions in the country. Due to the latitudinal extension and the presence of large mountainous systems, there are many biogeographical regions. Complex topography also favors the formation of numerous habitats in each region.

Mexico is known for megadiversity of the species of flora and fauna. It ranks third in the world, after Brazil and Columbia, in total number of species of plants and animals (Toledo 1994). Mexico is second in the number of species of mammals (after Indonesia), and first in the number of species of reptiles.

Mexico is one of the centers of formation of the American flora, thus it has diverse vegetation. According to the fundamental monograph by Rzedowski (1983), the vegetation of Mexico belongs to Holarctic and Neotropical floristic kingdoms with two regions within each of the kingdoms. In the Holarctic kingdom, there are North American Pacific and Mesoamerican Mountainous regions, and in the Neotropical kingdom—Xerophytic Mexican and Caribbean regions. On the lower level, the Mexican territory is divided into 19 floristic provinces (Fig. 3.5). Totally, there are 32 types of vegetation in Mexico (Rzedowski 1983).

In the northern part of the country, the vegetation is scarce and shrub-like, which is called "matorral" in Mexico. In places it is microphyllous matorral with dominant species of creosote bush ("gobernadora" in Mexico), mesquite, yuccas, and ocotillo (candlewood) associated with limestone outcrop. On coarse alluvial sediments, there is rosetephylous matorral with agaves, stools (desert spoons), and cacti. The cacti are widespread in all the northern and central parts of Mexico. There are more than 500 species of cacti ranging from small ones to giant varieties of more than 4 m high. Agaves are also widespread and diverse: there are about 140 species recorded in Mexico. The vegetation type of the southern part of the Mexican tableland is characterized as savanna with graminaceous and amaranth grasslands, shrubs and scarce trees, represented mainly with acacias. On the inner slopes of the mountains around the tableland, there are temperate mixed forests with oaks, pines, hardbeam, firs, linden, and many other arboreal species. The diversity of tree species is very high; for example, there are more than 40 species of pine in Mexico. The windward slopes of the mountains are wetter and warmer, with tropical rain and semideciduous forests. At elevations of less than 1,000 m asl, the vegetative communities are dominated by deciduous species such as evergreen oaks, sycamores, and diverse plants of the Moraceae, Leguminosae, Burseraceae, Bombacaceae, and Boraginaceae families. At altitudes between 1,000 and 2,000 m asl, there are mixed oak–pine forests, and at higher elevations—temperate coniferous forests with pine and fir species. The distribution and relative altitudes of the belts of vegetative communities strongly depend on the latitude, topography, and local conditions. On the slopes oriented toward the Mexican Gulf and in places on the slopes oriented to the Pacific Ocean at elevations between 1,500 and 2,500 m asl are montane cloud forests (bosque mesófilo de montaña, bosque de niebla). Before the Spanish conquest, about two-third of the country was covered by forests. Actually less than 20 % of the Mexican territory has significant forest massifs, mainly in the southern and eastern parts of the country. The biogeographical regionalization of the country considers so-called "potential" vegetation, i.e., the ecosystems, which could exist under given environmental conditions and evidenced their existence at corresponding territories.

The fauna of Mexico belongs to two major ecoregions of the Earth—to the Nearctic in the northwestern part of the country, and the Neotropic in the lowland parts to the south from the Tropic of Cancer. In the northern part, the most abundant mammals are deer (whitetailed and others), pronghorn, squirrels, gophers, and predators such as puma, wolves, skunks, foxes, raccoons, coati, and otter. The tropical mammals include peccary, tapir, armadillos, howler monkeys and spider monkeys, potto, jaguars, ocelots, and many other wild cats. In general, there are more than 500 species of mammals in Mexico. The birds are numerous, with about 1,000 species that reside or visit Mexico; their diversity is especially high in the tropics. Reptiles include about 720 species of snakes, lizards, crocodiles, and turtles. The number of species of amphibians is close to 300, including very specific animals, such as Oaxacan caecilian and axolotl. The number of invertebrates is difficult to estimate.

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4 Major Soil Types and Their Classification

4.1 Classification Systems

Soil classification is an essential tool for presentation and comparison of soil data. However, different soil classifications are used in different countries, thus making difficult an adequate transfer of information (Eswaran et al. 2003; Krasilnikov et al. 2009). The main issue that caused the diversity of pedological classifications and did not permit until now the development of a universal classification is the peculiarity of soil cover of the geographical regions of the world. The soils that seem unimportant and marginal in their properties and distribution in one region might be widespread in the other; consequently, in the second region this group of soils might be classified in more detail, and even recognized at a higher taxonomic level.

There are two soil classifications that are believed to include worldwide coverage, and all the existing soil natural entities, namely the World Reference Base for Soil Resources, or WRB (IUSS Working Group WRB 2006), and the USDA Soil Taxonomy, or ST (Soil Survey Staff 1999). Both of the classification systems have their advantages and disadvantages, and the selection depends mainly on personal customs and university education of each specialist. Mexico is unique in the sense of soil classification. An official system for soil mapping was based on FAO World soil Map legend, the precursor of the WRB (CETENAL 1970), and WRB is actually used for soil mapping and inventory (INEGI 2002a, b). However, due to proximity to the United States, a significant part of scientific research and applied projects uses ST as a basic soil classification system, especially in the northern part of the country. Thus, the literature on soils of Mexico uses either WRB or ST systems. For the convenience of the readers we use in this book both classifications, the original name with the closest corresponding name of the other system in brackets.

For presenting the most abundant soils of Mexico we decided to avoid their presentation by classification units. Formal soil grouping based on quantitative criteria may be dangerous for pedological studies. The danger is that soil classification gives an illusion of complete knowledge: giving formal names to soils, it is easy to believe that we understood the genetic and geographical essence of soil bodies. Usually this belief is misleading. In most pedological and geographical studies, soil classification is a common language and a convenient form of grouping soils rather than the final aim of the investigation. Some soil groups' names hide the genetic essence of the soils rather than clarify it. For example the names Cambisols (WRB) or Inceptisols (ST) do not provide much information, because they imply soils that are not well developed in a wide range of climates or environments, or weathered clayey soils with elevated cation-exchange capacity, or any other soils, which have at least one diagnostic criterion, but do not meet the definitions of other orders or taxa.

Soil classification is definitely useful as a communication tool and for mapping, to show the differences in soil properties, but not for reconstructing geographical and evolutionary links between them. Though evolutionary concept is tightly integrated in the structure of soil classifications, the latter reflects "horizontal" relation among soil entities, i.e., aggregates soils of the same stage of development (Krasilnikov et al. 2009). Unlike biological classifications, the pedological ones never group soil chronosequences (immature soils, developed soils, and old soils) in the same taxa. The evolutionary sequences of soils are not easy to establish, and we can only develop hypothesis on the origin of soils and their previous history; these reconstructions may be subjective and depend on the personal experience of the researcher. That is why for pedogenetic and pedogeographical studies, it is better to use the language of particular pedogenetic processes and properties, and to suggest ad hoc grouping dependently on the aims of the study. For example, for our review it seems better to use provisional grouping of soils on the basis of their evolutionary and geographic unity rather than formal classification scheme.

P. Krasilnikov et al., *The Soils of Mexico*, World Soils Book Series,
DOI: 10.1007/978-94-007-5660-1_4,

For this book we decided to make an ad hoc grouping of Mexican soils as follows:

1. Volcanic soils.
2. Texturally differentiated soils, or soils having a clay-enriched subsurface horizons (argic (WRB)/argillic or kandic (ST) horizons).
3. Soils with a brownish poorly differentiated profile.
4. Soils with a developed humus-enriched topsoil.
5. Shallow soils derived from silicate consolidated rock.
6. Shallow soils derived from limestone.
7. Saline and alkaline soils.
8. Expanding and shrinking soils: Vertisols and similar soils.
9. Soils with carbonate and gypsum accumulation.
10. Hydromorphic soils, both organic and mineral.
11. Strongly weathered soils.
12. Poorly developed soils in unconsolidated sediments.
13. Anthropogenic soils [Anthrosols and Technosols (WRB)].
14. Less abundant and less studies soils.

Here, we present a short characteristic of these provisional soil groups based both on the data from the literature and our own field research. For each group we tried to present several representative profiles. Unfortunately, not all the soils were characterized equally; the specification depended on the extension of each soil group, on the variation of properties of soils within the provisional groups, and on the degree of exploration of soils. Unfortunately, until now our knowledge about soils in Mexico is not perfect.

4.2 Volcanic Soils

Our understanding of volcanic soils includes all the soils formed in pyroclastic sediments, from young soils in recently deposited volcanic tuffs and ashes, to the well-developed soils in older volcanic sediments with partly crystallized clays. Thus, in this subsection we include not only Andosols (WRB) or Andisols (ST) that constitute the core concept for volcanic pedogenesis, but also much less developed soils.

The evolutionary scheme for volcanic soils in Mexico is based mainly on the fundamental monograph of Mielich (1991). The first soils to form in freshly erupted volcanic ashes and tephras do not have significant differentiation into genetic horizons. The weathering is not sufficiently developed to produce secondary minerals. In ST these soils are classified as Entisols, and their volcanic origin is stressed at the subgroup level (Vitrandic subgroups). In the WRB, these soils are classified as Tephric Regosols. In any climate, these soils have a simple profile A/C, with an incipient horizon with humus accumulatives. Volcanic glass is a soil mineral component easily subjected to weathering and very soon one can visualize a shallow and pale, Bw horizon. Usually, organic matter accumulation also increases. However, the physical and chemical properties of these soils are still similar to the initial pyroclastic sediments. A combination of weak morphology with poor chemical transformation is especially typical for soils formed in acid volcanic ashes with high potassium content, which are much more resistant to weathering than Ca–Mg ashes. These soils are classified in ST as Inceptisols (Vitrandic subgroups), and in the WRB—as Tephric Cambisols. The initial processes of soil weathering lead to the formation of characteristic initial products of volcanic glass synthesis: short-ordered aluminosilicates (allophanes and imogolite) (Dahlgren and Ugolini 1989). Since the volcanic glass dissolves quickly, the soil solution has a high silica and aluminum saturation, and poorly ordered aluminosilicates readily precipitate from the solution. Iron compounds precipitate mainly as ferrihydrite. The replacement of volcanic glass by secondary products is gradual; initially, the content of short-ordered aluminosilicates is relatively low, although the other properties are already modified, e.g., increasing water-holding capacity. The soils, where volcanic glass is still a dominant component of mineral part, are already referred to a special group: Andisols order (ST) or Andosols reference group (WRB). However, to stress the immaturity of these soils they are grouped in special taxa, the Vitrands suborder in the ST, and Vitric Andosols in the WRB. Further, weathering increases the content of the short-ordered component and to the divergence of the properties of volcanic soils, depending on the initial composition of volcanic glass and bioclimatic conditions. A common feature of developed Andisols/Andosols is the presence of X-ray amorphous components (either short-ordered aluminiosilicates or Al-organic complexes), ferrihydrite, high water-holding capacity and phosphate retention, high organic matter content, low bulk density, and thixotropic aggregates (Dahlgren and Ugolini 1989). The following evolution of volcanic soils leads to clay crystallization and formation of other soils that correspond to actual pedoenvironments. The newly formed clay minerals are represented by halloysite or smectite, depending on regional and local conditions. The resulting soils are mostly classified as Alfisols (ST)/Luvisols (WRB), and in valleys and local depressions, Vertisols (ST/WRB) are common. The processes of transformation of Andisols/Andosols into “zonal” soils are well documented (Sedov et al. 2003a; Solleiro Rebolledo et al. 2003). These processes are partly responsible for differentiation of soils in the region of the Transmexican Volcanic Belt (Gómez-Tagle-Rojas 1985). The rates of transformation of primary pyroclastic materials into Andisols/Andosols depend on many factors, especially on climate and mineralogical composition of the ash and tephra. In hot humid climates, the transformation of ash takes slightly more than 1000 years, while in drier and cooler climates the process is much slower. Basic volcanic glass readily weathers under favorable climatic conditions, while K-rich acid volcanic glass can resist weathering for a much longer period. Further, crystallization of clays and formation of developed texturally differentiated soils (Alfisols/Luvisols) is a much slower process and may take several tens thousands of years (Sedov et al. 2003a).

Recently, a number of reports were published on the soils that had properties that fitted the definition of Andisols/Andosols, but formed in nonvolcanic materials, usually effusive igneous rocks (e.g., Garcia-Rodeja et al. 1987; Dümig et al. 2007). We believe that these findings show both an impressive convergence of properties of soils formed in different (though similar) parent materials and the poverty of the criteria for soil allocation in actual classification schemes. In Mexico, “Andosols” formed in nonvolcanic materials have not been described.

Soils in recent volcanic ashes are widespread in Mexico within the Transmexican Volcanic Belt, which is known for its current volcanic activity. A recent example of strong activity was reported in 1943 in Michoacán state, when Paricutín volcano formed (Arias 1944); the eruption, however, was effusive and produced mainly basaltic lavas. In the southern part of the country, in the region Sierras de Chiapas y Guatemala, volcanism is also active. The latest eruption of El Chichón volcano in 1981 produced a significant amount of volcanic ash that in places formed deposits more than 10 m thick. Some fresh volcanic ashes may be transported by water fluxes, forming layered sediments. These immature soils were described in Mexico State (Gama-Castro et al. 2000; Segura-Castruita et al. 2005) as Tephric Regosols and Tephric Fluvisols (WRB). The papers mentioned above reported that these soils had almost no differentiation into pedogenetic horizons, but had better physical properties for agricultural use because of their higher water-holding capacity.

These soils might be either acid or have a reaction close to zero, depending on bioclimatic conditions; generally, the volcanic soils found in humid areas under forest are more acid than those found in semiarid climates under grasslands. High phosphorus retention was reported for these soils; the retention was higher in soils poor in organic matter.

Extensive research has been conducted on the genesis and properties of soils in volcanic sediment by Nicolás Aguilera-Herrero (e.g., Aguilera-Herrero 1965) and his coworkers. This school discerned young soils in volcanic ashes and “ando” soils (Peña 1978, 1980; Álvarez 1983). Unfortunately, most of the publications of Aguilera-Herrero and his followers were published in the “grey” literature and now are not readily available. The research of this school covered practically all the national area, where volcanic soils were present, but focused mostly on the Andisols/Andosols of the Transmexican Volcanic Belt (Cervantes 1965; Aceves 1967; Allende 1968; Domínguez 1975; Lorán 1976; Navarro 1976; García-Calderón 1984; García-Calderón et al. 1986; Medina 1993; Valera-Pérez 1994; Tenorio 2003). The research showed that most of the developed volcanic soils of Central Mexico had deep humus-accumulative horizons with granular (“caviar”) structure and color varying from brownish to black. Fine granular thixotropic aggregates represented one of the most typical morphological attributes of these soils, independent of the bioclimatic conditions. Most probably, the hypothesis of biogenic origin of these aggregates (Dubroeucq et al. 1992a, 2002; Barois et al. 1998) is not very reliable. High aggregate stability in Andosols has been verified by the results of observation by transmission electron microscopy (TEM) of the clay fraction reported by Warkentin and Maeda (1980). Also, scanning electron microscopy (SEM) allowed the identification of microstructural aggregates of silt size in Andosols of Transmexican Volcanic Belt (Valera-Pérez et al. 1997).

A notable feature of Andisols/Andosols is that the field texture is described as greasy; this is different from the typical clay sensation in soils containing crystallized clay minerals. In most Andisols/Andosols, the texture is between clay and silt loam. However, this feature is often misleading, because it is common that the texture recognized in the field does not correspond with that obtained in the laboratory. This contradiction comes both from errors in field texture determination due to thixotropic nature of allophonic clays, and from the difficulty in soil dispersion for laboratory texture analysis.

Andisols/Andosols are commonly deep; they are often stratified as a result of periodic accumulations of pyroclastic materials. Intermittent accumulation of volcanic ash and other pyroclastic materials have a considerable impact on the genesis and morphology of Andosols (Aguilera-Herrero 1969; Valera-Pérez 1994). In active volcanic regions, where intensive pyroclastic eruptions are common (listing the Valley of Mexico, Teotihuacán valley and Nevada de Toluca volcano slopes as the best studied regions), it is common to find soils with deposits of pyroclastic material and buried soils at the depth of more than 1 m (Solleiro Rebolledo et al. 2003, 2006). In the areas close to active volcanoes, such as Popocatepetl, the accumulation of pyroclastic materials is rapid, and one can observe a series of developed buried soils within the control section in these sediments (Fig. 4.1a). In the regions remote from the sources of volcanic eruption products, the layers of ash are shallow (between 10 and 40 cm), and soil profiles are thin and underdeveloped (Fig. 4.1b) or form pedocomplexes, sinlithogenic soils with relatively equal rates of pedogenesis and sediment deposition (see Smolnikova 1967). Also thin layers of ash are

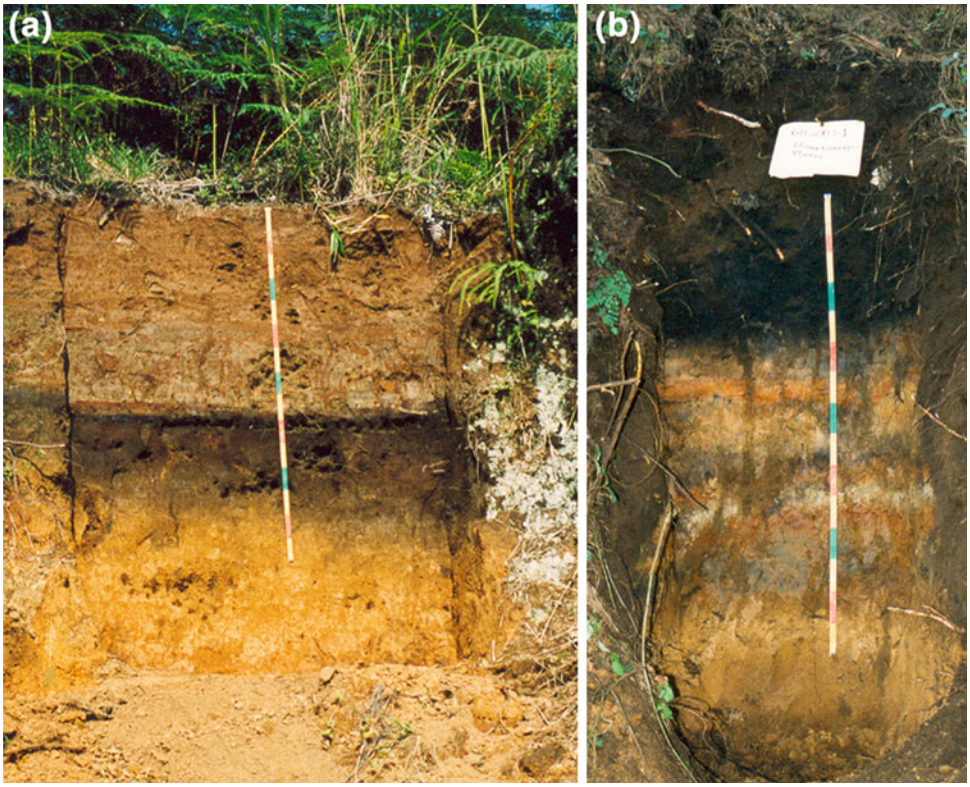

Fig. 4.1 Typical profiles of volcanic soils (Andisol/Andosol) in Puebla State: **a** a profile with a buried soil, Teziutlan district, **b** a polycyclic profile, Huauchinango district (photos by P. Krasilnikov)

easily incorporated and not readily apparent, but the ash does influence soil properties. In Mexico, these pedocomplexes are tephra-soil sequences poorly differentiated into horizons with uniform or slightly fluctuating vertical distribution of organic carbon (Mielich 1991).

Most Andisols/Andosols in Mexico have low bulk density, which is considered a diagnostic feature for this group. However, many volcanic soils have layers with high proportion of unweathered volcanic glass or, alternatively, already crystallized clays, and these layers have higher bulk density values. Aguilera-Herrero (1969, 1989) reported values of bulk density of 0.74 to 0.86 g cm^3, Alvarez (1983) reported for the Sierra Tarascan Andosols in Michoacan values between 0.68 and 0.90 g cm^{-3} and values between 0.72 and 1.22 g cm^{-3} in Andosols of the "Sierra Nevada" (DF, Mexico and Morelos states) were documented by Hidalgo (1988) and Hidalgo and Etchevers (1986), and Andosols in the region Tlatlauquitepec, state of Puebla (Saucedo et al. 1989; Saucedo 1990) had an average bulk density of 0.82 g cm^{-3}. Low bulk density values and the presence of fine short-ordered materials result in high water-holding capacity of these soils that may exceed 100 % (e.g., Ikkonen et al. 2004).

The accumulation of humus is a notable feature of the Andisols/Andosols. Humus composition in these soils in Mexico is characterized by a broad C/N ratio that varies between 8 and 20 (Aguilera-Herrero 1969). The same author reports values of 0.01–0.85 % of N in Andosols of Mexico. Of interest is the composition of organic matter in volcanic soils. Initially, all the developed volcanic soils were believed to have deep dark humus horizon; the name "ando" itself means "dark soil" in Japanese (Simonson 1989). However, further studies showed that volcanic soils might have both black horizons rich in humic acids, which have been called *melanic*, and brownish horizons where fulvic acids were dominant, which have been called *fulvic*.[1] According to common opinion (e.g., Takahashi et al. 2004), *melanic* horizons form under graminaceous vegetation, or indicate the existence of grasslands in the past, while *fulvic* horizons form under arboreal vegetation in more humid conditions. However, recent studies in Mexico demonstrated that black thick horizons occur in Mexico under humid mountainous pine and fir forests, and pale brown A horizons are more typical for drier climates and corresponding grass vegetation (Sedov et al. 2003b). These observations have been used for paleogeographical reconstruction, and showed a good correspondence with other paleographical methods (Sedov et al. 2003b). Our own experience shows no close correspondence between the

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[1] In laboratory the *melanic* and *fulvic* horizons may be distinguished using the melanic index, which is derived by dividing the absorbance spectrum intensity at 450 nm by the absorbance at 520 nm of a 0.5 N NaOH soil extract. The horizon is regarded as *melanic*, if it has melanic index less than 1.7, and as *fulvic*, if it has melanic index more than 1.7.

color of surficial horizons in volcanic soils and actual ecosystems. However, we should agree that black melanic horizons are more widespread under the shade of mountainous coniferous and cloud forests (Ticante 2000; Tenorio 2003) than under dry grasslands.

Commonly, Andisols/Andosols have a high anion adsorption capacity. The magnitude of this property affects the important nutrients assimilated with a negative charge and the effectiveness of applied fertilizers. High phosphorus retention was reported for these soils (Alcalá de Jesús et al. 2009); the retention was higher in soils poor in organic matter. The results obtained by Valera-Pérez (1994), showed a clear upward trend in the percentage of phosphate retention in soils, in inverse proportion to the increase of organic matter and a direct function of the percentage increase in aluminum and iron content assets.

One of the properties of Mexican volcanic soils is the presence of a specific cemented horizon locally called "tepetate". The indigenous term tepetate originated from náhuatl words *tetl* that meant stone or rock, and *pétlatl* that meant straw mat. Literally it meant "stone mat", and was used by Aztecs for any indurated soil layer or even for rock outcrops (Servenay and Prat 2003; Gama-Castro et al. 2007). Actually, the word is used in the scientific literature in a narrow sense, indicating hard layers in volcanic soils. In early studies, the origin of this layer was ascribed to post-volcanic diagenetic processes, but recently the hypothesis on pedogenetic formation of tepetate is believed to be more reliable (Acevedo-Sandoval and Flores-Román 2000). From the point of view of soil classification the place for this horizon is not well defined, because of the broad range of properties and types of cementation or compaction of such layers. Some tepetates are cemented by significant amounts of opal, in places in combination with carbonates or iron and manganese hydroxides (Oleschko 1990) that resembles *duripan* (*duric horizon*), the others do not have visible opal cementation (Oleschko et al. 1992) or have compaction without cementation and may be associated with *fragipan* (*fragic horizon*). Recent studies showed that opal is present in the form of extra-thin coatings even in the tepetates, which have no visible opal cementation (Poetsch 2004). Tepetates constitute a major problem for soil management, since erosion often exposes these layers to the surface, and further hampers soil management (Gama-Castro et al. 2007). However, these horizons may be crushed and then successfully used for agriculture (Flores-Román et al. 1997). The most resistant varieties of tepetates are used as constructive materials in Central Mexico.

Mineralogical composition of volcanic soils varies dependently on the stage of their development, bioclimatic, and local conditions of their formation. At the initial stage primary minerals constitute the soil, including its clay fraction. These minerals are represented by volcanic glass of various compositions (e.g., see Fig. 4.2). At the next stage short-ordered minerals form, such as allophanes and imogolite. These minerals are difficult to identify using traditional methods, such as X-ray diffraction analysis, and their presence was evidenced in volcanic soils of Mexico mainly using chemical and microscopic techniques (García-Calderón et al. 1986; Valera-Pérez 1994). In humid environments, the X-ray diffractograms of clay fractions of Andisols/Andosols show no peaks except that of primary aluminosilicates and quartz. The X-ray amorphous components may be represented either by allophane-like minerals or by Al-humus complexes; the latter materials are common in acid soils, where soil acidity is too high for allophane and imogolite formation. Further development of volcanic soils leads to conversion of poorly crystallized components into halloysite-type minerals (Vela-Correa and Flores-Román 2006). In semiarid conditions, halloysite was reported to form together with X-ray amorphous components from the very beginning (Dubroeucq et al. 1992a). Halloysite and metahalloysite are believed to be the most abundant clay minerals of aged Andisols/Andosols, especially in tepetate layers (Hidalgo et al. 2010). The concentration of halloysite in most soils is the highest in the surface horizons; the phenomenon supports the hypothesis that mineral synthesis starts from the soil surface and then extends to the deeper horizons. After crystallization the clay can move in the profile forming clay skins (Sedov et al. 2010) (Fig. 4.3), if water percolates the soil profile at least seasonally; in places clay skins may be found even in tepetates (Gutiérrez-Castorena et al. 2007).

Here, we present an example of morphological description with some chemical data of a typical volcanic soil in Cologne Ohuapan, Tlaltetela municipality, the State of Puebla (García-Calderón et al. 2007).

Geographical coordinates: 96°58′ E, 19°14′ N

Altitude: 950 m

Landform: Upper part of a slope of a watershed of eastern aspect

Slope: Complex, 15–20°.

Geology: Quaternary volcanic ash and basaltic breccias

Vegetation: *Coffea arabica* L. var. typica L., under the shade of *Inga jinicuile* (palo tinto) and oaks *Quercus sp.*

Classification (ST): Ashy, amorphic, mesic Typic Hapludand

Classification (WRB): Fulvic Andosol Bathiándic.

O1 0–3 cm—litter composed mainly of slightly decomposed leaves of coffee, oaks, and "palo tinto"; abrupt wavy boundary, bulk density (BD) = 0.58 g cm^{-1}; $\text{pH}_{\text{H}_2\text{O}} = 5.5$; cation-exchange capacity (CEC) = 40.6 $\text{cmol}_c\ \text{kg}^{-1}$.

Ap 3–14 cm—10YR 3/3 dark brown; silt loam; weak fine granular structure, friable and thixotropic; slightly plastic and adhesive; abundant fine roots, few medium, and

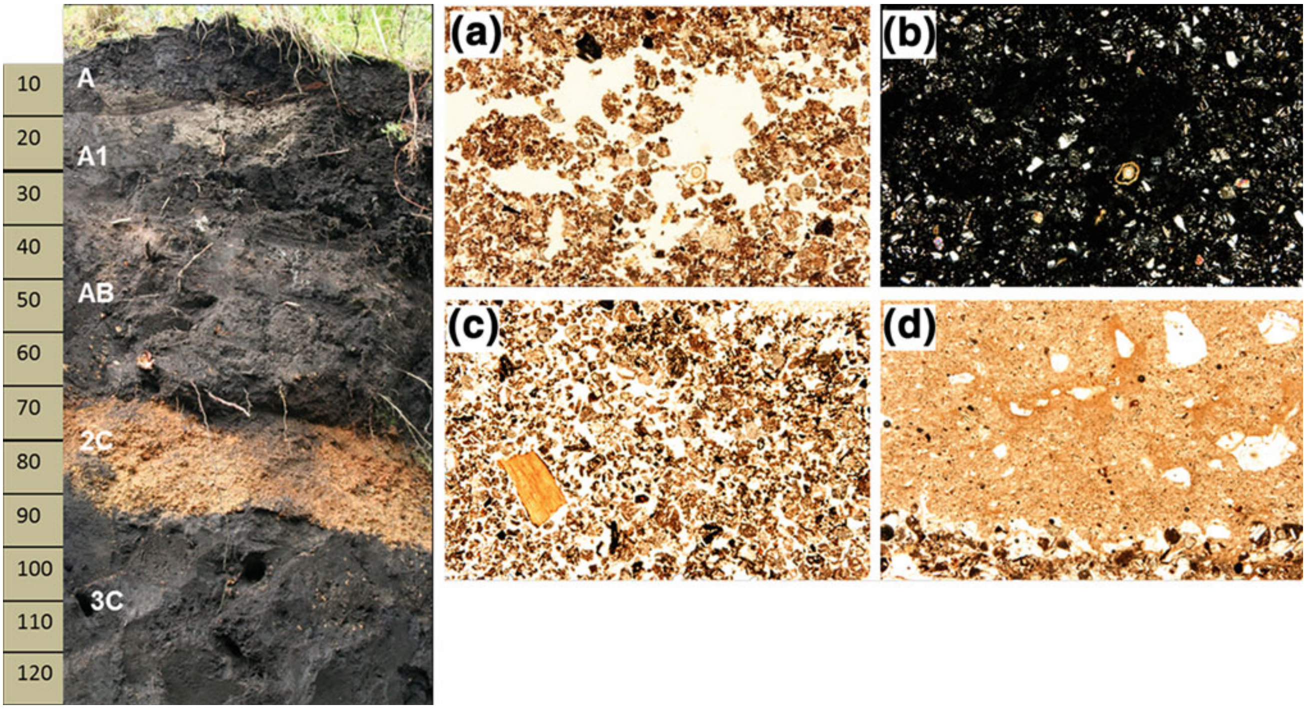

Fig. 4.2 Microstructure of an Andisol/Andosol from Popocatepl volcano, Mexico State: **a** Crumb structure, Ap horizon, **b** the same with crossed polarizers, **c** intergrain micro-aggregates structure, A/Bw horizon, **d** layers of pumice (*yellow*) and volcanic ash, 2C horizon (photos by Ma. del C. Gutiérrez-Castorena)

coarse roots, abundant very fine pores; abrupt wavy boundary; compaction = 1.75 kg cm^{-2}; $pH_{NaF} = 11.0$; BD = 0.71 g cm^{-1}; $pH_{H_2O} = 4.8$; clay content 4 %; organic C = 7.17 %; CEC = 24.1 $cmol_c$ kg^{-1}; phosphate retention 68 %; melanic index 4.70.

A12 14–24 cm—10YR 3/3 dark brown; silt loam; weak fine granular structure, friable and thixotropic; slightly plastic, and adhesive; greasy feeling; abundant fine roots, few medium and coarse roots, abundant fine pores; diffuse wavy boundary; compaction = 2.15 kg cm^{-2}; $pH_{NaF} = 11.2$; DA = 0.75 g cm^{-1}; $pH_{H_2O} = 5.1$; clay content 4 %; organic C 4.87; CEC = 23.6 $cmol_c$ kg^{-1}.

A13 24–43 cm—10YR 3/4 dark brown, silt loam, moderate medium subangular blocky structure; friable and thixotropic; greasy feeling, slightly adhesive; abundant fine roots, many medium roots; abundant fine pores; compaction = 1.17 kg cm^{-2}; $pH_{NaF} = 11.2$; DA = 0.80 g cm^{-1}; $pH_{H_2O} = 5.6$; clay content 6 %; organic C = 3.38 %; CEC = 22.6 $cmol_c$ kg^{-1}; melanic index 4.47; clear plane boundary.

AB 43–70 cm—10YR 4/4 dark yellowish brown; silt loam; medium moderate subangular blocky structure; friable and thixotropic; greasy feeling, slightly adhesive; abundant fine roots, many medium roots; very abundant fine pores; compaction = 0.75 kg cm^{-2}; $pH_{NaF} = 11.2$; DA = 0.79 g cm^{-1}; $pH_{H_2O} = 5.8$; clay content 8 %; organic C = 2.19 %; CEC = 22.4 $cmol_c$ kg^{-1}; melanic index 3.90; clear wavy boundary.

Bw 70–113 cm—10YR 5/6 yellowish brown; silt loam; moderate coarse subangular blocky structure; friable, greasy feeling; moderately plastic and slightly adhesive; many fine roots and single coarse roots; many fine pores; compaction = 2.58 kg cm^{-2}; $pH_{NaF} = 11.2$; DA = 0.79 g cm^{-1}; pH_{H_2O} 5.4; clay content 6 %; organic C = 0.3 %; CEC = 22.4 $cmol_c$ kg^{-1}; phosphate retention 72 %; diffuse wavy boundary.

2Ab 113–150 cm—10YR4/3 dark brown; silt loam; loam; weak fine granular structure; friable and very thixotropic; abundant fine and medium roots; abundant fine and medium pores; compaction = 1.25 kg cm^{-2}; pH_{NaF} =11.4; DA = 0.80 g cm^{-1}; $pH_{H_2O} = 5.6$; clay content 10 %; organic C = 1.29 %; CEC = 24.6 $cmol_c$ kg^{-1}; melanic index 4.60.

The volcanic soils are found throughout the Transmexican Volcanic Belt, including a small enclave Los Tuxtlas at the coast (Fig. 4.3), in the Sierras de Chiapas and Guatemala region, with two major volcanoes El Chichón and Tacaná, and at the Baja California peninsula in a small area around the volcano Tres Vírgenes. Poorly developed Entisols and Inseptisols (Tephric Regosols and Cambisols) derived from fresh pyroclastic sediments are widespread near El Chichón volcano and in the eastern part of Transmexican Volcanic Belt. Developed Andisols/Andosols may occur in all areas with recent volcanism, from Nayarit to Veracruz states, and cover large areas in the Sierra Nevada, Sierra de las Cruces, and Chichinautzin comprising the

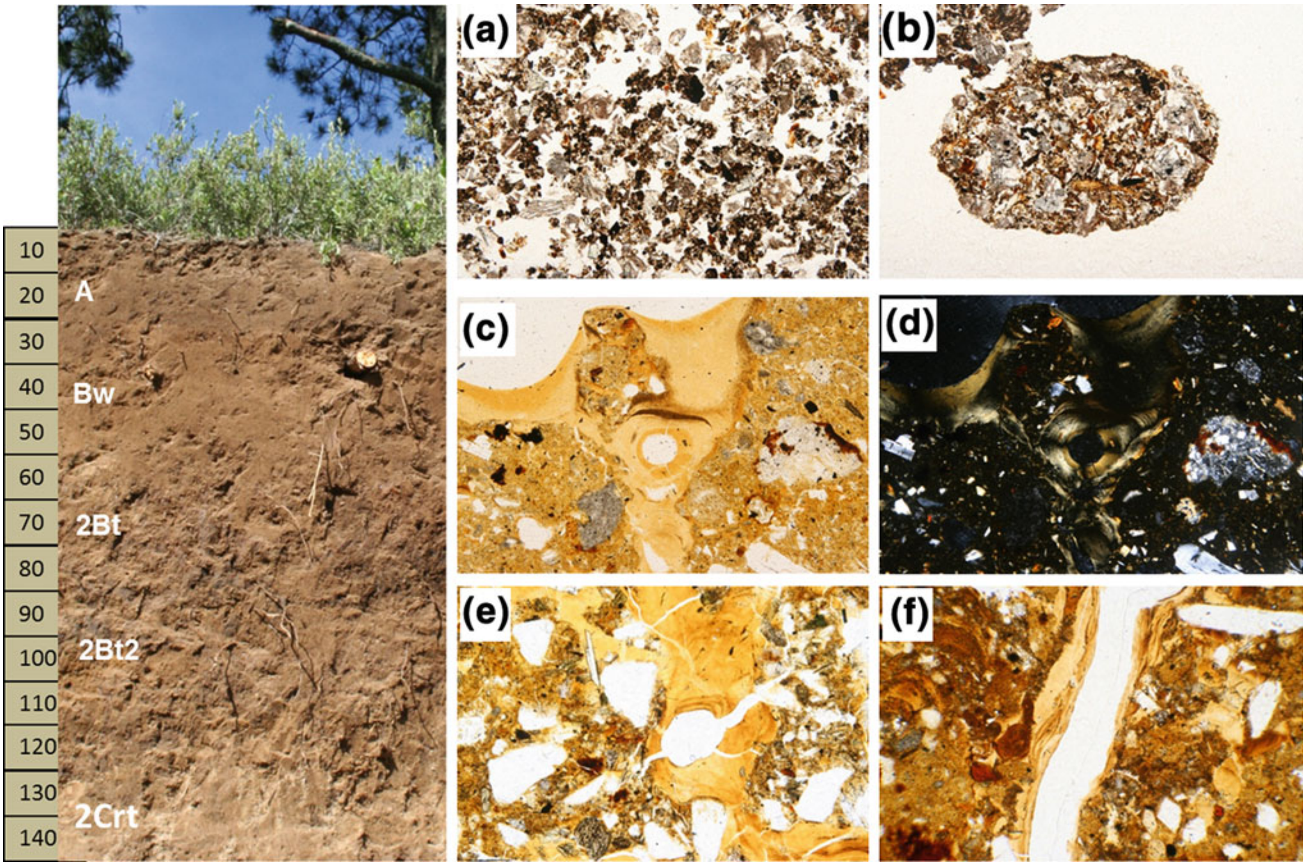

Fig. 4.3 Microstructure of an aged Andisol/Andosol from Tlaxcala State: **a** crumb structure in the A horizon, **b** mite excrements in the A horizon, **c** juxtaposed coatings of 1:1 (*whitish colors*) and 2:1 (*yellowish colors*) clay minerals in the 2Bt horizon, **d** the same as previous photo, but with crossed polarizers, **e** and **f** clay coatings in the 2Bt2 horizon (photos by Ma. del C. Gutiérrez-Castorena)

states of Mexico, Puebla, Morelos, and Mexico City. In the state of Tlaxcala they occupy the wetter areas near the volcano Malitzin, Veracruz, and in Puebla they are located in the vicinity of Cofre de Perote and Pico de Orizaba volcanos; these soils are believed to be the most typical for the country (Dubroeucq et al. 1992a, 2002). There are Andisols/Andosols on large alluvial fans and on the slopes of Xinantécatl (Nevado de Toluca), Nevado de Colima, and Volcan de Fuego in the states of Colima and Jalisco. In the state of Michoacán, they occupy large areas of the Sierra Tarascan Angangueo. In the Hidalgo state, in the Huasteca region and the Sierra Norte de Puebla, there are minor extensions of developed volcanic soils.

Volcanic soils are used in Mexico both for agriculture and forestry. The latter practice is profitable: the forests grown on Andisols/Andosols have a high average annual production in the states of Michoacán, Jalisco, and Puebla. Large areas in the state of Michoacán are occupied by avocado and fruit trees (pear, peach, and plum tree). In the states of Puebla and Veracruz, there are large areas of these soils under coffee agroecosystems with surrounding areas used for growing sugarcane or as pasture for cattle. The most valuable property of Andisols/Andosols for agriculture is their ability to retain water for weeks and months after the end of the rainy season.

A limiting factor for crop production on developed volcanic soils is their high phosphate retention, which affects field crops such as corn, oats, wheat, potatoes, and some others. Also some volcanic soils are affected by acidification that strongly increases Al activity and the crops may be affected by Al toxicity. The Andisols/Andosols are relatively resistant to soil erosion because of their high water retention capacity: surficial runoff is not very common, because the rainwater readily percolates and is retained in the soil. In mature volcanic soils, water retention is favored by large surface area is a result of the presence of poorly ordered clays (allophane, imogolite) and humic substances. However, the burning of waste corn and especially sugarcane results in the crystallization of allophane and a decline of water retention. In this case, small aggregates of the topsoil are easily transported by water and wind. Many Andosols are affected by landslides and other mass movement processes, which are also a result of its high moisture retention capacity. The soil increases its weight adsorbing water, and when passing the liquid limit, begins to slide on the hillside. These processes are especially common in sediments, where relatively recent volcanic ash has underlying clay material, e.g., a paleosol (Sedov et al. 2003b). As this situation is quite common in Mexico, the frequency of mass movements is great.

4.3 Textually Differentiated Soils

Soils with clay-enriched B horizon are represented by two orders (Alfisols and Ultisols) in Soil Taxonomy, and by five reference groups (Albeluvisols, Acrisols, Alisols, Lixisols, and Luvisols) in the WRB. The number of taxonomic groups supports the broad distribution and high variety of properties of these soils. However, we decided to discuss them under the same heading. The differences in properties, which are used for grouping these soils, include mainly base saturation and clay activity. These features well distinguish soils on a global scale, dividing base-saturated soils with 2:1 clays of temperate areas, and leached soils with 1:1 clays of tropical and subtropical regions. However, in a real soilscape, especially in the mountains, strong variation in properties may be observed, and soils of different groups may be found in close proximity. For example, slope processes in places result in a complex mosaic of strongly weathered and freshly exposed sediments (Krasilnikov et al. 2007); since clay illuviation is a relatively quick process, soils with *argillic* (*argic*) horizons form in both types of sediments. Consequently, soils in weathered sediments that have low-activity clays and low base saturation are found side by side with soils in recently exposed parent material that have active clays and high base saturation. However, the pattern of distribution of different groups of soils with clay-enriched B horizons is generally governed by bioclimatic conditions, both past and present.

The global distribution of soils with subsurface clay-enriched horizon is commonly associated with humid climates, because the main soil-forming process is believed to be downward clay movement in soil profile with percolating water. However, a number of alternative processes such as clay loss in topsoil due to horizontal water flow, or clay formation in situ in subsoil horizons were proposed (see e.g., Driessen et al. 2001). The reason for the search for alternative hypothesis was that many soils do not have any evidences of clay movement in the profile. The studies made in various parts of the United States confirmed that at least in some soils preferential weathering at certain depth might be a major mechanism of textural differentiation (Simonson 1949; Cody and Daniels 1968). Thus, the range of pedoenvironments under which clay enrichment occurs may be very wide, especially if we consider possible past wetter climates in many arid areas of the world.

Strongly weathered and leached texturally differentiated soils that correspond to Ultisols (ST) or Alisols and Acrisols (WRB) form in Mexico mainly in hot humid climates in ancient regoliths. Most of these soils have intensive reddish and reddish yellow colors. The structure varies among the horizons: the topsoil has either granular or subangular blocky structure, depending on texture, and the illuvial B horizon has strong angular blocky structure.

A description of a typical soil profile of a weathered texturally differentiated soil, located in Sierra Sur de Oaxaca Mountains, is presented below (García-Calderón et al. 2006).

Geographical coordinates: 97°06′12.9″ W and 16°07′ 41.5″ N

Altitude: 920 m

Landform: Mountain slope of W aspect

Slope: Backslope of 20–25°

Geology: Proterozoic gneisses

Vegetation: *Coffea arabica* L. var. typica L., under the shade of Tropical semideciduous forest (*Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia alliodora*, и *Ficus* spp.).

Classification (ST): Fine-loamy, mixed, subactive, thermic Typic Haplohumult

Classification (WRB): Cutanic Alisol (Humic, Chromic).

A1, 0–12 cm—Moist; dark reddish brown (5YR 3/4) when moist; clay loam; granular structure; few fine and medium gravel; abundant medium and fine pores; abundant medium and thin roots; clear plain boundary.

A2, 12–20 cm—Moist; dark brown (5YR 3/2) when moist; sandy silt loam with granular structure; few fine and medium gravel; abundant medium and fine pores and micropores; abundant thick, medium, and thin roots; earthworms, insect larvae, mites; clear wavy boundary.

AB, 20–48 cm—Moist, dark reddish brown (5YR 3/4) when moist; sandy clay loam with coarse blocky structure; a large amount of medium and fine pores; few argillans on pore walls; few fine and medium gravel; abundant thick, medium, and thin roots; insect larvae, mites; clear wavy boundary.

Bt1, 48–66 cm—Moist; reddish brown (5YR 4/6) when moist; clay loam to clay; angular blocky structure; a small amount of medium and fine pores; argillans are abundant in the pores and sparse on ped faces; few fine and medium gravel; few medium roots; gradual plain boundary.

Bt2, 66–82 cm—Moist; reddish brown (5YR 4/6) when moist; clay loam to clay; blocky structure; few medium and fine pores; abundant argillans on pore walls and on ped faces; few fine and medium gravel; few medium roots; gradual smooth boundary.

BC, 82–125 cm—Moist; reddish brown (5YR 4/6) when moist; sandy silt loam; coarse blocky structure; few medium and fine pores; few argillans on pore walls and on ped faces; few fine and medium gravel; gradual smooth boundary.

C, 125–150 cm—Moist; reddish brown (5YR 4/6) when moist; sandy silt loam; coarse blocky structure; few medium and fine pores; abundant fine and medium gravel.

In most soils there is no bleached *albic* horizon; if any is present, it results from the accumulation of recent colluvial material (e.g., Krasilnikov et al. 2005; Krasilnikov and García-Calderón 2005). A description of such a profile is presented below (see also Fig. 4.4a):

Geographical coordinates: 96°23′19″W 15°54′48″ N

Altitude: 770 m

Landform: Mountain slope of SW aspect

Slope: Convex slope of more than 30°

Geology: Proterozoic gneiss and anorthosite

Vegetation: *Coffea arabica* L. var. typica L., under the shade of Tropical semideciduous forest (*Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia alliodora*, and *Ficus* spp.).

Classification (ST): Fine kaolinitic, thermic Typic Haplohumult

Classification (WRB): Cutanic Albic Alisol (Ruptic, Chromic).

A, 0–40 cm—Moist; dark reddish brown (5YR 3/3) when moist; gravelly clay loam; crumb–granular structure; abundant medium and thin pores and micropores; few argillans on pore walls; few fine and medium pebbles; few cobbles; abundant thick, medium, and thin roots; earthworms; insect larvae; ticks; clear wavy boundary.

EB, 40–66 cm—Moist; pink (5YR 7/4) when moist; gravelly clay loam; crumb and angular blocky structure; abundant medium and thin pores; abundant pebbles; few cobbles; few thick and medium roots; ticks; clear wavy boundary.

2Btb, 66–100 cm—Moist; dark red (2.5YR 3/6) when moist; clay loam to clay; subangular and angular blocky structure; a small amount of medium and thin pores; abundant argillans on pore walls and on ped faces; few fine and medium pebbles; few medium roots.

In places soils have a thin layer on the surface composed of recent volcanic ashes. The color of these layers depends on the composition of ash and recent organic matter accumulation. In some profiles, whitish acid volcanic ash forms a layer that may be mistakenly described as an *albic* horizon. For example, we described a profile of a Hapludalf (ST)/Novic Cutanic Luvisol (WRB) in the catchment of Peña Camello river, Michoacán state (near the city of Morelia) under the shade of a mountainous pine-oak forest. The region is known to be affected by periodic accumulation of pyroclastic materials. In the soil profile, the A horizon is poorly developed (2–4 cm thick), it is grayish brown sandy loam with platy structure. Below there is an almost unaltered by pedogenesis horizon AC (4–35 cm) composed of recent volcanic ash. It is light brown sandy loam with some humus mottles and, with subangular blocky structure and few roots. Below there is a series of 2Bt horizons down to 80 cm, all of them have intense crimson-red color, the texture is loam to clay loam, the structure is angular blocky (prismatic), with evident argillans on the surface of the soil aggregates. Lower in the profile there is nearly unaltered poorly consolidated andesitic tephra (2C horizon). Field tests with NaF and phenolphthalein, which is believed to detect active aluminum or allophanes, showed strong reaction in the two topsoil horizons, and practically no reaction in the 2Bt and 2C horizons. The absence of reaction in the *argic* (*argillic*) horizons confirms the hypothesis of crystallization of clays in older pyroclastic sediments, which is one of the requirements for clay illuviation. Early studies in places mistakenly reported these soils as Podzols, and due to that even Podzols were reported in mountainous zones of Western Mexico at the FAO Soil Map of the World. Even more pronounced whitish layer may be observed in some regions in San Luís Potosí state, although the region is far from the active volcanic zones. A soil profile prepared in Garrochitas, San Luís Potosí, for the field tour of the International Conference “Soil Geography: New Horizons” (organized by INEGI and UNAM) is shown in Fig. 4.4b. The description of the profile is presented below.

Geographical coordinates: 22°09′36.5″ N and 100°42′ 10.2″ W

Altitude: 770 m

Landform: Mountain slope of SW aspect

Slope: Plane slope of 5–10°, with strong gulley erosion.

Geology: Pyroclatic deposits of various ages over basaltic material.

Vegetation: Grasslands with *Bouteloua gracilis*, *Aristida laxa*, *Muhlenbergia rigida* and various herbaceous species: *Salvia ballotaeflora*, *Heliotropium* sp., *Dalea lutea*, *Dyssodia acerosa*, *Ageratum corymbosum*, *Dyssodia setifolia*, *Brickellia veronicifolia*, *Xanthocephalum dracunculoides*, *Eryngium comosum*, and *Verbena canescens*.

Classification (ST): Fine-loamy, glassy, active, thermic Typic Durustalf

Classification (WRB): Vitric Cutanic Luvisol (Manganiferric, Ruptic, Siltic, Chromic, Novic, *Duric*).

Ap, 0–17 cm—dry; color: dark yellowish brown 10YR4/4 (moist) and light yellowish brown 10YR6/4 (dry); clay loam; coarse strong angular blocky structure; consistence: extremely hard when dry and friable when moist; very sticky and moderately plastic; abundant fine roots and

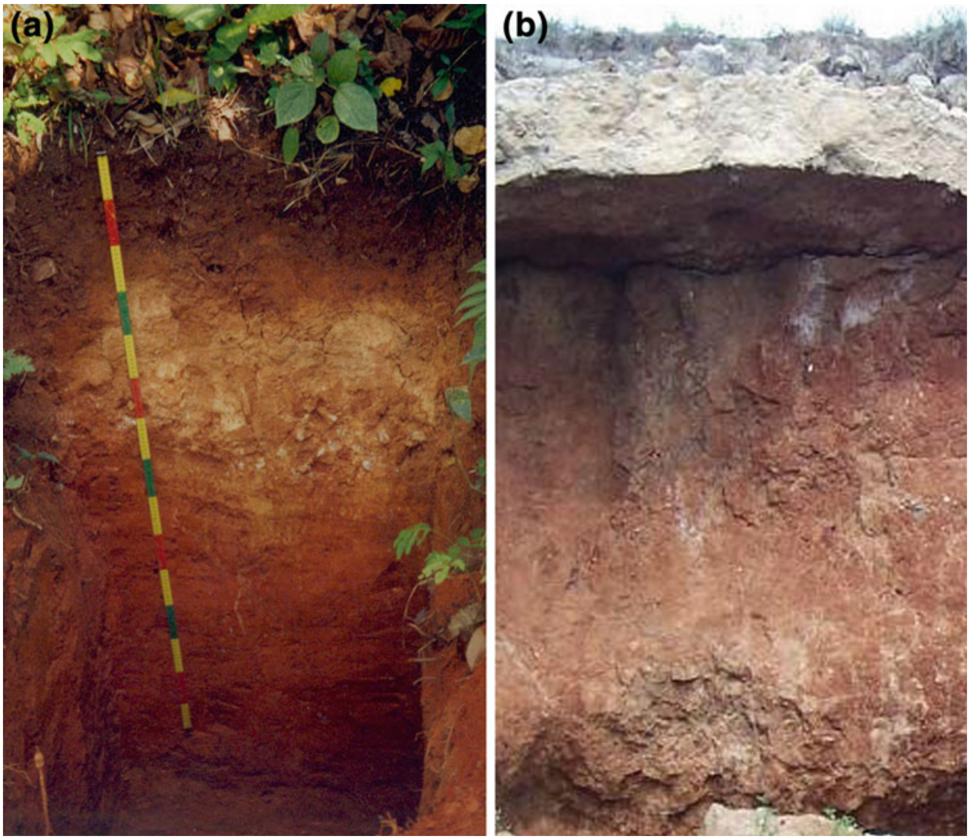

Fig. 4.4 Texturally differentiated soils: **a** Udult/Alisol with whitish colluvial material in the topsoil, Sierra Sur de Oaxaca (photo by P. Krasilnikov), **b** a polygenetic texturally differentiated soil in Garrochitas, San Luís Potosí (photo by C.O. Cruz-Gaistardo)

frequent medium roots; clear wavy boundary to the underlying horizon.

Bw, 17–29 cm—slightly moist; color: strong brown 7.5YR6/4 (moist) and light brown 7.5YR6/4 (dry); clay loam; medium strong angular blocky structure; consistence: hard when dry and friable when moist; very sticky and moderately plastic; fine cracks; few fine and medium roots; abrupt wavy boundary to the underlying horizon.

2Bt1, 29–48 cm—slightly moist; color: brown 7.5YR4/4 (moist) and light brown 7.5YR6/4 (dry); clay loam; coarse moderate subangular blocky structure; consistence: hard when dry and friable when moist; very sticky and moderately plastic; abundant clay coatings; fine cracks; frequent fine roots; abrupt plain boundary to the underlying horizon.

2Bt2, 48–75 cm—slightly moist; color: brown 7.5YR4/4 (moist) and light brown 7.5YR6/4 (dry); clay; coarse strong angular blocky structure; consistence: very hard when dry and friable when moist; very sticky and moderately plastic; few black small manganese nodules; clay coatings present; fine cracks; frequent fine roots; abrupt wavy boundary to the underlying horizon.

2C1, 75–96 cm—moist; color: brown 7.5YR5/4 (moist) and light brown 7.5YR6/4 (dry); clay; massive to coarse strong angular blocky structure; consistence: extremely hard when dry and very firm when moist; non-sticky and non-plastic; many cracks; few fine roots; large frequent mottles 5YR4/4; abrupt wavy boundary to the underlying horizon.

2C2, 96–120+ cm—moist; color: brown 7.5YR5/4 (moist) and pink 7.5YR7/4 (dry); massive; clay; consistence: extremely hard when dry and firm when moist; moderately sticky and slightly plastic; abundant medium mottles 5YR3/4.

Micromorphological observations show that the upper horizons of this soil consist mainly of volcanic glass (Fig. 4.5a and b). The A horizon is well aggregated by organic matter (Fig. 4.5a). The *argillic* (*argic*) horizons of this soil consist of ancient volcanic sediments that have transformed into the course of weathering into clayey masses, and clay illuviation is abundant in all the B horizons (Fig. 4.5c and d). The mineralogical study of the clay fraction of the soil showed that there were almost no crystallized clay minerals in the upper horizons, while the B horizons had a significant amount of mixed-layered illite-vermiculite. For details see the Field Guide published by INEGI (Sojo-Aldape et al. 2009).

Alfisols (ST)/Luvisols and Lixisols (WRB) are common all over the country and may form in a wide range of sediments. In Mexico, these soils are located mostly in subhumid and semi-arid areas, although they occur in the drier, or in the more humid parts of the country. They have perhaps the widest ecological range in Mexico, from tropical rainforests to the deserts of the north. Availability of clay illuviation in areas with a relatively low ratio of precipitation to evaporation is due to the fact that almost all the

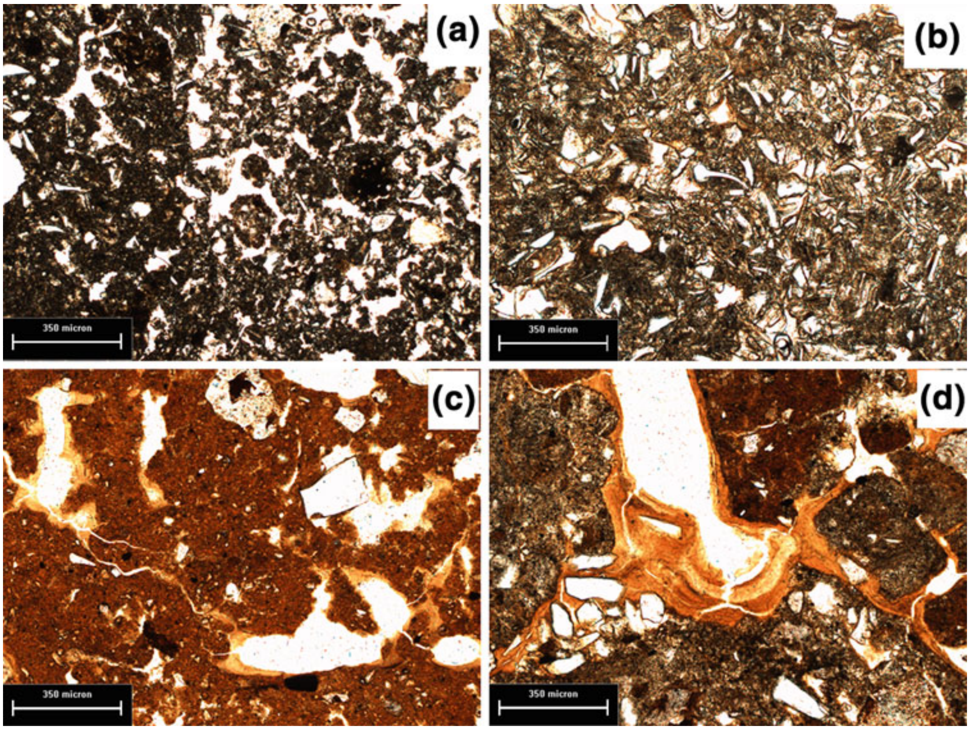

Fig. 4.5 Microscopic photos of thin sections derived from the horizons of Durustalf/Luvisol in Garrochitas, San Luís Potosí: **a** Ap horizon (0–17 cm), **b** Bw horizon (17–29 cm), **c** 2Bt1 horizon (29–48 cm), **d** 2Bt2 horizon (48–75 cm) (photos by S. Sedov)

annual precipitation occurs during the wet season, which lasts 4–5 months, that is, even in the semi-arid zone of the Valley of Mexico during the rainy season the monthly rainfall reaches at least 100–150 mm, which provides washing, leaching, and clay illuviation in soil profiles. Traditionally, it was believed that texture-differentiated soils (Luvisols or Argids in the terminology of Soil Taxonomy) in the northern arid areas of Mexico are relics of a more humid climates, but recent work by French researchers in the desert Chihuahua (Ducloux et al. 1995) suggests that textural differentiation is the result of neoformation of smectite and palygorskite clays in soils rather than their clay illuviation.

However, the majority of soils with textural differentiation of the profile may be found in humid and subhumid environments. Below we present a typical profile of an Alfisol/Luvisol formed under the shade of a mountainous forest; the mean annual precipitation is about 2,000 mm, according to the closest meteorological station. The profile was described in the natural reserve ‘Sierra Gorda’, near the village Puerto de San Agustín, municipality of Landa de Matamoros, Querétaro state (Krasilnikov and García-Calderón, unpublished data).

Geographical coordinates: 99°54′ W and 21°65′ N

Altitude: 1,570 m

Landform: Medium part of a hillslope of W aspect

Slope: Back slope of 30°

Geology: Cretaceous argillites and shales

Vegetation: Montane cloud forest: *Liquidambar styraciflua*, *Carpinus caroliniana*, *Clethra mexicana*.

Classification (ST): Fine, mixed, active, mesic Typic Hapludalf

Classification (WRB): Cutanic Luvisol (Humic).

O, 0–2.5 cm—litter

Ah, 2.5–6 cm—Moist; dark greyish brown (7.5YR 2.5/3) when moist; silt loam; fine granular structure; single stone and gravel; friable, slightly adhesive and plastic; abundant pores; abundant medium roots, few fine and coarse roots; many termites; clear wavy boundary.

A1, 6–20 cm—Moist; dark greyish brown (7.5YR3/2) when moist; loam; moderate fine and medium subangular blocky structure; single stones and gravel; friable, slightly adhesive and plastic; abundant pores; abundant fine and very fine roots, many medium roots; few termites; clear irregular boundary.

B11, 22–40 cm—Moist; strong brown (7.5YR4/3) when moist; clay loam; weak medium and coarse angular blocky structure; adhesive and slightly plastic; few stones and gravel; abundant pores; clay coatings in pores; many fine and very fine pores, few medium and single coarse roots; biogenic tunnel about 2 cm in diameter; clear irregular boundary.

B12, 40–70 cm—Moist; strong brown (7.5YR 5/4) when moist; clay; moderate coarse and medium angular blocky structure; adhesive and plastic; few stones and gravel; many pores; abundant clay skins in pores, single clay skins on ped surfaces; few fine and very fine roots; clear irregular boundary.

B13, 70–90 cm—Moist; strong brown (7.5YR 5/4) when moist; clay; strong coarse angular blocky structure; moderately adhesive and plastic; few stones and gravel; many pores; abundant clay skins in pores and on ped surfaces; few fine and single coarse roots; clear wavy boundary.

B14, 90–110 cm—Moist; yellowish brown and yellow (7.5YR6/8 and 8/3) when moist; clay; strong coarse angular blocky structure; adhesive and moderately plastic; many stones and gravel; many pores; abundant clay skins in pores and few on ped surfaces; few fine and medium roots; clear wavy boundary.

BC, 110–143 cm—Moist; brownish yellow (7.5YR5/8) when moist; clay; strong coarse angular and subangular blocky structure; moderately adhesive and plastic; abundant stones and gravel; many pores; single fine roots; sharp wavy boundary.

R, 143–150 cm—Weathered shale.

The microstructure of this soil may be seen in Fig. 4.6.

Generally, Alfisols/Luvisols may form in a wide variety of soil-forming rocks. They are common in volcanic ash; their distribution is hardly associated with current climatic conditions, since most of them are exhumed paleosols formed on Pleistocene ashes (Sedov et al. 2003a). These exhumed reddish soils are particularly widespread on the eastern and western extremities of the Transmexican Volcanic Belt, in the states of Puebla and Michoacan, respectively. The recent cover of volcanic ash is rather thin there, and in places it was completely washed away, exposing the red-clay weathering products of the older pyroclastic products reworked by pedogenesis. In such areas, for example, in the catchments of Pátzcuaro and Zirahuén lakes near Morelia, Michoacan, red-colored Alfisols/Luvisols form a complex erosional mosaic with less developed (García-Calderón et al. 2007).

Alfisols/Luvisolos occur in areas with humid tropical or subtropical climates in red clayey limestone eluvium (terra rossa), for example, at the plains of Yucatan (May-Acosta and Bautista-Zuñiga 2005) and in the mountains of Chiapas (Zenil-Rubio 2011). In montane cloud forests of Tamaulipas, National Park "El Cielo", texturally differentiated soils also form in relatively thin red clay derived from limestone rock weathering (Bracho and Sosa 1987).

Base-saturated soils with argillic/argic horizon may have either active or low-activity clays. In Soil Taxonomy, Alfisols with low-activity clays are included in Kand- and Kanhapl-great groups; in WRB, the soils with active clays are included in Luvisols reference group, and those with low-activity clays—in Lixisols group. The soils with low-activity clays mostly form in ancient sediments, and some were redeposited. For example, in Puebla state, near the town Jicotecpec de Juárez there is a zone of accumulation of ancient lacustrine sediments, mainly of kaolinitic composition. These deposits originated from ancient strongly weathered soils located upper on the slope, which have been moved by water fluxes and accumulated in the local lake depression. This zone is an important kaolin mining area;

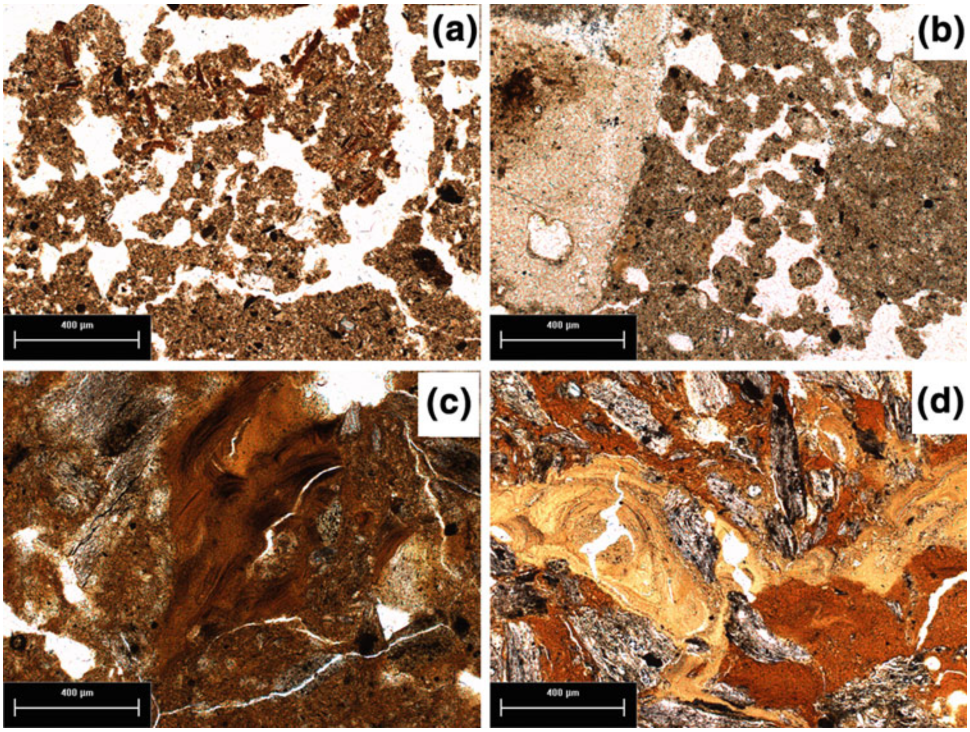

Fig. 4.6 Microscopic photos of the horizons of the Typic Hapludalf/Cutanic Luvisol, Puerto de San Agustín, Querétaro state: **a** biogenic structure in the A horizon, **b** mineral weathering and excrements of mites in the AE horizon, **c** humus-enriched clay coatings and compact structure in the B12 horizon, **d** thick clay coatings of various generations in the BC horizon (photos made by S. Sedov)

the soils, if not buried by recent volcanic ash, have base-saturated clay-enriched horizon with mainly low-activity clays (*kandic* or *argic* horizon). Also in places one can find soils with low-activity clays and high base saturation (Lixisols) in the semi-arid regions, where in previous more humid epochs the weathering and leaching were both active; present climate favors base accumulation rather than leaching. In other environments Lixisols seldom occur, and most of the reports of their findings in Mexico appeared to be erroneous (Bautista-Zuñiga et al. 1998; Sommer-Cervantes et al. 2003).[2]

The mineralogical composition of soils with clay-enriched horizons varies widely, because of the diversity of the group. For soils with illuviated clays the requirement is the presence of crystallized clays, because poorly ordered aluminosilicates cannot move in the soil profile with percolating water. Also, the presence of calcium carbonate inhibits clay illuviation. However, in some surface paleosols secondary carbonates occur as a result of recent eolian activity under arid conditions. Also the presence of carbonates of either lithogenic or pedogenetic origin may indicate that the soil formed by alternative process of clay enrichment, e.g., by aeolian accumulation of coarser material on the surface, selective erosion of fine particles in the topsoil, new clay formation in the subsoil, and so on. Usually, an attentive study of soil morphology helps discovering the path of soil formation in these doubtful cases.

The soils with low-charge clays by definition have mostly kaolinite in the fine fractions. Gibbsite is less common (see, for example, García-Calderón et al. 2006 and Krasilnikov et al. 2007). In soils with more active clays, a variety of layer silicates are present, depending on the parent material. In soils derived from pyroclastic material, the most common clay components are halloysite and metahalloysite (e.g., Sedov et al. 2003a). Smectite may be present, if the source material contains significant amounts of this mineral. In the latter case, the *argillic*/*argic* horizons exhibit some properties similar to that of shrinking and expanding soils (Vertisols), such as cracking in the dry state, and the presence of stress cutans.

All the soils with clay-enriched horizons are extensively used in agriculture and as such are subjected to strong degradation. Alfisols/Luvisols are highly productive soils; they are used for such crops as corn, wheat, barley, and beans. Also they were shown to be good for avocado, coffee, and a number of local crops of minor commercial use. Soil erosion is the major problem, especially in mountainous and hilly areas of Mexico. Forestry use of these soils decreases the losses due to erosion. The productivity of pine and pine-oak forests grown on such soils is high, and the forest vegetation protects soils from erosion.

With a scarce reserve of nutrients, aluminum toxicity issues, high phosphorus sorption, crusting, and very high erodibility, Ultisols/Acrisols are generally less productive soils. However, they are also used for crops with low demand for nutrients and tolerant to excessive acidity, such as pineapple or coffee plantations. Forestry use should be especially encouraged on these soils. A good option is closed-canopy coffee growing, which has been successfully used in Mexico for more than 150 years. The practice involves partial cutting of the original forest vegetation and cultivating coffee under the shadow of remaining trees. The productivity of these coffee plantations is relatively low, but the quality of coffee is high (Staver 1998).

4.4 Soils with Brownish Poorly Differentiated Profile

The soils with weakly differentiated brownish profiles are common all over the Mexican territory. Rozanov (1977) observed underdeveloped brown soils are widespread in all the mountainous systems, independently on bioclimatic conditions. The formation of poorly developed soils on the slopes of the mountains was ascribed to low pedogenesis rate of the soils in the conditions of continuous sheet erosion (see Birkeland 1984). Rozanov (1977) even stated that immature brown soil dominated in all the mountainous systems; a slightly speculative statement, because opposite examples are numerous. At least for Mexico brown soils, though being ubiquitous, do not form the dominant component of soil mantle; the most common situation in Mexican mountains is a combination of mature, moderately developed, and shallow strongly eroded soils (e.g., Krasilnikov et al. 2011).

Taxonomically, most of these soils fit into the order of Inceptisols in Soil Taxonomy and Cambisols in WRB. However, the concept of these taxa is much broader than brown soils with minor translocation of the products of pedogenesis. Actually, all the soils with morphologically evident pedogenetic horizon lacking specific diagnostic horizons are referred to Inceptisols/Cambisols. As a result, these taxonomic groups are practically midden heaps for all the soils with underdeveloped properties, indifferently on the path of their development. Consequently, in real geographic space Inceptisols/Cambisols form combinations

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[2] A typical error in the classification of soils with *argic* horizon is that the authors forget to recalculate the cation exchange capacity (CEC) on the clay content. In accordance with the definition of Lixisols, these soils have base saturation >50 % and CEC of the clay fraction <24 $\mathrm{cmol_c\ kg^{-1}}$, with CEC of the clay calculated as soil CEC multiplied by 100 % and divided by the percentage of clay fraction. For example, the activity of a soil containing 20 % of clay and having CEC = 10 $\mathrm{cmol_c\ kg^{-1}}$ will be 50 $\mathrm{cmol_c\ (kg\ of\ clay)^{-1}}$. If you forget to do this simple operation, Luvisols would be incorrectly classified as Lixisols.

with all the soil taxonomic units, showing a kind of circumference around more developed soils in all the areas where the pedogenetic factors potential is lower, or where erosion or sediments deposition hamper soil formation.

To make a long story short, we can distinguish the following pedogenetic groups of brown poorly differentiated soils in Mexico.

1. Mountainous soils formed on the slopes freshly exposed by slope processes or affected by continuous sheet erosion. These soils are common in humid areas, and constitute a common component of a mosaic with more developed soils, for example, Ultisols/Alisols or Alfisols/Luvisols, and shallow strongly eroded soils (see examples in Krasilnikov et al. 2007, 2011).
2. Soils formed in arid and semiarid regions, where, on the one hand, the precipitation is not enough for significant clay illuviation, and on the other hand, local conditions do not favor the accumulation of carbonates, gypsum, or soluble salts. These soils correspond mainly to the Cambids suborder in Soil Taxonomy, though the moisture regime is not restricted to *aridic* one.
3. Soils formed in calcium carbonate-rich sediments, from limestone to flysch. Conceptually, these soils are close to the concept of *terra fusca* (Kubiëna 1970), the soils derived from limestone by residual accumulation of silicate components in the course of carbonate dissolution. In contrast to reddish *terra rossa* soils that form mostly in mediterranean or humid tropical areas, brownish terra fusca is usually found under more temperate climates. The high proportion of silicate clay and silt in flysch favors the formation of deep brown soils. In Mexico, these soils are abundant in Sierra Madre Oriental, in places they form a mosaic with rendzinas—humus-rich shallow soils on limestone rock (Rendolls/Rendzic Leptosols).
4. A small group of strongly acid soils form under the shade of low montane cloud forests. These soils have been described in Sierra Juarez mountains that constitute the northernmost part of Sierra Medre del Sur (Bautista-Cruz et al. 2005; Álvarez-Arteaga et al. 2008). These soils are classified as Dystrudepts/Folic Cambisols (Hyperdystric).

Since the genetic origin of these soils may be different, their properties and potential use also vary. A typical profile of mountainous soil with poorly differentiated profile is presented below (for details see Krasilnikov et al. 2005). Figure 4.7 illustrates this soil.

Geographical coordinates: 97°06′12.9″ W and 16°07′ 41.5″ N

Altitude: 730 m

Landform: Mountain slope of W aspect

Slope: Back slope of 30°

Geology: Proterozoic gneisses and anortosites

Vegetation: *Coffea arabica* L. var. typica L., under the shade of Tropical semideciduous forest (*Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia aliodora*, and *Ficus* spp.).

Classification (ST): Loamy-skeletal, mixed, active, thermic Dystric Eutrudept

Classification (WRB): Haplic Cambisol (Skeletic, Eutric).

O, 0–3 cm—litter

A, 3–30 cm—Slightly moist; yellowish brown (10YR 5/4) with light brown (7.5YR 6/4) mottles; sandy loam; fine and medium weak granular structure; stoniness 30 %; few

Fig. 4.7 Dystric Eutrudept/Haplic Cambisol, Sta. María Huatulco, Oaxaca State (photo by P. Krasilnikov)

coarse and medium roots, abundant fine and very fine roots; worms, biogenic tunnels; porous; wavy clear boundary.

ABw, 30–70 cm—Slightly moist; light brown (7.5YR 6/4) with reddish yellow (7.5YR 6/6) mottles; sandy loam; medium weak granular and fine weak subangular blocky structure; stoniness about 80 %; few medium roots; very few worms; slightly porous; smooth gradual boundary.

CR 70 + cm—Slightly moist; reddish yellow (7.5YR 6/6); loamy sand; stoniness over 90 %.

The soil has a relatively low pH (between 5 and 6), but high base saturation (>60 %). It has organic C concentration >1 % throughout the profile, about 2 % of nonsilicate iron, extracted with sodium dithionite-citrate-bicarbonate solution, and has in its exchangeable complex Ca as the main cation.

An example of strongly acid mountainous soil is shown below. The profile was described in the mountainous system Sierra Juárez within the Sierra Norte de Oaxaca, Tuxpan area, the municipality of San Felipe Usila. See Álvarez-Arteaga et al. (2008) for details.

Geographical coordinates: 96°32′55″ W and 17°38′ 41″ N

Altitude: 1,520 m

Landform: Mountain slope of EN aspect

Slope: Back slope of 20–25°

Geology: Proterozoic mica-chlorite schists

Vegetation: Mountain cloud forests (transition zone to tropical rain forest), 52 arboreous species, including *Cyrilla racemiflora* L., *Ticodendron incognitum* Gómez-Laurito & LD Gómez, *Pinus chiapensis* (Martínez) Andresen, *Podocarpus matudae* Lundell., *Zinowiewia* sp., and *Liquidambar styraciflua* L.. Abundant bromeliads, orchids, palms on the ground and other species characteristic of the rain forest.

Classification (ST): Coarse-loamy, mixed, active, mesic Humic Dystrudept

Classification (WRB): Folic Cambisol (Humic, Hyperdystric).

O1, 0–10 cm—Litter of varying degrees of decomposition, remains of fallen branches and tree trunks, mostly overripe, rotten fragments of wood and green mosses.

O2, 10–18 cm—Moist; very dark brown (10YR 2/2); very friable; slightly plastic; weak granular structure; roots of all sizes occupy about 50 % of the horizon; single hyphae of fungi; wavy clear boundary.

H, 18–30 cm—Slightly moist; black (10YR 2/1); strong granular and fine subangular blocky (lumpy) structure; the horizon contains more mineral material than the horizon above; slightly plastic; friable; many fine roots, few medium and large roots; clear way boundary.

AE, 30–40 cm—Slightly moist; brownish–yellow (10YR 6/6); sandy loam to silt loam; medium moderate subangular blocky structure; slightly plastic; soil aggregates in the upper part of the horizon are permeated with humus, gravel, and crushed stone (chlorite schists and quartz) constitute about 10 % of the horizon; single coarse roots, rare medium, and fine roots; clear wavy boundary.

Bw1, 40–75 cm—Moist; yellowish–brown (10YR 5/6); sandy loam to silt loam; moderate medium angular blocky structure; some thin clay coatings on ped faces; rare fine and medium roots; gravel and crushed stone (chlorite schist, to a lesser extent quartz) constitute less than 10 % of the horizon; gradual wavy boundary.

Bw2, 75–140 cm—Moist; reddish–yellow (7.5YR 6/8); sandy loam; moderate medium angular blocky structure with some prismatic aggregates; thin clay coatings on ped faces; few fine and medium pores; single fine and medium roots, including dead ones; gravel and crushed rock (mainly chlorite schist with single quartz fragments) occupy 10–20 % of the horizon; gradual wavy boundary.

BC, 140–165 ↓ cm—Moist; brownish–yellow (10YR 6/6); sandy loam to silt loam; weak coarse subangular blocky structure; slightly plastic; compact; boulders; and gravel (predominantly chlorite schist with rare fragments of quartz) constitute 30–40 % of the horizon's volume; single fine and medium roots.

The soil is strongly acid, with pH of water extraction between 2.8 and 4.3; the lowest pH values occur in the topsoil. The base saturation is extremely low: in mineral horizons it varies between 1 and 2 %. Organic matter content is high, down to 70 cm depth organic C concentration is over 2 % (Álvarez-Arteaga et al. 2008). Genetically, these soils are close to Spodosols/Podzols, but the aluminum and iron compounds concentrate mainly in the surficial mineral horizon. The dominant minerals of the clay fraction of these soils are gibbsite and kaolinite, that resembles strongly weathered tropical soils like Oxisols/Ferralsols, but in contrast to the latter groups the studied brown soils of montane cloud forests have a big reserve of weatherable minerals and high CEC.

Due to universality of brown poorly differentiated soils for Mexican territory, it is difficult to name common physical and chemical properties. Also the land use and limiting factors for agriculture vary in a wide range. Generally, there are soils suitable for various uses, because they lack such negative features as excessive moisture, strong compaction, indurated layers, or strong phosphorus retention. For some brown soils in the mountain stoniness and susceptibility to erosion may be limiting factors for their use in agriculture.

4.5 Soils with Developed Humus-Enriched Topsoil

Soils with well-developed humus horizon (mollic or umbric), even if you do not take into account the dark-colored volcanic soils, are widely represented in Mexico.

In the WRB, these soils refer to four reference groups: Chernozems, Kastanozems, Phaeozems, and Umbrisols. In Soil Taxonomy, the soils with a mollic epipedon are all classified as Mollisols, and those with an umbric horizon mostly fit into Humic Great Groups of Dystrudepts.

The climates typical for humus-enriched soils vary from humid to subarid that are easy to show using the WRB terminology. The most humid conditions are typical for Umbrisols, which have the whole profile leached and unsaturated with bases. Subhumid environments correspond to Phaeozems that are less leached, have base saturation over 50 %, but have no secondary carbonates. Chernozems, initially associated with subhumid to subarid climates of Russian steppes, have high base saturation and secondary carbonates. Kastanozems correspond to even drier climates; this group is poorly defined in the WRB, because it has the same set of diagnostics as Chernozems, but Kastanozems have slightly lighter color of the mollic horizon. In Mexico, the variation in climatic conditions is great, and all these groups may be found at the territory of the country. The correspondence of the WRB groups with Soil Taxonomy units is complex (Krasilnikov et al. 2009). Umbrisols correspond to several Great Groups of Inceptisols, such as Humic, Lithic Humic, and Humic Psammentic Dystrudepts. Phaeozems mainly fit into Udolls and Rendolls, Chernozems—into both Udolls and Ustolls, and Kastanozems—into Ustolls and Xerolls. The correspondence is not perfect, because different criteria are used for classifying these soils in different systems.

Kastanozems/Ustolls and Xerolls in Mexico are common in subhumid and semiarid regions. In dry areas, the accumulation of humus and its chemical composition (high proportion of fulvic acids), determine relatively light color of the humus horizon (chroma higher than 2 in moist state). The name Kastanozems, derived from the word “chestnut, castaneous”, is not really characteristic for the group; in many cases, the color of the mollic horizon is reddish or pale. Overall, the average color of the surface horizon clearly refers to the semiarid conditions, which favor the dominance of fulvic acids in the composition of soil organic matter (Driessen et al. 2001). Also the color of humus horizon depends on the processes of biochemical transformation of organic matter into soil profile. The black color indicates strong internal oxidation of humus compounds that depends on soil moisture regime. It is known that dark colors are typical for epipedons of soils in high altitudes, where the temperatures drop in winter below zero: freezing favors coagulation of humic substances and formation of more condensed black components. In most of the Mexican territories, the winter temperatures seldomly drop below zero, which may explain the light color of the topsoil even of the soils rich in organic matter. In some profiles, the color of the topsoil depends to a large part on the color of parent material and/or on mixing of shallow dark surficial horizon with brownish B horizons by tillage.

Secondary calcium carbonates constitute an essential component of these soils. The formation of pedogenetic calcite is one of the most common processes in soils: primary calcium carbonates dissolve, saturated solution moves downwards with percolating water, and secondary calcite precipitates with increasing partial carbon dioxide pressure and water evapotranspiration (Mermut and Landi 2005). The presence of primary carbonates is not obligatory: in the sediments with no free lithogenic carbonates (e.g., in volcanic ashes) secondary calcite may form by co-precipitation of exchangeable calcium and dissolved carbonic acid. The vertical distribution of pedogenic carbonates is tightly related with the soil moisture regime. Since the secondary carbonates in most soils are regarded as illuvial, the depth of their precipitation reflects the balance between water percolation, on the one hand, and evaporation and transpiration, on the other hand. The more humid the climate, the deeper are the secondary carbonates. The morphology of pedogenetic carbonates is also informative. Hard nodules and cemented layers in most cases form due to hydrogenic accumulation in the soils where groundwater level is or was close to the actual soil surface.

In most of Mexican Kastanozems/Ustolls and Xerolls, the secondary carbonates are found throughout the profile, with a distinct maximum, determined morphologically by the abundance of secondary carbonates and by the intensity of reaction with HCl, directly below the *mollic* horizon. In some profiles, the maximum of secondary carbonates may be found slightly deeper. Morphological forms of secondary carbonates are represented by soft accumulations of various sizes, which are called in the Mexican literature “discontinuous carbonates” (Pérez-Zamora 1999). Also there are other morphological forms of carbonates such as diffuse carbonates or hardened layers. Gypsum accumulations may be found, in places forming “desert roses”, at the depth of 2–3 m. In places due to drier climate, shallow groundwater or to aeolian accumulation, gypsum may be found within soil profile and even in the topsoil.

These soils form in a variety of parent materials: in marine clays and loams, in evolved volcanic ashes, and in ancient alluvial sediments. In the case of volcanic ashes, Kastanozems form in pyroclastic sediments older than Holocene time, because clay minerals crystallization is required for the development of the profile of these soils (Solleiro-Rebolledo et al. 2006). The majority of these soils form heavy-textured materials. Some of these soils have a significant amount of rock fragments of various sizes, especially those derived from alluvial sediments and regoliths of rocks weathered in situ. Many Kastanozems formed in clayey parent material have *vertic* properties such as deep cracking during the dry season (Kuhn et al. 2003).

Below we present a morphological description of a soil profile that was prepared for the field tour of the International Conference "Soil Geography: New Horizons" (organized by INEGI and UNAM). The profile is located in Zacatecas state, the annual precipitation is 450 mm, mean annual temperature 17 °C, the climate is semiarid subtropical with a maximum of precipitation in summer. Natural vegetation is represented by grasslands with *Bouteloa gracilis*, *Aristida laxa*, *Muhlenbergia rigida* and various herbaceous species: *Salvia ballotaeflora*, *Heliotropium* sp., *Dalea lutea*, *Dyssodia acerosa*, *Ageratum corymbosum*, *Dyssodia setifolia*, *Brickellia veronicifolia*, *Xanthocephalum dracuculoides*, *Eryngium comosum*, and *Verbena canecens*.

Geographical coordinates: 103°26′3.38″ W and 24°21′ 43.7″ N

Altitude: 1,901 m

Landform: Gentle slope of EN aspect

Slope: 2 %.

Geology: Pliestocene river terrace

Vegetation: Rainfed maize field.

Classification (ST):

Fine, mixed, superactive, isothermic Aridic Calciustoll

Classification (WRB): Calcic Kastanozem (Clayic).

Ak11, 0–32 cm—Dry; dark brown 7.5YR3/2 (moist) and brown 7.5YR4/2 (dry); silty clay loam; coarse moderate subangular blocky structure; consistence: slightly hard when dry and friable when moist; moderately sticky and plastic; few fine and medium roots; strong reaction with HCl; gradual wavy boundary.

Ak12, 32–39 cm—Dry; dark brown 7.5YR3/2 (moist) and brown to dark brown 7.5YR4/2 (dry); silty clay loam; coarse moderate subangular blocky structure; consistence: slightly hard when dry and friable when moist; moderately sticky and plastic; few fine roots; strong reaction with HCl; clear wavy boundary.

Bk21, 39–54 cm—slightly moist; brown 7.5YR4.5/3 (moist); clay loam; fine moderate subangular blocky structure; consistence: friable when moist; moderately sticky and plastic; few fine roots; fine (0.2–0.5 cm) loose disperse calcium carbonate accumulations; strong reaction with HCl; clear wavy boundary.

Bk22, 54–78 cm—slightly moist; brown 7.5YR5/3 (moist); clay loam; fine moderate subangular blocky structure; moderately sticky and plastic; few fine roots; frequent fine (0.2–0.5 cm) loose disperse calcium carbonate concentrations; strong reaction with HCl; clear wavy boundary.

Bk23, 78–94 cm—Slightly moist; reddish brown 5YR4/3 (moist); clay loam; fine strong subangular blocky structure; moderately sticky and plastic; few fine roots; frequent coarse (1–2 cm) loose disperse calcium carbonate concentrations; strong reaction with HCl; abrupt wavy boundary.

Bk24, 94–118+ cm—Slightly moist; reddish brown 7.5YR5/3 (moist); silty clay loam; fine strong subangular blocky structure; moderately sticky and plastic; few fine roots; abundant coarse (1–2 cm) loose disperse calcium carbonate concentrations; strong reaction with HCl.

The soil is relatively poor in organic C (about 1 % in the plough layer), has alkaline reaction (pH 8.0–8.5), and base saturation close to 100 %. The clay fraction contains mainly illite with minor amounts of mixed-layered illite-vermiculite and chlorite-vermiculite.These soils are used for several crops: mainly for wheat in the north, and for corn and beans in the central and southern parts. The limitation for its use is often a shortage of water. If irrigation is introduced, their salinity status should be monitored. They are also used for extensive grazing (Sommer and Cram 1998).

Chernozems are darker than Kastanozems: they form in slightly moister climates, and thus correspond to Udolls and some Ustolls in Soil Taxonomy. In other respect, these soils are very close both in properties and in environments to the Kastanozem group discussed above.

Chernozems in Mexico are found mainly in tropical and subtropical subhumid climate in Transmexican Volcanic Belt, in Sierra Madre Oriental mountains, and in the coastal lowlands of the Gulf of Mexico. Climatic conditions and clayey soil-forming material mainly of marine origin favor the development of *vertic* properties (in dry season the upper horizon is broken by cracks), but the manifestation and extension of these properties are not enough to call these soils Verstisols (a soil group discussed below). In places darker soils are found because of the presence of parent material rich in calcium carbonate. High concentrations of calcium usually favor the formation of darker humus horizon. If moisture regime allows secondary carbonate formation, soils having both primary and secondary carbonates form. Below we present an example of a soil formed in unconsolidated calcareous marine sediments in Veracruz State (Fuentes-Romero et al. 2004). The study region receives between 1,000 and 1,100 mm of rainfall annually, mainly in late summer and autumn. The mean annual temperature is 22 °C with almost no difference between the seasons. The natural vegetation (subdeciduous tropical forest) is strongly degraded and replaced by the plantations of tropical crops, citric, or used for grazing.

Geographical coordinates: 97°34′30″ W and 20°38′ 07″ N

Altitude: 81 m

Landform: Gentle slope of E aspect

Slope: 2–5 %.

Geology: Neogene calcareous marine clay

Vegetation: Partly under citrus plantations, partly under pasture.

Classification (ST): Fine-loamy, carbonatic, isothermic Vertic Calciustoll

Classification (WRB): Endogleyic Vertic Chernozem (Calcaric).

Ak, 0–30 cm—Dry; very dark grayish brown 10YR3/2 (moist) and dark grayish brown 10YR4/2 (dry); silty clay loam; medium strong granular and angular blocky structure; consistence: hard when dry and friable when moist; sticky and plastic; abundant hard and soft fragment of calcium carbonate; many fine, coarse, and medium roots; abundant ants, insect larvae; strong reaction with HCl; clear irregular boundary.

ABv, 30–45 cm—Dry; non-uniform color: alternate spots of dark grayish brown (10YR4/2) and yellow (10YR7/8) and olive yellow (2.5Y6/6) mottles; clay loam; coarse strong angular and subangular blocky structure; some aggregates have shiny surfaces; consistence: very hard when dry and firm when moist; moderately sticky and plastic; subvertical cracks; few medium and fine roots; small soft and hard fragments of calcium carbonate; strong reaction with HCl; clear wavy boundary.

Bk, 45–95 cm—slightly moist; brownish yellow 10YR7/8 (moist) and yellow 10YR6/8 (dry); clay loam; medium moderate subangular blocky structure; consistence: friable when moist; moderately sticky and plastic; few fine roots; fine and medium loose disperse calcium carbonate accumulations; moderate reaction with HCl; clear wavy boundary.

BCkg, 95–135 cm—moist; complex color with yellow 10 YR 7/8, olive yellow 2.5Y6/6, and light greenish gray 10Y7/1 mottles; clay loam; coarse moderate subangular blocky structure; moderately sticky and plastic; few fine roots; frequent coarse loose and hard calcium carbonate concentrations; strong reaction with HCl.

The soil has neutral to slightly alkaline reaction throughout the profile. The content of organic C is high, up to 6 % in the surficial horizon. It is difficult to divide the primary or secondary calcium carbonates in the profile: only micromorphological observations showed that secondary calcite fills the pores (Sedov, unpublished data). The clay mineralogy of these soils was not studied in detail, but the reports on the mineralogy of the region (Viniegra 1950) and observations of soil morphology and physical properties indicate high proportion of smectite minerals. Due to the calcareous nature of the sediments, the concentration of calcium in the exchangeable complex of these soils is much higher than that of the other exchangeable cations. The profile of this soil is shown in Fig. 4.8.

Like the previous group, Chernozems are utilized for a great variety of crops. These soils form in more humid environments than Kastanozems, and thus are less affected by droughts. Many of these soils form in marine clayey sediments rich in smectite, and may have certain negative physical properties such as excessive compaction and cracking in the dry state. Generally they are difficult to till. Possible solution for preventing overdrying of the topsoil may be drop irrigation or use of agrarian and agroforestry practices aimed at increasing of water storage in soils.

The most extensive group of soils with deep humus-rich horizon is represented by Udolls/Phaeozems. These soils are saturated with bases throughout the profile, but do not have illuvial secondary carbonates. Some of these soils have a horizon of clay illuviation (*argillic/argic* horizon). These soils may occur under a wide range of environments, where

Fig. 4.8 Vertic Calciustoll/Vertic Chernozem, Papantlarillo, Veracruz State (photo by P. Krasilnikov)

water percolation is intensive enough for the leaching of calcium carbonates, but not exchangeable bases. Usually, such climatic conditions also favor the accumulation of soil humic substances in the topsoil. The soils with the range of properties mentioned above are genetically different, and may be provisionally divided into several groups:

1. Soils developed in sedimentary silicate rocks, weathering regoliths, and colluvium products derived from igneous rocks under grassland vegetation of subhumid climate.

These soils correspond to the current climate and landscapes; many of these soils have evidences of clay illuviation (Argiudolls/Luvic Phaeozems). Their distribution is determined by climate, and they occur mostly in humid and subhumid areas of the states of Mexico, Michoacan, Puebla, and Tlaxcala. Also these soils are common in all the mountainous systems, where they occur under temperate, subtropical, and tropical forest. In the mountains, the range of vegetation where similar soils may be found is very wide: from pine-oak forests in the upper limit down to deciduous and semi-deciduous tropical forests at the lower elevational limit (e.g., Krasilnikov et al. 2011).

2. Soils developed under humid and semi-humid climates in unconsolidated parent material rich in calcium carbonate.

Genetically, these soils are similar to Chernozems formed in calcareous sediments, but due to a moister water regime, they do not have enough secondary carbonates in the profile. These soils are common at the Coastal Plain of the Gulf of Mexico and in Sierra Madre Oriental Mountains.

3. Soils developed in depressions and valleys where clay content, geochemical accumulation, and/or the age of pedogenesis are insufficient for the formation of Vertisols. These soils form under a broad range of climates with distinct dry and wet seasons in accumulative positions. The parent materials range from volcanic ash to alluvial and lacustrine clayey sediments.
4. Soils initially poor in organic matter, but altered by prolonged agricultural use and/or irrigation.

Many soils in the arid and semi-arid regions of Mexico initially have high base saturation, but lack the humus-enriched dark topsoil. Under cultivation, if the land management is good, especially if compost or wastewater is applied, these soils accumulate organic matter in quantities sufficient to be classified as Udolls/Phaeozems. For example, the Federal District soil maps indicate mostly Phaeozems. The majority of these soils were under the cornfields. It is important to distinguish anthropogenic Udolls/Phaeozems and Anthrepts/Anthrosols—the soil group, completely changed by man, for example chinampas soils. In the FAO map legend, which did not include Anthrosols, these soils were recognized in the Phaeozems group, but in the current classification should be reviewed so it is possible to recognize the two groups. The formation of Phaeozems is favored by irrigation with sewage, as in the Mezquital Valley where these soils are very extensive. Irrigation with high mineralization waters can result in desert soil salinization and alkalinization, and the soils are classified as sodium-affected Udolls/Phaeozems.

Here, we present an example of a soil with a humus-enriched topsoil studied in Jilotepec de Abasolo, the State of Mexico, which shows certain compaction (vertic properties) and thus is close in properties to a Vertisol (Álvarez-Arteaga 1993).

Geographical coordinates: 99°32′29″ W and 19°58′ 10″ N

Altitude: 2,438 m

Landform: Undulating valley, gentle slope of northern aspect

Slope: <2°.

Geology: Neogene calcareous marine clay

Vegetation: Forb pasture.

Classification (ST): Fine, smectitic, isothermic Typic Hapludoll

Classification (WRB): Vertic Leptic Phaeozem (Clayic).

A1, 0–12 cm—dry; very dark brown 10YR2/2 (moist) and dark grayish brown 10YR 4/2 (dry); clay loam; coarse strong subangular blocky structure; consistence: very hard when dry, friable when moist; sticky and plastic; abundant fine roots; many rock fragments (basalt) of various sizes; pH in water (1:2.5) is 5.7, the organic C content is 1.7 %, CEC is 17.4 cmol kg^{-1}; clear wavy boundary.

A2, 12–35 cm—dry; black 10YR 2/1 (moist) and very dark grayish brown 10YR 3/2 (dry); clay; strong medium subangular blocky structure; consistence: very hard when dry, friable when moist; sticky and moderately plastic; vertical cracks; many rock fragments (basalt) of various sizes; few fine and medium roots; pH in water (1:2.5) is 6.5, the organic C content is 2.9 %, CEC is 28.2 cmol kg^{-1}; clear wavy boundary.

Bw, 35–50 cm—slightly moist; dark grayish brown 10YR 4/2 (moist) and grayish brown 10YR 5/2 (dry); clay; strong medium subangular blocky structure; consistence: very hard when dry, friable when moist; sticky and plastic; vertical cracks; many coarse rock fragments (basalt); few fine roots; pH in water (1:2.5) is 6.8, the organic C content is 1.5 %, CEC is 43.7 cmol kg^{-1}; diffuse wavy boundary.

BC, 50–65 cm—slightly moist; dark grayish brown10YR 4/2 (moist) and grayish brown 10YR 5/2 (dry); loamy clay; strong medium subangular blocky structure; consistence: very hard when dry, friable when moist; sticky and plastic; abundant coarse rock fragments (basalt); pH in water (1:2.5) is 7.0, the organic C content is 0.1 %, CEC is 36.3 cmol kg^{-1}, the horizon is underlain by a fragmented basalt rock.

Soils with mollic epipedon, but lacking secondary calcium carbonates, are very common all over Mexico. Their use and management depend on the specific ago climatic conditions. In the temperate areas with flat and gently undulating topography they are very good for corn and wheat, in tropical areas they are successfully used for a variety of tropical fruits such as mango or citric cultures and for pastures. In the mountains, these soils are successfully used for coffee production.

The group of acid soils with deep humus horizon (Dystrudepts/Umbrisols) is one of the least studied in Mexico. Like in other parts of the world, these soils form in Mexico mainly in mountainous regions under the shade of humid tropical and temperate forests and under highland meadows (paramos). There are two principal environmental niches for these soils. First, they are normal climax soils for the altitudinal belt of highland meadows and slightly lower transitional zone of sparse pine forest (Krasilnikov et al. 2011). At lower elevations these humus-rich soils are replaced by texturally differentiated soils (Alfisols/Luvisols) under the shade of pine-oak forest. Second, these soils form in many other environments as a stage of soil succession on young surfaces exposed by slope processes (García-Calderón et al. 2006; Krasilnikov et al. 2007). According to the latter sources, a typical succession of soils on freshly exposed surfaces in tropical mountainous forests starts from humus accumulation that leads to the formation of Udolls/Phaeozems. Further, soil development results in the leaching of bases and formation of acid–base poor soils with humus-enriched topsoil. Finally, clay illuviation starts in the soils leading to the formation of Alfisols and Ultisols/Luvisols and Alisosols. Since this mechanism is very common on the mountainous slopes, especially in the belt of semideciduous tropical forests, the area occupied by acid humus-rich soils is considerable.

Geographical coordinates: 97°06′12.9″ W and 16°07′ 41.5″ N

Altitude: 1,084 m

Landform: The lower third of a backslope, southwest aspect

Slope: 25–30°.

Geology: Sandy-gravelly regolith of gneisses

Vegetation: Coffee plantation under the shade of natural semideciduous tropical forest: *B. alicastrum*, *E. cyclocarpus*, *Pterocarpus acapulcensis*, *B. simaruba*, *Caesalpinia coriacea*, *C. pentandra*, *C. aliodora*, и *Ficus* spp.

Classification (ST): Coarse-loamy, mixed, isothermic Humic Dystrudept

Classification (WRB): Haplic Umbrisol (Brunic, Chromic).

O, 0–3 cm—litter consisting of partly decomposed leafs of the current year.

A1, 3–18 cm—moist; dark gray 7.5YR 3/1 (moist); silt loam; moderate granular structure; slightly hard; friable; slightly sticky and plastic; porous; few rock (gneiss) fragments of various sizes, some of the fragments are strongly weathered, abundant fine, and medium roots; earthworms and their tunnels; smooth clear boundary.

A2, 18–36 cm—moist; dark brown 7.5YR 3/2 (moist); sandy loam to silty loam; medium moderate lumpy-granular structure; brittle to friable; slightly sticky and plastic; porous; few gravel and crushed gneiss fragments; few fine and medium roots; few worms and maggots; irregular clear boundary.

Bw, 36–90 cm—moist; yellowish–red 5YR 5/8 (moist); silt loam; moderate medium angular blocky structure; brittle to friable; plastic and slightly sticky; gravel and crushed gneiss fragments; few medium roots, single large roots; clear irregular boundary.

BC, 90–120 cm—slightly moist; strong brown 7.5YR 5/8 (moist); sandy loam; weak medium angular blocky structure; loose to friable; non-plastic; more than 50 % of the volume constituted with gneiss fragments of various stages of weathering; single medium and coarse roots.

In the highlands these soils are used mainly for grazing, in the lower mountainous zones—for coffee production. For other crops they are not very good because of acid reaction.

4.6 Shallow Soils Derived from Silicate Consolidated Rock

Shallow soils are recognized in many soil classification systems at the highest level of taxonomy due to the limiting effect of close consolidated rock (Krasilnikov et al. 2009). In the WRB system these soils are classified as Leptosols, while in the previous FAO legend version three groups of shallow soils existed: Rhendzinas, shallow soils over limestone rock, Rankers, shallow mountainous soils with *umbric* horizons, and Lithosols, very shallow soils (total depth less than 10 cm). Actual grouping of such soils in one reference group is practical, because it is not convenient to have several taxonomic units with the same property limiting soil productivity. However, genetically, and even geographically the three groups used in FAO legend are different, and some authors argue against their mixing (e.g., Gama-Castro et al. 2004). Also the USDA Soil Taxonomy places the soils derived from limestone in the Rendolls suborder, while shallow soils are mainly classified as Lithic Great Groups in various other orders. That is why in this review we also describe the soils derived from silicate and calcium carbonate rocks separately.

Shallow soils in silicate rocks usually correspond to the areas where the sedimentary unconsolidated cover is absent or thin, and the erosion is more intensive than weathering.

All over the world these conditions are typical for mountainous regions, especially those with active tectonics. Since in Mexico young active mountains occupy the major part of the national territory, shallow soils are also widespread. Most of the shallow soils in silicate rocks correspond to the regions of Baja California, Sierra Madre Occidental, and Sierra Madre del Sur. In Sierra Madre Oriental the parent material is mostly of sedimentary origin, and most places contain calcium carbonate. In the Transmexican Volcanic Belt recent pyroclastic sediments are common, thus reducing the total area of exposure of igneous rocks (Fig. 4.9).

Besides the mountainous regions, shallow soils occupy some of the plain in the northern deserts, where the intensity of deflation is high, for example, in Coahuila and Nuevo León states. In general, these soils constitute an important component of dynamic landscapes of Mexico. As we stated before, in the majority of Mexican landscapes, the leading processes are related to the loss and accumulation of sediments. Shallow soils represent the extreme expression of the loss of sediment due to water and wind erosion.

Fig. 4.9 Shallow soil in volcanic ashes over andesitic rock under mountainous fir forest, National Park “El Chico”, Hidalgo State (photo by P. Krasilnikov)

The morphology and properties of shallow soils vary dependently on climatic conditions, parent material, and vegetative communities. The only common feature is their shallow depth and in most cases stoniness.

4.7 Shallow Soils Derived from Limestone

Shallow soils in consolidated rock rich in calcium carbonate, mostly in limestone, are very common in Mexico. In the old FAO legend, the majority of these soils were classified as Rendzinas, in the WRB they are included in Rhendzic Leptosols. If the depth of these soils is more than 25 cm, the soils are classified as Rhendzic Phaeozems (IUSS Working Group WRB 2006). In the USDA Soil Taxonomy, the majority of shallow soils derived from limestone are included in the Suborder of Rendolls (Soil Survey Staff 1999). It is important to note that all the taxonomic groups mentioned above include soils that have *mollic* epipedon over partly fragmented limestone rock. However, the variety of soils derived from limestone and similar materials is much broader than typical Rhendzina soils, which have well-structured very dark mollic horizon. In Mexico, many soils in limestone-derived material look different; in places, the products of limestone weathering are not enriched with humus and form reddish clayey covers similar to those found in *terra rossa*. In some other limestone-derived soils the content of humus is low, and the surface horizon is composed of limestone fragments of sand and silt size with an admixture of poorly decomposed organic matter. Finally, in places the unconsolidated limestone rock is exposed directly on the surface, and its microtopography may be either smoothened by water or have a characteristic surface with sharp “dog’s teeth” spikes. In such landscapes fine earth accumulates mainly in depressions. In fact, the reasons that determine the development of each of the mentioned mechanisms are not yet well understood. Kubiëna (1970) noted that humus-enriched horizons form mainly in soils, which have at least several per cent of silicate material, otherwise physical disintegration of limestone or its complete dissolution occurs. However, climatic conditions, vegetation, and land use should be also considered (Shang and Tiessen 2003).

The most extensive area of shallow soils on limestone exists in Mexico at the Yucatan Peninsula (Aguilera-Herrero 1958). This region of Mexico is a big emerging block composed of limestone formed during the epochs from Mesozoic era to Neocene. The soils of Yucatan are mostly shallow to very shallow (Bautista-Zuñiga and Palacio-Álvaro 2005). According to Bautista-Zuñiga et al. (2011), the mosaic of soils of Yucatan depends on the stage of the development of karst landscape. In the most recent karst development stage, landforms are horizontal and subhorizontal plains with few sinkholes and uvalas. The soils are shallow, with small amounts of fine earth. In the juvenile stage, as karst development proceeds, relief differentiation and the amount of fine earth increase. The subhorizontal plains with a predominance of very shallow soils are gradually transformed into rolling plains with larger dolines and uvalas. At this stage, shallow soils dominate on summits, and more developed soils, in places even with evidences of clay illuviation, form on backslopes and toeslopes. With increasing time of dissolution of the bedrock in good drainage conditions, the edges of the mounds tend to be rounded and hills (20–100 m elevation) become more frequent. This results in the formation of isolated hills due to rock dissolution. The amount of fine earth increases on toeslopes leading to the formation of deeper soils with *cambic* and *argillic/argic* horizons, while shallow soils occur on ridge and hill summits.

In the Yucatan, the pedogenetic processes are somewhat different in the soils formed on the elevated positions and in hydromorphous soils of depressions. In uplifted autonomous positions, the main process is the dissolution of primary calcium carbonates and in places concurrent organic matter accumulation. No secondary pedogenic carbonates form in these soils. In contrast, the soils of the depressions, both shallow and deep (including organic peat soils), have distinct accumulations of secondary carbonates (Solleiro-Rebolledo et al. 2011).

The other extensive area of shallow soils derived from limestone is the region of Sierra Madre Oriental. This physiographical region consists of sedimentary rocks similar in their origin and age to the Yucatan Peninsula, but strongly uplifted by plate tectonic movements. The soils of the slopes of Sierra Madre Oriental are mostly shallow, even if formed in rocks with a significant proportion of silicate material, e.g., in flysch, because of strong erosion on mountainous slopes. Bracho and Sosa (1987) described shallow soils formed in limestone rocks under the shade of montane cloud forest in the National Park “El Cielo” in Tamaulipas: the soils were rich in organic matter and the fine earth, but did not show reaction with hydrochloric acid indicative of strong leaching. In depressions and on some terraces there were deeper clayey soils formed from the sediments transported along the slopes. The shallow soils of these extrahumid ecosystems had dark-colored topsoil rich in organic matter (Bracho and Sosa 1987), like the majority of soils formed under humid conditions. Similar morphology was reported by Mendoza-Vega and Messing (2005) for these soils in mountainous tropical rain forests of Chiapas State. However, Zenil-Rubio (2011) described a number of yellowish and reddish shallow soils with low organic matter content in the same region of Chiapas. We found an intermediate situation in the semideciduous mountainous forest of Sierra Sur de Oaxaca; the morphological soil description is presented below, and other details may be consulted in Krasilnikov et al. (2007).

Geographical coordinates: 96°17′04″ W and 15°55′ 52″ N

Altitude: 1,335 m

Landform: The upper part of a backslope, western aspect

Slope: 25–30°.

Geology: Limestone and related colluvial deposits

Vegetation: Coffee plantation under the shade of natural semideciduous tropical forest: *Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia aliodora*, and *Ficus* spp.

Classification (ST): Loamy-skeletal, carbonatic, isothermic Lithic Haprendoll

Classification (WRB): Rendzic Phaeozem (Skeletic).

A, 0–25 CM—moist; 5YR 3/3 dark reddish brown (moist), gravelly sandy silt loam; fine medium subangular blocky structure; firm; plastic; abundant limestone rock fragments of various sized (up to 40 % of the horizon volume); abundant fine and medium roots, many coarse roots; worms and insect larvae present; irregular clear boundary.

Bw, 25–45 CM—moist; 5YR 4/4–3/4 reddish–brown to dark reddish–brown (moist); very gravelly loam; fine and medium moderate subangular blocky structure; firm; abundant limestone rock fragments (up to 65 % of the horizon volume); many fine roots, few medium and coarse roots; irregular sharp boundary.

R, 45+ CM—less than 10 % fine earth in cracks; moist; 5YR 4/6 reddish–yellow (moist); silt loam; few roots penetrating the cracks.

This profile is characterized by a reaction close to neutral (pH 6.6–6.7 both in water and KCl extracts), base saturation of 87 %, high clay content, and elevated carbon concentration (up to 7 %) with a predominance of humic over fulvic acids. The mineralogical composition of the clay fraction was diverse and included illite, vermiculite, chlorite, and kaolinite minerals. Similar results were reported for the mineralogical composition of shallow limestones of Yucatan (Bautista-Zuñiga and Palacio-Álvaro 2005). Also for soils in the Yucatan, Dudek et al. (2006) reported the presence of mixed-layered kaolinite-smectite that was attributed to the transformation of volcanic ash of aeolian origin. It is necessary to note that the latter situation is not very common for limestone soils.

The use of shallow soils in limestone material is usually considered to be strongly limited by the difficulties in management and by small amount of fine earth and consequently of available nutrients. However, the shallow soils of Yucatan supported the ancient Mayan civilization that is still partly an enigma for archeologists. Some of the existing theories include the management of seasonal shallow lakes where peryphyton left on the soil surface served as a natural fertilizer (Bautista-Zuñiga and Palacio-Álvaro 2005).

4.8 Saline and Alkaline Soils

Arid climate that dominates almost a half of the Mexican territory favors accumulation of soluble salts in soil profiles. Despite that fact, the area of saline soils in the country is relatively small. The main areas of saline soils in Mexico include extensive valleys of lacustrine and alluvial origin in the arid part of the country from the very north to the internal section in the south. In the central part of the country, these soils usually coincide with saline lakes, completely dried or drying periodically, such as the infamous ex-lake Texcoco in Mexico State, Laguna de Totolcingo in Puebla State, and the vicinity of Pátzcuaro and Cuitzeo lakes in Michoacán State. In the USDA Soil Taxonomy, the majority of these soils are classified as Salids, but some of the soils rich in soluble salts have wetter moisture regimes than *aridic*, including *aquic* moisture regime, and thus should be mostly included in the Halaquept Suborder. In the WRB system, these soils form the Solonchak reference group; some soils with high exchangeable sodium percentage and evidence of vertical clay migration might be included in the Solonetz group.

One of the most typical saline soils of arid northern part of Mexico was found in the Laguna de Mayrán, situated in the south of Coahuila state. The profile was shown during the field tour before the International Conference "Soil Geography: New Horizons", already mentioned above. Laguna de Mayrán occupies an area of 116,000 km^2 and is the largest flooded salted desert flatland in the country. The deposits are of alluvial and lacustrine origin, some of them calcareous and/or gypsiferous, bordered by mountains of igneous rocks. The area possesses significant recourses of subterraneous water, which lies on the basement of limestone formations. The water is stored in loose alluvial and lacustrine sediments, and the width of this water-holding layer varies from several tenths of meters at mountain footslopes to 350–400 m in the central part of the catchment. The depth of water table occurs at 40–140 m; during the last 50 years the depth increased 30–120 m due to over exploitation of water. The water quality is poor, with the mineralization between 200 and 3,600 ppm, and is getting worse with time, because the deeper layers of water in the basin are more ancient and saline. Also these layers contain significant amounts of toxic elements, including arsenic. The majority of soils of the region have accumulations of soluble salts, gypsum, and calcium carbonate. The climate is uniform throughout the flatland: it is semiarid subtropical, with mean annual precipitation 150,300 mm, mean annual temperature 21 °C. The natural vegetation is represented by desert microphyllous matorral with dominant species creosote bush (*Larrea tridentata*), mesquite (*Prosopis* spp.), Adam's needle (*Yucca* spp.) with some ocotillos (*Fouquieria* spp.) at the outcrops of limestone rocks. At coarse, alluvial sediments in places it is possible to find almost undisturbed desert rosetephylous matorral with agaves and cactuses (*Agave lechuguilla* and *Opuntia* spp.). In the areas of distribution of saline soils the matorral vegetation is mixed with halophytic communities, with the dominant species *Atriplex* spp., *Suaeda nigra* and *Allenrolfea* spp., and in some cases there is no apparent vegetative cover. The agriculture, previously, was focused at cotton production. Actually, the main activity of the agriculturalists is cattle breeding, principally dairy cows like Holstein. Vast areas are occupied by alfalfa plantations. The other important crops for the region are sorghum, fodder corn, and mellow. All the agricultural production is irrigation based. High mineralization of water causes in places the anthropogenic salinization of soils. The morphological description of a typical profile is presented below.

Geographical coordinates: 102°40′36″W and 25°23′21.0″N

Altitude: 1,091 m

Landform: Bottom of a desert flood plain

Slope: 0°.

Geology: Alluvial and lacustrine deposits, consisting of gravels, sands, loams, and clays.

Vegetation: No vegetation.

Classification (ST): Clayey over loamy, mixed, semiactive, thermic Calcic Haplosalid

Classification (WRB): Calcic Puffic Solonchak (Sodic, Aridic, Siltic).

Ak1, 0–13—dry; 2.5Y6/2 light gray (moist) and 2.5Y7/1 light gray (dry); silt clay loam; coarse strong subangular blocky structure; consistence loose (dry) and friable (moist); moderately sticky and plastic; single fine roots; very strong reaction with HCl; clear plain boundary.

Akb1, 13–28—dry; slightly darker than overlying horizon, 10YR6/3 light gray (moist) and 10YR7/2 light gray (dry); clay loam; very fine moderate subangular blocky structure; consistence slightly hard (dry) and very friable (moist); moderately sticky and plastic; few roots; very strong reaction with HCl; gradual wavy boundary.

Akb2, 28–53—slightly moist; grayish brown to light olive brown 2.5Y5/3 (moist) and 10YR7/2 light gray (dry); silt loam; fine moderate subangular blocky structure; consistence very friable (moist); slightly sticky and plastic; single roots; very strong reaction with HCl; clear wavy boundary.

CAkb, 53–91—moist; 2.5Y5/2 grayish brown (moist) and 2.5Y7/1 light gray (dry); silt loam; fine moderate subangular blocky structure; moderately sticky and plastic;

calcium carbonate concentrations are present as fine frequent hard concretions; very strong reaction with HCl; gradual wavy boundary.

Ckb 91–120+—moist; 2.5Y5/2 grayish brown (moist) and 2.5Y7/1 light gray (dry); silt loam; structureless; moderately sticky and plastic; calcium carbonate concentrations are present as fine frequent hard concretions; very strong reaction with HCl.

The soil profile is shown at Fig. 4.10. This soil has low organic carbon content throughout the profile (less than 1 %), high pH values (between 8.5 and 9.0), and very high content of free calcium carbonate and soluble salts. The dominant salts are sodium sulfate and sodium bicarbonate. Since the basin of Laguna de Mayrán is endorheic, the salts accumulate in the groundwater and in soil in the course of weathering of the rocks of the adjacent landscapes. Due to the arid climate, the evaporation results in high concentration of salts in the surficial soil horizons. In places the salts form a crust of a puffy layer on the soil surface.

In the region of the Transmexican Volcanic Belt, the origin of salts and the morphology and properties of soils are somewhat different from those typical for the north of the country. Although the main source of salts is also the process of weathering of sediments, in the volcanic region the release of cations, mainly sodium, is much more intensive than in other areas. Thus, salinization occurs even under much wetter climates than in the northern arid areas. The dominant soluble salt in these soils is sodium bicarbonate that also attributes to the high alkalinity of the soils (Gutiérrez-Castorena and Ortiz-Solorio 1999). The former Lake Texcoco should be considered as the largest surface in Mexico affected by extreme salinity and alkalinity of soils. Before the arrival of the Spaniards in the heart of the Valley of Mexico was a system of lakes, two of them (Xochimilko and Chalko) were brakish, and three (Texcoco, Zumpango and Saltokan) were saline. After draining the water the bottom of Texcoco Lake was completely exposed, and almost all the soils formed there contain a certain amount of

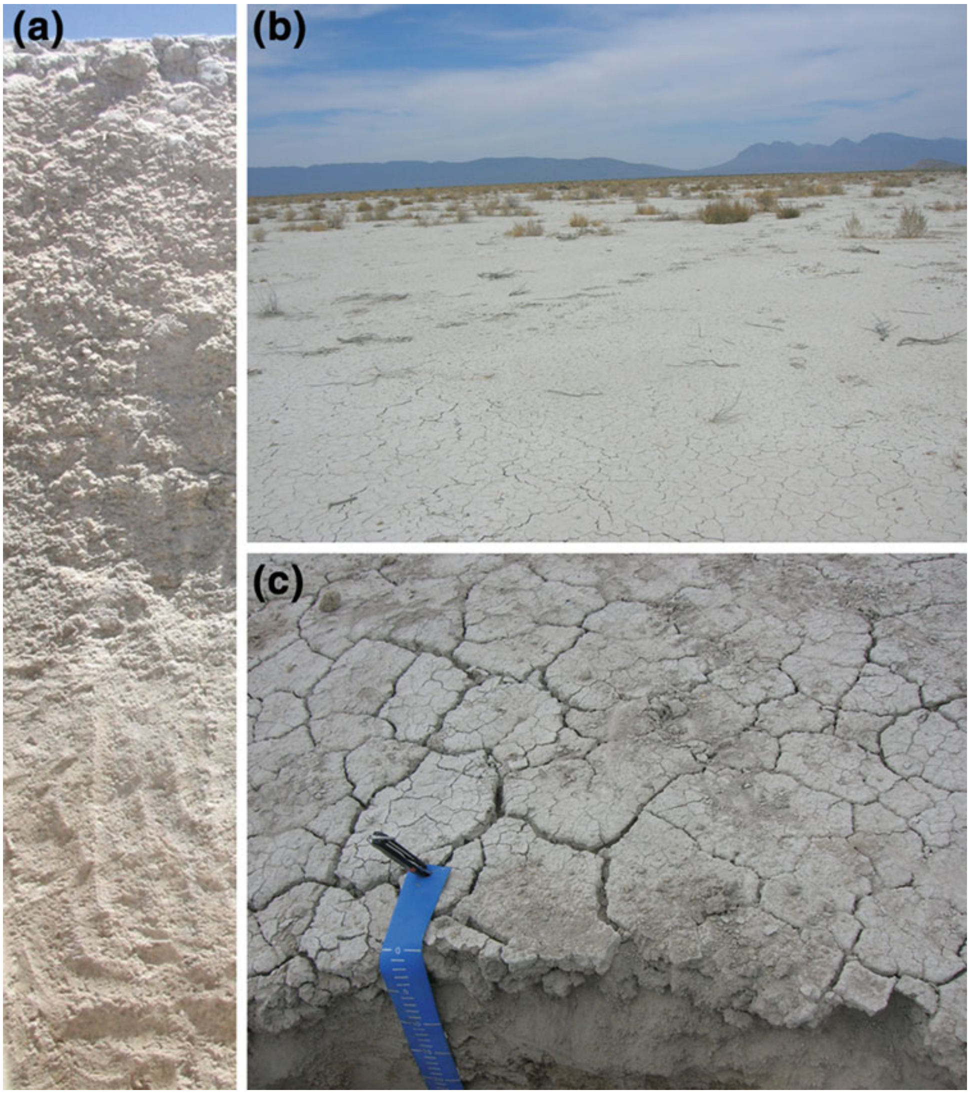

Fig. 4.10 Haplosalid/Solonchak in the Laguna de Mayran, Coahuila State: **a** soil profile, **b** landscape with sparse vegetation, **c** soil surface (photo by C.O. Cruz-Gaistardo)

soluble salts. Alkaline environment and abundance of easily weathered volcanic glass leads to enhanced migration of silicon and the formation of tumors of opal in sediments and soil profiles (Gutiérrez-Castorena et al. 2005, 2006). Shallow groundwater table makes reclamation of these soils using leaching and the application of gypsum or sulfur inefficient. A similar situation is observed in a number of other closed valleys of the Transmexican Volcanic Belt. Alkaline soils rich in exchangeable sodium and having evidences of clay translocation in the profile are usually associated geographically with strongly saline soils, occupying the outskirts of closed valleys and the most exalted stations. These alkaline soils are included in the Natric Great Groups of Mollisols and Alfisols in the American Soil Taxonomy and in Solonetz reference group in the WRB. Morphologically, alkaline soils with clay differentiation in Mexico tend to have dark color throughout the profile and the lack of a columnar structure in the *natric* horizon; usually, the structure observed in this horizon is strong angular blocky. Most of such soils have a mixture of properties of saline soils and alkaline soils with no free soluble salts. Clay illuviation is impossible in the presence of strong electrolytes, and the presence of the evidences of clay movement in saline soils should be ascribed either to past or to fluctuating environments. The latter hypothesis is more probable, because periodical fluctuation of water table, climatic conditions, and coincident salt dynamics have been reported for various regions of Mexico.

Also soil salinity is observed in the mangrove and coastal soils, including the soils having evidence of iron sulfide accumulation and further oxidation. These soils are classified as Sulaquepts and Sulfaquents in Soil Taxonomy and Salic and Thionic Flyuvisols in the WRB. It should be noted, however, that the salinity in these soils sharply decreases with increasing distance from the shore, and the total area occupied by saline coastal soils is not very big (Giani et al. 1996; Méndez-Linares et al. 2007). This is partly explained by the fact that the low flat coast where mangrove vegetation is formed, is usually tied to river deltas, and soils are partially washed by fresh water. The most extensive areas of these soils are found in the southern Gulf of Mexico in Tabasco and southern Campeche and Veracruz (Palma-López et al. 1985; Palma-López and Cisneros 1997; Moreno-Cáliz et al. 2002).

4.9 Expanding and Shrinking Soils

Heavy clayey soils that expand when moist and shrink when dry are widespread all over the world. These soils, called Vertisols in internationally recognized scientific soil classifications (both in ST and WRB), have more indigenous synonyms, than any other soil type. Vertisols form mainly in heavy clayey sediments of marine or lacustrine origin; however, there are also Vertisols formed in weathered volcanic ashes or extrusive volcanic rocks. High content of clay dominated by smectites, results in the physical properties of these soils. In the dry season Vertisols are extremely hard and compact, and have deep and broad cracks. In the wet season they are plastic and sticky. Smectites form organic-mineral complexes with soil humus; these complexes give dark color to these soils, even when the total content of organic matter is low. Most of these soils are found in tropical environments in Mexico, but they are also found in subtropical and temperate belts. In the dry season Vertisols are almost impossible to plough; they are dangerous for construction; also these clayey materials are unsuitable for pottery. However, most Vertisols are rich in nutrients, and when properly managed, may be rather productive. Just some of the terms used for naming Vertisols in folk classifications include: *smolnitza* (Balkans), *smonitsa* (Austria, Chroatia), *paklavitsa*, *natsepena*, *lyuta*, *kipra*, *kara–suluk*, *sakyztoprak* or *stikliva* (Bulgaria), *morogan* (Romania), *barros* (Portugal, Spain), *kankar*, *karail*, *mar*, *regoor*, *regar* or *regada* (India), *tierra negra* (various parts of Latin America), *tierra masa* or *gumbo* (Cuba), *sonsocuite* (Nicaragua), *cuacab li ch'och'* (Guatemala), *massape* or *coroa* (North–Eastern Brazil), *pradera negra* (Uruguay), *tirs* (Algeria, Tunis, Marocco), *badobe*, *dian–pere* or *teen suda* (Sudan), *mursi* (Mali, Sudan), *firki* (Nigeria), *kaamba* (Congo), *dambo* or *fadamma* (Eastern Africa), *kadondolyo*, *mbuga*, *wapi*, *lukanda* or *manda* (Tanzania), *gova*, *isidhaka* or *dhakiumnyama* (Zimbabwe), *flei*, *vley* or *fley* (South Africa), and *gilgai* (Australia) (Krasilnikov et al. 2009).

Swelling and shrinking soils include Vertisols and some other soils with similar physical properties, but failing, for example, the depth criterion for Vertisol order or reference group. Many clayey soils have only some particular properties of Vertisols, for example, the formation of deep cracks when dry. A huge number of papers discuss the genesis, physical properties, and use of Vertisols in agriculture; to mention the most general works, we should list the books edited by Wilding and Puentes (1988) and Ahmad and Mermut (1996). Smectites are the usual products of the weathering of rocks rich in bases, if the leaching of elements is not very intensive. Smectites are easily transported by water and subsequently accumulate in alluvial, marine, and lacustrine clays. Therefore, Vertisols commonly develop in marine and lake sediments; also Vertisols form in redeposited products of weathering of carbonate-rich sedimentary and metamorphic rocks. A variety of sediment sources that contain smectite clays determine the widespread distribution of Vertisols worldwide. They occur in all areas where there are dry and wet seasons, from tropical to temperate zone.

As mentioned above, Vertisols are the soils of valleys and depressions, and not quite typical of the slopes. In Mexico, there are some limited areas of heavy clayey soils on the dry inland slopes of Sierra Madre del Sur, where basic and limestone rocks are widespread. However, Vertisols are much more common at the coastal plains and in the intermountain valleys in all the mountainous systems of the country. In the mountains, they not only occupy vast plain areas between the mountainous ridges, but also occur in the form of patchiness in depressions in undulating uplifted areas. Morphology and properties of Vertisols vary depending on their location, climate, and the origin of the parent rock. On the coastal plains, Vertisols commonly form in smectite-rich marine clays. An example of such a soil profile was described in the Pleistocene marine terrace near the city of Tapachula, Chiapas, under a mango plantation. This soil was formed in binomial marine sediments: smectite clay underlain by calcareous sand. The upper horizon was completely embedded in the clay deposits: it was characterized by a complete set of properties that were typical for Vertisols: the formation of cracks, slickensides, in places self-mulching topsoil. In the intermontane basins of southern Mexico, many Vertisols do not have the characteristic dark color. For example, in the Necaxa Valley (Oaxaca State) we presented at the WRB tour in 2005 a profile of Vertisol-like clay soil of intensive red color. Soil-forming material was mainly derived from the weathering products of the rocks of adjacent mountains. Vertisols are fairly common in volcanic deposits of the Transmexican Volcanic Belt. In this physiographic region, almost all the lowlands have Vertisols or soils with vertic properties. The genesis of these soils in volcanic ash is somewhat more complicated than that of the Vertisols formed in already existent smectite clays of sedimentary origin. It is believed that the smectites are formed synthetically in supersaturated solutions, at the expense of producing rapid dissolution of volcanic glass. Many Vertisols in the Transmexican Volcanic Belt formed in lacustrine sediments. For example, the deposits of the former Lake Texcoco that constitutes a significant portion of the territory of Mexico City, contain about 30 % of smectite in the clay fraction of sediment, which creates serious problems with construction in the city (Warren and Rudolph 1997). The lacustrine smectites are mostly of local pedogenetic origin. Even in small depressions with no accumulation of lacustrine sediments the soils formed in volcanic ashes commonly have a certain content of smectites and thus exhibit at least some vertic properties. The properties of Vertisols and similar soils depend on the climatic conditions and local conditions. Many Vertisols formed in the arid parts of the country contain secondary carbonates. The clayey soils formed in wetter areas, in contrast, commonly are free of salts and carbonates and may have evidences of water stagnation. Here, we present an example of the profile near Rio Gallinas, Zacatecas State, prepared for the tour before the conference “Soil Geography: New Horizons”. The site is located within the physiographical province Sierra Madre Oriental on the border with the Coastal Plain of the Gulf of Mexico. The area is characterized by humid warm climate with annual precipitation of 1,500 mm and mean annual temperature of about 22 °C.

Geographical coordinates: 99°14′42.88″ W and 21°57′ 0.83″ N

Altitude: 315 m

Landform: Alluvial terrace

Slope: 2°.

Geology: Clayey alluvial deposits.

Vegetation: Sugarcane plantation.

Classification (ST): Fine, smectitic, thermic Typic Calcustert

Classification (WRB): Calcic Vertisol (Humic).

Ap11, 0–13 cm—moist; 10YR1/1 black (moist); clay loam; fine moderate subangular blocky structure; loose consistency when dry and very friable when moist; slightly sticky and plastic; fine cracks; abundant fine roots; very weak reaction with HCl; abrupt wavy boundary.

Ap12, 13–30 cm—moist; 10YR1/1 black (moist); clay; medium moderate angular structure; consistence slightly hard when dry and friable when moist; moderately sticky and plastic; many slickensides; abundant fine roots; weak reaction with HCl; abrupt wavy boundary.

B21v, 30–60 cm—moist; 7.5YR2.5/2 very dark brown (moist); clay; massive structure; consistence hard when dry and firm when moist; very sticky and plastic; abundant slickensides; many evident large reddish mottles (2.5YR3/5); few fine roots; very weak reaction with HCl; gradual wavy boundary.

B22v, 60–75 cm—moist; 7.5YR2.5/2 very dark brown (moist); clay; massive structure; consistence hard when dry and firm when moist; very sticky and plastic; abundant slickensides; frequent evident large reddish mottles (2.5YR3/5); few fine roots; no reaction with HCl; gradual wavy boundary.

B24v, 76–92 cm—moist; 2.5YR3/2 dusky red (moist); clay; massive structure; consistence hard when dry and firm when moist; very sticky and plastic; abundant slickensides; strong reaction with HCl; abrupt plain boundary.

Cv, 92–100+ cm—moist; 2.5YR3/2 dusky red (moist); clay; massive structure; consistence very hard when dry and firm when moist; very sticky and plastic; very strong reaction with HCl.

The profile and microscopic photos of the studied soils are presented at Fig. 4.11.

Almost all clayey Vertisol-like soils are used in agriculture; depending on the climatic conditions they are widely used for cotton, wheat, corn, sugarcane, or some tropical

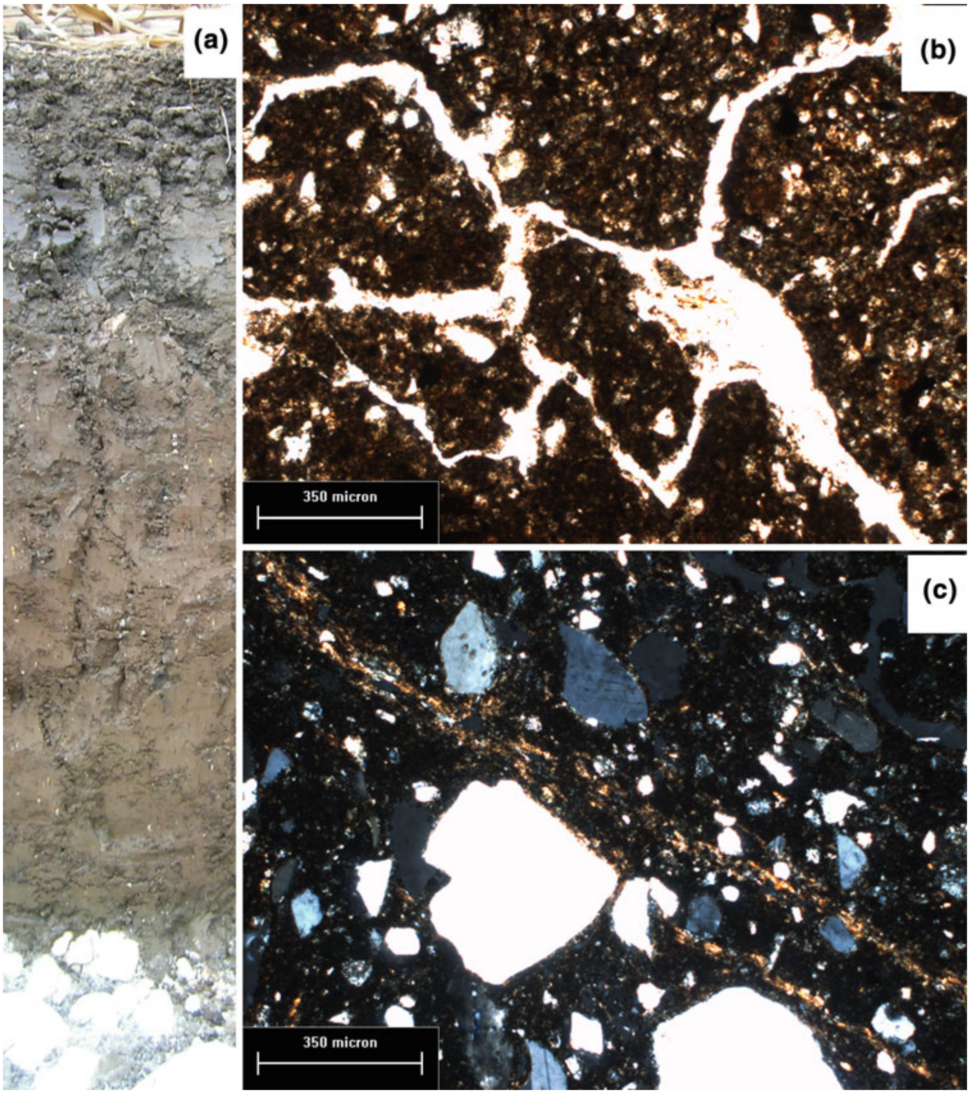

Fig. 4.11 Typic Calciustert/Calcic Vertisol at the Río Gallinas site, Veracruz State: **a** soil profile, **b** typical angular structure in the topsoil, **c** stress cutans in the AB horizon, with crossed polarizers (photos made by S. Sedov)

fruits like mango. Consequently, certain degradation of their chemical and physical properties occurs. For example, after 6 years in cultivation a Vertisol in Nuevo León (Northeast) lost more than half of the initial content of organic carbon and total nitrogen (Bravo-Garza and Bryan 2005).

4.10 Soils with Carbonate and Gypsum Accumulation

The soils with calcium carbonate and gypsum accumulation commonly occur in the environments where leaching is not sufficient for removing these relatively soluble compounds from the soil profile. Calcium carbonate is less soluble, and thus can be found in a wider range of environments. Secondary calcium carbonate is a common component of humus-enriched soils, *calcic* groups of Mollisols (Chernozems and Kastanozems).

In this section we discuss the soils, which have accumulations of secondary calcium carbonate, but do not have a developed dark-colored topsoil horizon rich in organic carbon. Most of these soils occur in dryer areas, than humus-enriched soils, because the lack of water results in less productivity of plant biomass, lower biological activity, thus leading to the decrease in the rate of humus accumulation. In the USDA Soil Taxonomy (Soil Survey Staff, 1999), the majority of such soils are believed to develop under arid climate and to have, consequently, an *aridic* moisture regime. These soils are commonly classified into the Aridisols Order, mostly in the Calcids Suborder. In places, similar soils may be found on slopes under humid climates: these soils are the products of water erosion of the soils, which once had a deep topsoil rich in organic matter.

However, the majority of profiles that have secondary calcium carbonate as the main characteristic feature are the soils of semiarid and arid regions. There are two main mechanisms of calcium carbonate enrichment in soils: illuviation and hydrogenic accumulation. The first process is believed to be the most important for calcium carbonate-enriched soils. The origin of primary calcium carbonate might be different. In most soils, primary sedimentary calcium carbonate is initially present in parent material, and percolating water just moves the carbonates downwards. In arid environments similar to Mexico aeolian accumulation of various forms of carbonates was reported (Gile et al. 1981). At a certain depth that depends on the amount of rainfalls and infiltration rate of the soil calcium carbonate form secondary accumulations. In other soils calcium carbonate might be initially absent, and it forms by simple reaction of carbonic acid with exchangeable calcium. The latter mechanism requires rapid release of calcium in the coarse of parent rock weathering. Research in the Sonoran Desert showed that the soils formed in volcanic rocks commonly had a horizon cemented with calcium carbonate, while the soil formed in granodiorite and metamorphic rocks were carbonate-free (Graham and Franco-Vizcaino 1992).

For the soils enriched with illuvial calcium carbonate the depth of their occurrence and the morphological form of carbonate accumulations serve as a diagnostic feature for the moisture regime and the dynamics of soil water movement. The more precipitation occurs in the region, the deeper are the carbonates in the soil profile. The depth of leaching can hardly be related quantitatively to the amount of rains, because the leaching also depends on soil texture and the frequency and intensity of the rainfalls. The texture determines the soil permeability: leaching of carbonates occurs much deeper in sandy soils than in loamy or clayey ones. Also the balance between the potential evaporation and rainfalls is important, and many other factors, such as the density of vegetation, and the processes of erosion and aeolian addition. The vegetation plays a complicated role in the water balance of soils. On the one hand, vegetation, especially arboreal one, provides shade, and thus decreases the temperature of the soil, and thus the evaporation and capillary uplift of soil moisture. On the other hand, the root systems of the plants intercept the percolating water and use it for transpiration. For example, the depth of leaching under Mediterranean climate is bigger under the climate with a summer maximum of precipitation, because during a cool, rainy winter the water percolates freely with minor interference of the root systems of plants. Amundson et al. (1997) showed that in Baja California carbonate coatings formed on the lower surface of the rubble in a Mediterranean climate (winter rainfall maximum) and at the top surface of the rubble in a summer–autumn rainfall peak.

The morphological forms of secondary carbonates include soft powdery lime, coatings on peds, concretions, pseudomycelia (carbonate infillings in pores, resembling mycelia), and surface or subsoil crusts, or hard banks. Cemented concretions, either integral or hollow, indicate hydromorphic conditions in the soils, past or present. Also the majority of hard crusts are formed at the actual or past level of groundwater table, mostly at the flood plains or at the toeslopes of the mountains and hills; this situation is widespread in Mexico. However, some hard calcium carbonate accumulations may also form due to intensive leaching, especially in the deposits initially rich in carbonates, or if considerable aeolian accumulation of carbonates occurred. Usually, the illuviation of calcium carbonate requires a long period of geomorphic and climatic stability, which is not the case for Mexico. Carbonate hardpans known as *caliche* in the northern part of Mexico almost completely are the products of hydrogenic accumulation. Another local name for these cemented layers is *tepetate* (Flores-Román et al. 1997); this term has been used for all the hardened horizons, but in the contemporary scientific literature is narrowed to hard layers of volcanic soils. Since in places the formation of these hardpans occurred under different environmental conditions, one can observe evidences of degradation (dissolution) of carbonate hardpans (Fig. 4.12).

In most of these soils secondary carbonates are diffuse, having a form of powdery lime, but in places soft accumulations can be found (Pérez-Zamora 1999). The pseudomycellia form of secondary carbonates is common in the majority of calcium-enriched soils, indicating alternating leaching and evaporative moisture regimes. In many such soils, pseudomycellia are not readily found in the field, but quite evident when the soil is studied under a microscope.

According to INEGI, the soils with accumulation of calcium carbonate (Calcisols/Calcids) are very common in Mexico, and occupy more than 18 % of the national territory. However, there are few studies of these soils; obviously, this is due to the relatively small value of arid carbonate-rich soils for agriculture. The main area of distribution of Calcisols/Calcids in Mexico is the arid north of the country. They are also common in arid valleys of the entire internal territory of Mexico.

Since extensive areas in Mexico are covered with limestone and other sedimentary rocks rich in calcium carbonate, in many places it is difficult to separate soils having residual primary carbonates and pedogenic carbonate accumulations. The division of primary and secondary carbonates is not only important from an academic point of view. It has also a practical significance, because it provides clues to the moisture regime of soil. In the field the distinction may be somewhat difficult, but microscopic observation usually helps to identify the origin of carbonates.

Due to their wide extension in the country, the soils with calcium carbonate accumulations vary in morphology. An example of one of such soils is presented below. The

Fig. 4.12 Petrocalcid/Petric Calcisol near the Faculty of Agriculture of the Autonomous University of San Luís Potosí (**a**). The *petrocalcic* horizon has evidences of contemporary dissolution (**b**). The person in the pit is the professor of the Faculty José Carmen Soria-Colunga (photo by P. Krasilnikov)

description was provided by Abel Ibáñez-Huerta and Elizabeth Fuentes-Romero, who included it in an unpublished report. The profile was made in Cucapá Ejido Mestizo, Hidalgo, Baja California State, near geothermoelectric station.

Geographical coordinates: 115°18′02″ W and 32°24′08″ 21°57′0.83″ N

Altitude: 7 masl

Landform: Alluvial terrace

Slope: <1°.

Geology: Mixed alluvial deposits with possible aeolian input.

Vegetation: Wheat field.

Classification (ST): Sandy over loamy, carbonatic, thermic Sodic Xeric Haplocalcid.

Classification (WRB): Hyposalic Calcisol (Ruptic, Sodic, Hyperochric, Arenic, Novic).

AC1, 0–35 cm—dry; brown to dark brown (10YR 4/3); sandy texture; structureless (single grain); loose consistency when dry; slightly firm when wet; non-adhesive; non-plastic; few pore channel; common fine roots; very strong reaction with HCl, pH 9.69, EC 7.9 dS cm^{-1}; clear smooth boundary.

AC2, 35–60 cm—dry; brown to dark brown (10YR 4/3); sandy texture; structureless (single grain); loose consistency when dry; soft when wet; non-adhesive; non-plastic; few fine pore channels; common medium and fine roots; very strong reaction with HCl, pH 9.91, EC 3.5 dS cm^{-1}; abrupt smooth boundary.

2AC, 60–75 cm—dry to slightly moist; dark brown (10YR 3/3); silty clay loam; coarse moderate subangular blocky structure; slightly hard consistency when dry; firm when moist; adhesive; plastic; few medium pores; common fine roots; very strong reaction with HCl; pH 8.38, EC 7.1 dS cm^{-1}; clear wavy boundary.

2Bw, 75–95 cm—dry; dark brown (10YR 3/4); clay loam; moderate coarse angular and subangular structure to massive structure; slightly hard consistency when dry; friable when moist; very adhesive; very plastic; common fine pore channels and medium vesicular pores; some cracks 2 to 5 mm wide; common medium roots; very strong reaction with HCl; pH 8.64, EC 4.5 dS cm^{-1}; clear smooth boundary.

2BC, 95–125 cm—slightly moist; dark yellowish brown (10YR 4/4); clay; moderate to strong coarse angular and subangular blocky structure; hard consistency when dry; firm when moist; very adhesive; very plastic; few fine pore channels; common clay coatings; presence of cracks and slickensides; very strong reaction with HCl; pH 8.87, EC 4.6 dS cm^{-1}; clear smooth boundary.

3C, 125–150 cm—moist; dark yellowish brown (10 YR 3/4); silt loam; weak coarse subangular blocky structure; slightly hard when dry; friable when moist; slightly adhesive; slightly plastic; common fine and medium pore channels and vesicular pores; few fine roots; very strong reaction with HCl; pH 8.61, EC 6.9 dS cm^{-1}.

The soils with high content of calcium carbonate commonly have neutral or slightly alkaline reaction. In the driest regions, such as in Baja California, these soils are also

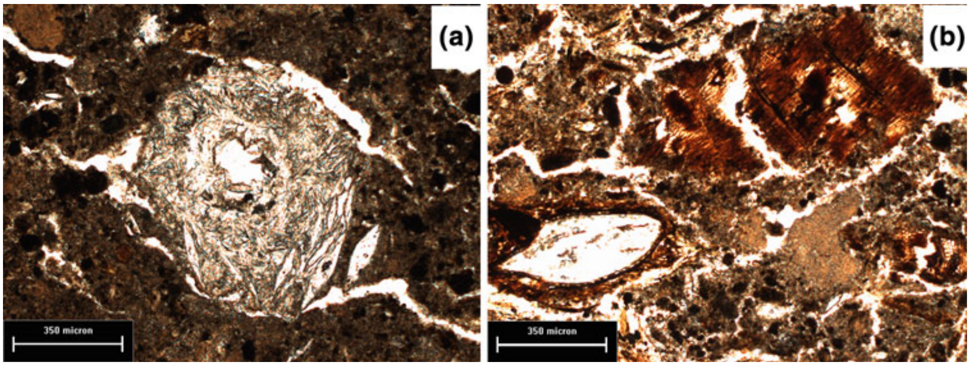

Fig. 4.13 Microphotos of Aridic Ustorthent/Gypsisol at the Rio Verde site, San Luís Potosí State (see text). **a** secondary gypsum in the pores of the C1y horizon, **b** underdecomposed organic matter in the A1k horizon (photos made by S. Sedov)

affected by sodicity. The physical properties of these soils vary depending on the texture and sodium content. The growth of crops in these soils presents few management problems and in this sense, generally, there are three main groups of plants: those that grow well in calcareous soils, those which do not grow well in these soils and those tolerant to a wide range of pH. The most frequent crop rotations is corn—wheat—alfalfa; the other products are squash and broccoli. If a layer cemented with calcium carbonate is present close to the surface, it may act as a physical barrier limiting the roots' growth. In general, the agricultural use of these soils is limited due to their coincidence with the areas with arid climate rather than with their infavorable properties.

Soils with intensive gypsum accumulation are not common in Mexico. The existence of these soils requires a combination of a very dry climate and a source of sulphates, such as sulphate-rich groundwater or parent material. Although secondary gypsum is common in the deep horizons of many soils of arid regions of Mexico, for example, in Kastanozems/Ustolls and Udolls, only for a few soils is the accumulation of gypsum a leading pedogenetic process. These soils mainly form in the gypsum-enriched sediments in arid regions of the states San Luís Potosí and Nuevo Leon. The climatic conditions of these areas are not dry enough to form soils with significant secondary gypsum accumulations. In contrast, the sediments, initially a mixture of calcium carbonates and sulfates, gradually loose more soluble gypsum in the course of leaching, and the upper layers usually are enriched with residual calcium carbonate. However, some of these soils may be classified as Gypsids/Gypsisols. Though the major part of gypsum has lithogenic origin, some of this is reworked into secondary pedogenic gypsum crystals that form mainly in voids (Fig. 4.13a). An interesting feature of these soils is poor decomposition of organic matter (Fig. 4.13b) that is typical mainly for modern humus of forest soils. Gypsum-enriched parent material and aridity decreases the biological activity that results in poor humification of the organic matter of these soils.

Below there is a description of soil formed in gypsiferous sediments at the site Rio Verde in the San Luís Potosí Sate. This profile was shown during the field excursion before the International Conference on Soil Geography held in Huatulco, Oaxaca, in November 2009.

Geographical coordinates: 99°55′48.5″ W and 21°57′ 0.77″ N

Altitude: 1,894 m

Landform: alluvial terrace

Slope: 2°.

Geology: silt alluvial deposits.

Vegetation: Grassland and shrubs with gypsophyllic vegetation.

Classification (ST): Coarse-loamy, gypsic, thermic Aridic Ustorthent

Classification (WRB): Epicalcic Hypergypsic Gypsisol (*Gypsiric*).

A1k, 0–4 cm—slightly moist; very dark reddish brown 10YR3/2 (moist) and dark reddish brown 10YR4/2 (dry); silt; fine moderate subangular blocky structure; consistence: loose when dry and very friable when moist; moderately sticky and plastic; very strong reaction with HCl; few medium and fine roots; clear wavy boundary.

AC12 k, 4–14 cm—dry; light brownish grey 10YR6/2 (moist) and light grey 10YR7/2(dry); silt; granular structure; moderately sticky and plastic; strong reaction with HCl; single fine roots; clear irregular boundary.

C1y, 14–35 cm—dry; light grey 10YR7/2 (moist) and white 10YR8/1 (dry); silt; medium moderate angular blocky structure; consistence: hard when dry and firm when moist; moderately sticky and plastic; weak reaction with HCl; clear wavy boundary.

Cm21y, 35–58 cm—dry; light grey 10YR7/2 (moist) and white 10YR8/1 (dry); silt; massive structure; consistence: extremely hard when dry and extremely firm when moist;

moderately sticky and plastic; very weak reaction with HCl; gradual wavy boundary.

Cm22y, 58–105 cm—dry; light grey 10YR7/2 (moist) and white 10YR8/1 (dry); silt; massive structure; consistence: very hard when dry and very firm when moist; moderately sticky and plastic; frequent small pinkish mottles (10YR6/5); continuous cementation; very weak reaction with HCl, abrupt wavy boundary.

Ry, 105–112+ cm—whitish hard gypsiferous material.

The gypsiferous soils in Mexico usually have slightly alkaline reaction due to the admixtures of calcium carbonates and in places of sodium carbonate and sulfate. The content of organic matter is low in most of the profiles. The cation-exchange capacity is generally low. The mineralogical composition of these soils was never reported for Mexico. The texture of these soils is described as silty in the field, but difficult to determine in the laboratory using standard pipette or hydrometer methods, because gypsum particles crush during the pretreatment, and clay-sized particles may dissolve in the process of sedimentation.

The use of gypsum-enriched soils is limited because of their occurrence in dry areas, and due to their low water-holding capacity (Martínez-Montoya et al. 2010); also they tend to subside under irrigation. The natural vegetation is represented mainly by desert grasses and shrublands, which in places are used for grazing.

4.11 Hydromorphic Soils

The hydromorphous soils, both mineral and organic, form under the influence of continuous saturation with water, either derived from groundwater or from precipitation. The organic soils form in excessively wet areas, where the processes of organic debris decomposition are retarded due to anaerobiosis. It leads, if the productivity of vegetation is enough, to the accumulation of peat. The stage of decomposition of the plant residues in the peat reflects the intensity of organic matter humification, which depends on the temperature and the availability of nutritious elements. As a rule, the least decomposed peat is found in cold areas, in the regions with very low potential evaporation and relatively high amount of rainfalls, and low nutrient supply. The *Sphagnum* mosses that indicate especially poor habitats produce substances that inhibit the microbial activity and thus prevent intensive organic matter decomposition. In tropical and subtropical areas or at the sites with higher supply of the nutrients (e.g. in the regions with common limestone rocks) the organic matter is commonly much more humificated. In the international classifications, the organic soils are called Histosols. In the USDA Soil Taxonomy, they are divided into three suborders with increasing grade of organic matter humification: Fibrists, Hemists, and Saprists. In the WRB system they correspond to Fibric, Hemic, and Sapric modifiers in the Histosols reference group.

Organic soils occupy a modest place in Mexico. Histosols are found almost exclusively on the coastal plain of the Gulf of Mexico, in the deltas of the rivers Grijalva and Usumacinta in Tabasco (Palma-López et al. 1985; Palma-López and Cisneros 1997). This is a fairly typical tropical Histosols characterized by a high degree of decomposition of organic material. In some places the thickness of organic layer reaches 4 m (Randy Adams-Schroeder, personal communication). Most of the Histosols are found in protected areas (National Park “Pantanos de Centla”), but some of these soils are heavily polluted with oil products (Adams-Schroeder et al. 1999).

According to Palma-López and Cisneros (1997), the soil profile of a typical Histosol in the Tabasco State is composed of 70–100 cm organic matter layer that rests on clay mineral soil. The organic material does not present a significant differentiation in subhorizons, but may be tentatively divided into two layers. The upper layer consists of underdecomposed material penetrated with abundant living roots, and has a depth between 15 and 55 cm. The second layer consists of much more humificated organic material, its color is darker than that of the surficial layer darker and its thickness varies from 20 to 75 cm. Mineral soil rests below the organic layers with one or two horizons of clayey texture, massive structure and bluish or greenish gray color. The presence of a high water table is a salient feature in these soils. The organic soils are practically not used in agriculture. In places they may be used for grazing.

The soils with minor content of organic matter occur in mangroves along the coasts of Mexico, especially at the coast of the Gulf of Mexico. These soils are affected by saline and brackish water, unlike the soils of the extensive wetlands of Pantanos de Centla, which are fed with fresh water. The presence of salts determines specific arboreal mangrove vegetation, and the organic matter content is generally less and the grade of humification is more in these coastal soils that in the deltaic Histosols. Below we present a morphological description of the profile made near Tumilco, Veracruz State, on the coast of the Gulf of Mexico. In this area the annual precipitation is 1,700 mm, mean annual temperature 25 °C, the climate is humid tropical with a maximum of precipitation in summer. The profile was shown at the field excursion in 2009 before the International Conference on Soil Geography.

Geographical coordinates: 97°19′39.26″ W and 20°55′ 2.74″ N

Altitude: 1 m

Landform: coastal plain of lacustrine type.

Slope: 0°.

Geology: marine sediments covered with organic debris.

Vegetation: Well conserved black mangrove: Avicennia germinans (L.) L.

Classification (ST): Loamy, mixed, active, hyperthermic Fluvaquentic Vertic Endoaquolls

Classification (WRB): Salic Vertic Tidalic Fluvisol (Sodic).

Ah1, 0–15 cm—wet; black 10YR3/1 (moist); loamy texture; massive structure; consistence: friable when moist; strongly sticky and moderately plastic; abundant coarse prominent mottles 10YR1/1 with sharp boundary; few fine roots, frequent medium and coarse roots; few slickensides; clear wavy boundary.

Ah2, 15–55+cm—wet; black 10YR3/2 (moist); loamy texture; massive structure; consistence: friable when moist; strongly sticky and moderately plastic; abundant coarse prominent mottles with sharp border 10YR1/1; few fine roots, frequent medium and coarse roots; few slickensides.

There are also hydromorphic soils with even less content of organic matter along the coasts of the Mexican Gulf (Fig. 4.14). In Soil Taxonomy, these soils are mainly classified as Fluvents, and in the WRB as Gleyic Fluvisols and Gleysols. They mostly occur in relatively young sandy sediments, where the organic matter is not present in significant amounts. The negative feature of these soils is low availability of oxygen for roots and possible iron and manganese toxicity. However, in the tropical regions they serve well for planting bananas.

Another group of mineral soils is the surficial layers affected by continuous water saturation. In the WRB such soils are called Stagnosols, and in the USDA Soil Taxonomy, they mainly fall into Epiaquents and Epiaquepts Great Groups. These soils are coincide with flat areas with high amount of rainfalls and heavy textured sediments with low permeability. The main area of distribution of these soils is the southern part of the coastal plain of the Gulf of Mexico, where they form on extensive clay loamy marine and alluvial terraces. These soils also have a number of limitations for agriculture due to their excessive moisture content. However, they are successfully cultivated for a number of tropical fruits such as cocoa, and used as pastures for grazing.

In the inland areas of Mexico hydromorphic soils are not very common. Mountainous relief favors intensive surface runoff that does not permit excessive moisture accumulation in a soil profile. The other point is that in most places the soils with excessive water content have more limiting properties, such as salinity or vertic features that surpass the excessive moisture content: these soils are appraised by these specific properties rather than by their hydromorphic nature.

4.12 Strongly Weathered Soils

A usual concept of a tropical soil for any pedologist who never studied tropical soils is a deep reddish clayey regolith with almost no horizon differentiation; there is no need to

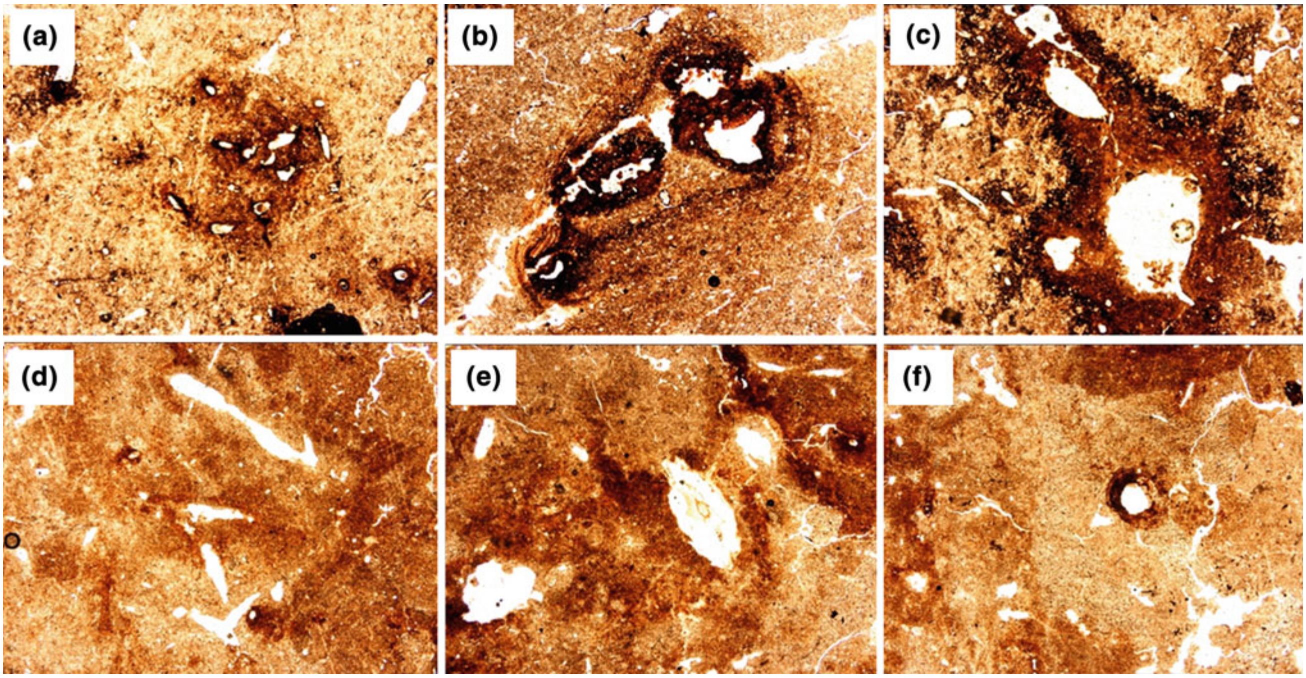

Fig. 4.14 Microphotos of a Aquent/Gleysol from Conduacan, Villahermosa, Tabasco. Low reduction degree: **a** manganese hypocoating, **b** and **c** manganese quazi-coatings. Moderate reduction degree: **d** and **e** iron depletion, and **f** hypocoating of Fe. Frame length 2.9 mm (photos made by Ma. del C. Gutiérrez-Castorena)

say that this concept may be blundering, especially in mountainous regions (Van Wambeke 1991). The formation of deep tropical soil is a long process that may require hundreds of thousand years (Targulian and Krasilnikov 2007) that implicate certain geomorphological stability. In the tropics, the distribution of mature soils is determined mostly by the intensity of erosional processes (Bremer 2010). Thus, the major territories with deeply weathered soils occupy in ancient flat areas with hot humid climates, such as Equatorial Africa or Amazonia. In Mexico, the distribution of deeply weathered soils is limited by the intensity of erosional and sedimentary processes.

Taxonomically, the tropical strongly weathered soils without textural differentiation are classified into the WRB as Ferralsols, Nitisols, and Plinthisols. Ferralsols, which correspond generally to the Oxisol Order of USDA Soil Taxonomy, are the most typical soils of stable tropical areas. The primary minerals are completely weathered in these soils, except the most resistant ones such as quartz, producing advanced products of mineral transformation such as kaolinite, iron (hydr)oxides and aluminium hydroxides. The cation-exchange capacity of these soils is extremely low; some of these soils even have a positive charge due to the exceptionally high zero-charge of gibbsite. This property determines high phosphate retention of these soils and phosphorus deficiencies of crops, when these soils are cultivated. These soils are commonly clayey, but clay in most of the profiles are aggregated in small extremely resistant sand-sized peds; this structure is called "pseudosand", and the hydrological properties of these soils correspond to those of sandy soils. Ferralsols/Oxisols is a group of soils that are not reflected on the soil maps of INEGI. Some papers reported the presence of Ferralsols/Oxisols in the extreme south, in Chiapas (Mendoza-Vega et al. 2003) and Tabasco (Palma-López and Cisneros 1997), but the laboratory analytical data were not complete and did not allow classifying the soils with enough confidence. Our research also showed the presence of similar soils in places on the upper, relatively gentle part of the slope, at heights between 1,000 and 1,300 m as under the shade of semideciduous tropical forests (Krasilnikov and García-Calderón 2005; Krasilnikov et al. 2007). At lower altitudes one can also find strongly weathered red-colored soils, but they are mostly mixed with fresh rock fragments that indicate their formation in transported slope sediments (Krasilnikov et al. 2011). Below is a description of a soil profile that represents tropical soils with no textural differentiation, located at the coffee plantation El Nueve, in the municipality Santa Maria Huatulco, Oaxaca State (Krasilnikov and García-Calderón 2005).

Geographical coordinates: 96°17′04″ W and 15°55′52″ N

Altitude: 1,260 m

Landform: mountainous ridge.

Slope: 25°–30°.

Geology: strongly weathered gneiss.

Vegetation: coffee plantation (*Coffea arabica* var. *typica* L.) under the shade of natural vegetation: *Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia aliodora*, and *Ficus* spp.

Classification (ST): Fine, kaolinitic, isohyperthermic Humic Rhodic Hapludox

Classification (WRB): Umbric Humic Ferralsol.

A, 0–55 cm—moist; dark reddish brown (5YR 3/3) in the moist state; clay loam; moderate fine crumb to granular structure; few fine and medium pebbles; a small amount of medium and large pores; few argillans and siltans on pore walls; abundant medium and fine roots; few earthworms; insect larvae; irregular clear boundary.

Bo, 55–100 cm—moist to slightly moist; red (2.5YR 4/6) in the moist state; clay loam; weak crumb structure; few fine and medium pebbles; abundant medium and fine pores; siltans on ped faces; few thick and medium-thick roots, few insect larvae; smooth clear boundary.

Bw, 100–155 cm—slightly moist; red (2.5YR 5/6) in the moist state; clay loam to clay; strong angular blocky structure; shiny ped faces; few fine and medium pebbles; few very fine pores; medium roots; smooth gradual boundary.

BC, 155–185 cm—moist; red (2.5YR 5/6–4/6) in the moist state; clay loam; coarse angular blocky structure; shiny faces of some peds; few fine and medium pebbles; few medium pores; few medium roots; wavy gradual boundary.

C, 185–200 cm—moist to slightly moist; dark red (2.5YR 3/6) in the moist state with yellow, white, and black mottles; gravelly silty loam; moderate coarse blocky structure; many pebbles and cobbles.

The reaction of all the horizons is moderately acid, with low ΔpH values, from 0.3 in the surface horizon to 0 in the parent material. The distribution of clay is almost uniform; at least, no distinct increase is detected in the B horizons. CEC and exchangeable bases content are relatively high in the surficial horizon, and low in the other horizons. The porous ferralic horizon has an extremely low CEC and a high content of nonsilicate iron compounds. The clayey horizon beneath the ferralic horizon has a stable angular blocky structure and shiny ped faces. Organic C content is high in the A horizon and decreases drastically with depth. X-ray data showed the dominance of kaolin minerals in all the soil horizons. In the surficial horizon, the presence of halloysite and gibbsite was registered. Only minor contents of 1.0 nm minerals (illites) were detected in the Bw horizon. It is necessary to say that the profile described above is not a typical Oxisol/Ferralsol because of the relatively high

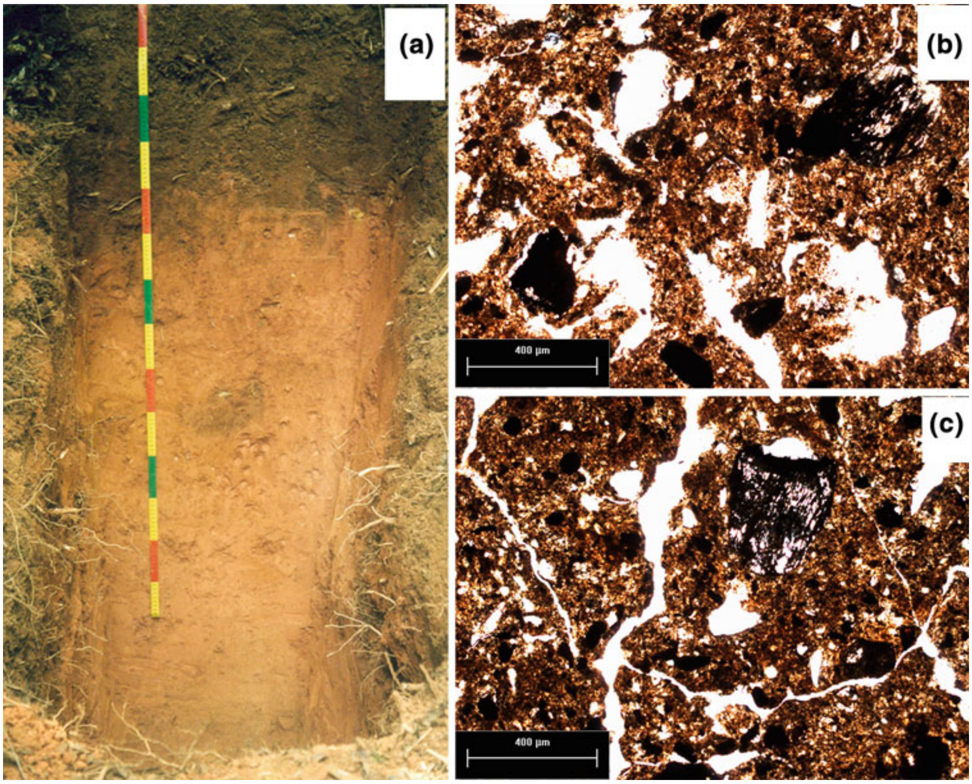

Fig. 4.15 Hapludox/Ferralsol at the El Nueve site, Oaxaca State (see text). **a** soil profile, **b** microphoto of porous Bo horizon, **c** angular blocky structure of the Bw horizon (photos made by S. Sedov)

content of weatherable minerals in the sand fraction. Though there is no evident features that show lithological discontinuity of the profile, one can suspect certain contributions of fresh material transported along the slope by gravity and surface runoff. The morphology of the profile and some microphotos are presented at the Fig. 4.15.

Nitisols is another reference group in the WRB that commonly corresponds to the tropical regions. In Soil Taxonomy, these soils are included partly in the Oxisols, and partly in the Ultisols order, dependently on the difference in clay content between the topsoil and subsoil horizons. These soils are similar to the group described above and also form in deeply weathered regoliths. However, they are richer in active minerals such as halloysite and poorly crystallized iron hydroxides, and have a well-developed angular blocky structure with shiny ped surfaces. Generally, it is believed that Nitisols form in the weathering regoliths of basic rocks such as basalt. The better hydraulic properties, slightly higher CEC and much higher biological activity make them better soils for agriculture than Ferralsols. Also these soils are more common in Mexico than Ferralsols. Perhaps, it is because the basaltic rocks weather easier than acid and intermediate volcanic rocks, thus less time is needed for deep regolith formation, and these soils have a chance to form during a shorter period of stability.

The other WRB reference group typical for tropics is Plinthisols. These soils are characterized by the presence of a layer with partial or complete cementation with hydrogenic iron oxides. In the USDA Soil Taxonomy, these soils are classified as numerous Plinthic and Plinthaqic Great Groups and Subgroups in the Oxisols and Ultisols Orders. These soils may be found in Mexico in the tropical regions in some flood plains, but no extensive areas occupied by the soils with plinthite were reported. In general, the tropical soils are still studied insufficiently in Mexico.

4.13 Poorly Developed Soils in Unconsolidated Sediments

The soils with underdeveloped profile are widespread world-wide. The absence of diagnostic features in soils is commonly associated with incipient pedogenesis, i.e. these soils are in recent sediments. Also in places the absence of diagnostics may indicate very low pedogenetic potential of the soil-forming factors.

For example, desert soils that have no marked accumulations of salt, gypsum and carbonates commonly do not show other evidences of pedogenesis, such as clay movement, organic matter accumulation, or pronounced modification of the rocks structure. In many dynamic landscapes, the pedogenesis is hampered by continuous erosion or, in contrary, sediment accumulation (Birkeland 1984). Due to the geomorphological dynamics of the major part of Mexico this kind of underdeveloped soils is quite abundant in the country. Almost all the soils are affected by water or wind erosion, and in some of them the intensity of material removal is high enough to hamper soil formation.

There are three taxonomic groups that comprise poorly developed soils, on the level of Suborders in Soil Taxonomy, and on the level of reference groups in the WRB. These groups are Fluvents/Fluvisols that include young alluvial soils, Psamments/Arenosols that include sandy soils with poorly developed profiles, and Orthents/Regosols that cover loamy and clayey soils with weakly expressed pedogenesis. A scholar may ask, why so many taxonomic groups for underdeveloped soils? The answer is that in poorly developed soils the origin of the parent material plays a major role in characterizing their properties, functions and possible use, and thus it is important to separate sands from clay and loam substrates and from layered alluvial sediments.

The Fluvents/Fluvisols are found along the rivers. The old flood plains stream terraces that correspond to almost all the valleys of Mexico commonly have more developed soils; in places with a series of buried paleosols under the surface profile (see Chap. 8 for details). In these valleys, there is no actual accumulation of alluvial sediments, and the soils already developed enough to be classified in other taxonomic groups. Poorly developed alluvial soils are found mainly in the flood plains of big lowland rivers such as Rio Grande, Rio Lerma, Grijalva, and Usumacinta. The properties and morphology of these soils reflect mainly the layered structure of the alluvial sediments (Fig. 4.16). Many alluvial soils have organic matter deposited by the water fluxes, and thus have an irregular distribution of organic carbon in the profile. The potential fertility of these soils is high because of high nutrients content and the proximity of groundwater. However, their management is commonly difficult because of regular flooding. The best use of these soils is for grazing.

Immature sandy soils are common worldwide in sandy deserts and in coastal dunes. In Mexico, the distribution of Psamments/Arenosols is not very extensive. Sandy deserts are few in Mexico; in Sonora, sandy soils are described in the pediments of tonalites (Graham and Franco-Vizcaino 1992), some eolian sands are present in the deserts of Baja California. Dubroeucq et al. (1992b) described sand dunes on the coast of the Gulf of Mexico: the ancient dunes had paleosols stratified into several profiles, and the recent sandy deposits had sandy soils, even when the deposits were aged. The main pedogenetic process detected in these soils was the dissolution and leaching of primary calcium carbonate particles. Many coastal regions also have marine sands with poorly developed soils. The soil consists of single sandy grains. The iron oxide coatings on the grains are of lithogenic origin. The organic matter content is low. The main limitation of the use of these soils is their very low water retention capacity. However, in extrahumid tropical regions it is not a big disadvantage: they are successfully used for such tropical cultures as banana and pineapple.

The other soils with underdeveloped profile, which are classified as Orthents/Regosols correspond to arid lands with low salt and carbonate availability, and to eroded areas. The erosion of soils is very extensive in Mexico. In detail they are discussed in Chap. 6.

4.14 Anthropogenic Soils

The soils transformed by humans are the focus of current pedological research. The area of the soils completely modified by anthropogenic action increases, including the soils of urban, traffic and industrial areas, as well as transported materials used for agriculture, hydrotechnical soil improvement and rural construction. Also the soils that underwent deep agricultural transformation are now regarded as taxonomic units different from their natural counterparts. It is natural because the composition, properties, external functions, and potential productivity of these soils differ greatly from the soils formed under the influence of natural soil-forming factors. The WRB has two reference groups that include all the deeply transformed soils. The group of Anthrosols includes all the soils that have been transformed in the course of agricultural use, including those receiving additional materials with irrigation water or as mineral improving agents (e.g. sand added to clayey or organic soils), or organic fertilizers (compost, manure, peat). The other group, Technosols, is more diverse and covers all the urban and industrial soils (included those coated with asphalt or concrete), transported materials, and archeological “cultural layers”. The USDA Soils Taxonomy is working on addressing the problem of soils changed by humans, but is hampered by the amount of change required to develop new, meaningful taxa. The Arents Suborder includes the soils mixed by deep ploughing, and Plagganthrepts Suborder includes the soils with initially thin or poor in organic matter epipedon, which have been deepened and enriched with humus by ploughing and fertilization.

In Mexico, the soils deeply transformed by agriculture are mainly associated with the activity of Pre-Hispanic civilizations that developed sophisticated systems of crop production even in rather infavourable conditions, like at Yucatan Peninsula with shallow soils on limestone.

One of the most amazing examples of the Pre-Hispanic soil use is so-called *chinampas* agriculture (Ramos-Bello et al. 2011). *Chinampas* are agroecosystems developed in the lacustrine zone of the catchment of Mexico in the areas that are periodically flooded or stay under shallow water. From the eleventh century local ethnic groups developed a

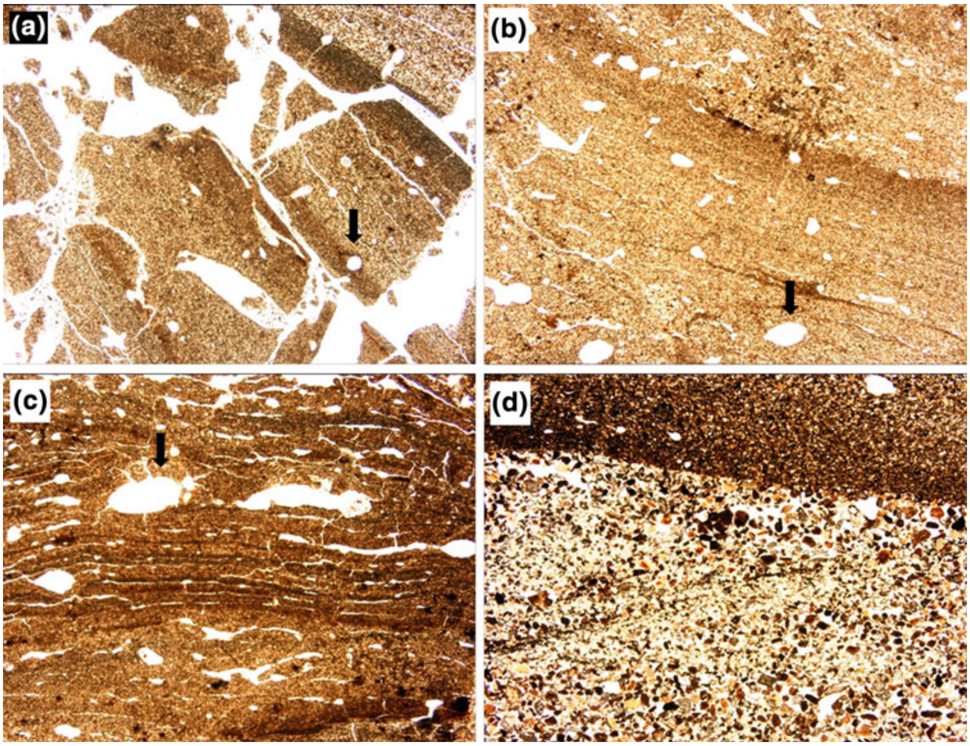

Fig. 4.16 Typic Ustifluvents/Fluvisols in the alluvial sediments in Texcoco ex-lake, Mexico State.: **a** angular blocky structure with a banded distribution pattern, Ap horizon; **b**, **c**, and **d** banded distribution pattern of sand grains of different sizes and mineral composition, and vesicules pores (*arrows*), C horizons. Frame length 5.2 mm (photos made by Ma. del C. Gutiérrez-Castorena)

specific culture and technology: irrigation by flooding, and formation of a series of elevated fields for agricultural production (Ezcurra 1990). *Chinampas* (a word of *nahuatl* origin: *chinamitl*—"straw bed", and *pan*—"over") are portions of soil material designed for capturing water. The fields were made by accumulation of organic matter, loamy lacustrine sediments, or any material which served to consolidate the islands, separated by a system of channels, which served for boating and drainage (Jiménez et al. 1995). The soil surface is about one meter over the water level. In the course of *chinampas* use, additional lake mud could be added, or excessive soils could be removed to construct new *chinampas* (Coe 1964). The origin and significance of these soils is discussed in more detail in the Chap. 7.

Below we present an example of a typical *chinampas* soil, located in Laguna del Toro, Xochimilco. The profile was shown at the WRB field excursion held in Mexico in 2005.

Geographical coordinates: 99°06′51.1″ W and 19°16′40.5″ N

Altitude: 2,235 m

Landform: lacustrine flatland.

Slope: 0°.

Geology: lacustrine sediments rich in organic matter.

Vegetation: stand of grass, actually the site is used for social events

Classification (ST): Fine-loamy, isotic, thermic Aquandic Endoaquoll

Classification (WRB): Salic Terric Anthrosol.

A1, 0–24 cm—slightly moist; black 2.5Y2/1; silty loam; weak fine granular structure; friable when moist; abundant fine roots; abundant fine, medium, and micropores; clear plain boundary.

A2, 24–40 cm—moist; very dark gray 2.5Y3/1; clay loam; moderate granular and moderate large, medium and fine subangular blocky structure; firm; abundant fine and very fine roots, rare medium roots; abundant macro and micropores; clear plain boundary.

A3, 40–80 cm—moist; polychrome, dark olive gray 5Y3/1 and dark gray 10YR4/1; silty clay; large strong subangular blocky structure; firm; many fine roots, rare medium roots; many micro and macropores; abrupt wavy boundary.

AB, 80–89 cm—wet; polychrome, black 10YR2/1 with light gray 2.5Y7/2 and grayish brown 10YR5/2; silty loam; fine and medium moderate granular structure; friable, slightly adhesive; few fine roots present; mny micro and macropores; clear wavy boundary.

Ab, 90–130 cm—wet; black 5Y2.5/1; silty clay loam; large moderate subangular blocky structure; firm; viscous; few fine and very fine roots present; abundant pores of various sizes; clear wavy boundary.

G1, 130–134 cm—wet; polychrome, light brownish gray 2.5Y6/2 with black 2.5Y2.5/1 to Gley1 2.5/N; silty sandy loam; massive structure; friable, sticky; few fine and very fine roots present; clear wavy boundary.

G2, 134–150 cm—wet; black Gley 1 2.5/1; loam; strong medium subangular blocky structure; sticky, non-adhesive, slightly plastic; few fine roots present; some pores present; clear wavy boundary.

Gh3, 150–163 cm—strongly wet; polychrome, black Gley1 2.5/N with light olive gray 5Y6/1; loam to silt loam; moderate medium subangular blocky structure; few fine roots present; common pores; abrupt plain boundary.

G4, 163–180 cm—strongly wet, flooded; black Gley 1 2.5/N.

This soils is characterized by high organic matter content that varies with depth. The bulk density of these soils is low because the mineral part is composed mainly of volcanic ash and the products of its weathering. The soil has a high level of salinity and sodicity. The *chinampas* soils are discussed in detail in the Chap. 7.

Actual soil management in places also results in the formation of deep cultivated layer, especially if high doses of organic fertilizers are applied. An example of such a soil is shown at Fig. 4.17

The Tehnosols, i.e. the soils transformed by human activities other than agriculture, are widespread in Mexico. These include urban soils and soils of opencast mining. These soils in Mexico occupy a vast territory, but so far the study of such soils are rare, and mostly relate to the environmental effects of weathering stockpiles of mines and quarries (Acevedo-Sandoval 2000). A perspective area of research in Mexico should be the study of urban soils, because Mexico City is one of the biggest world megapolices, and the study of its soils is of crucial importance for human health.

4.15 Less Abundant and Less Studied Soils

Mexico is a country with extremely diverse soils, and one can hardly identify soils that are not present in the country. Cruz-Gaistardo et al. (2006) mentioned that in the WRB terms only four groups of soils that are not reflected at the soil maps of INEGI (1:250,000), namely Ferralsols

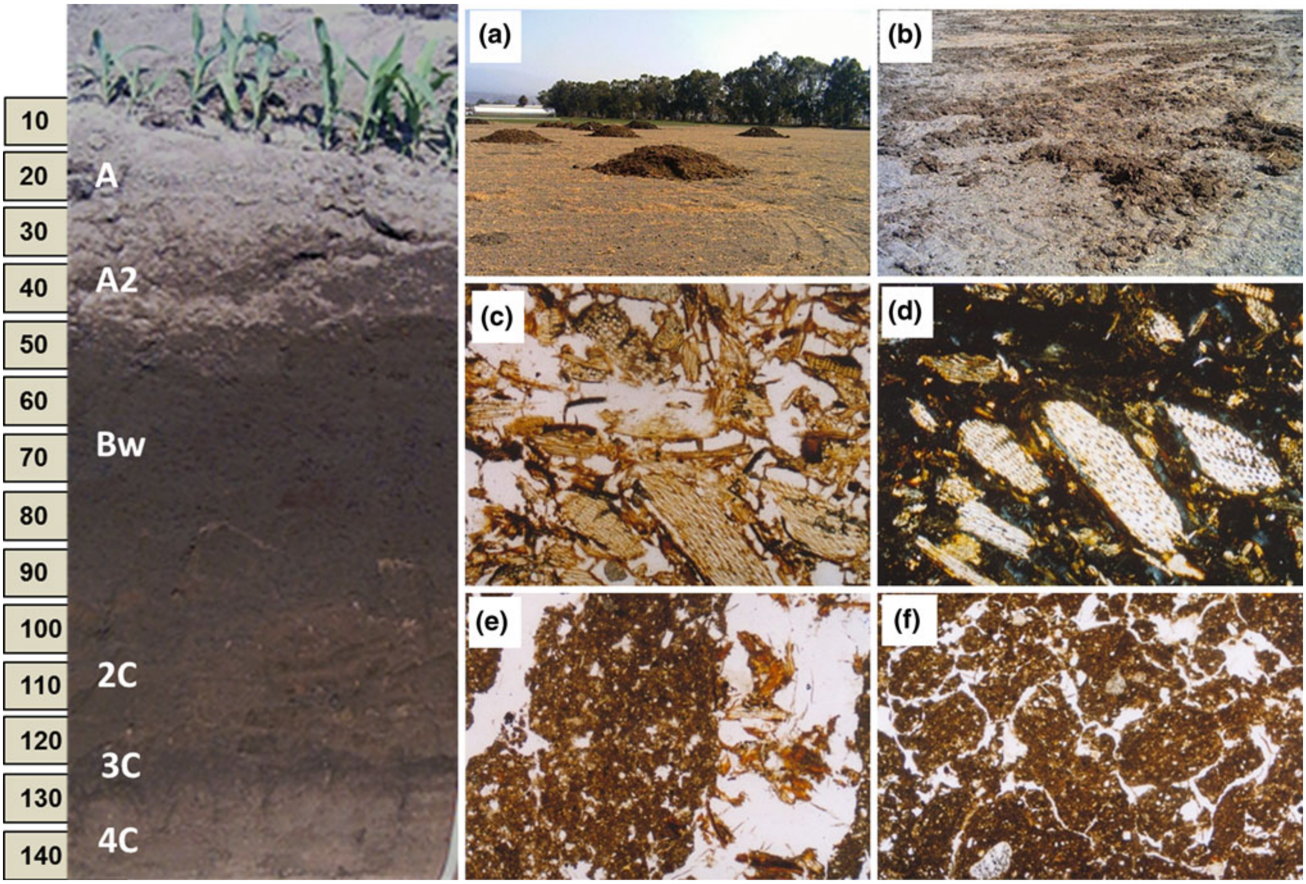

Fig. 4.17 Hortic Anthrosol (Eutric), and some microphotos of its topsoil horizon (Ap, 0–29 cm): **a** mounts of manure, **b** spreaded manure, **c** fragments of manure, **d** the same as b, but with crossed polarizers, **e** moderate grade of manure decomposition in the pore space, **f** granular and subangular blocky structure of the horizon. Frame length 5.3 mm (photos made by Ma. del C. Gutiérrez-Castorena)

(Oxisols), Podzols (Spodosols), Cryosols (Gelisols), and Albeluvisols (Glossic Great Groups in the Alfisols Order). As for Ferralsols/Oxisols, these soils have been described in a number of papers (see above), although they do not occupy areas sufficient for reflecting them at the medium-scales maps. The Podzols/Spodosols were recently described in the mountains under the shade of montane cloud forests (Álvarez-Arteaga et al. 2008). This paper describes specific soils formed in base-poor ferrigeneous chlorite shale that have evidences of true podzolization (cheluviation), surface gleying, and strong weathering. An example of a morphological description of one of these soils located in the Sierra Juárez mountainous ridge, in the so-called Chinantla zone of the Oaxaca State, is listed below.

Geographical coordinates: 96°32′30″ W and 17°38′40″ N

Altitude: 2,380 m

Landform: mountainous ridge.

Slope: plain slope 40° of northern aspect.

Geology: albite-mica-chlorite schists .

Vegetation: upland montane cloud forest, with *Quercus eugenifolia* Liebm., *Clethra galeottiana* Briq., *Ternstroemia hemsleyi* Hochr., *Cleyera integrifolia* (Benth.) Choisy. and *Weinmannia tuerckheimii* Engl.. Abundant epiphyte plants: lianas, mosses and lichens.

Classification (ST): Loamy-skeletal, mixed, subactive, isomesic Lithic Epiaquod

Classification (WRB): Stagnic Endoleptic Folic Albic Podzol.

Oi, 0–2 cm—litterfall of varying degrees of decomposition, green mosses grow on fallen leaves and on fragments of wood.

Oe, 2–10 cm—moist; very dark brown 10YR 2/2; layered structure; loose; slightly plastic; abundant fine roots; wavy clear boundary.

Oa, 10–27 cm—moist; very dark brown 10YR 2/2; weak granular structure; very friable, plastic; soils hands; the roots of all sizes take up 30–40 % of the horizon; at the lower limit of the horizon there is a lens of completely humified black material; clear wavy boundary.

Eh, 27–45 cm—moist; gray 10YR 5/1; loam; large moderate angular blocky structure; on the surface of peds there are black (10YR 2/1) humus skins, the transition from black to gray is gradual, giving the impression of impregnating the material with the surface; plastic; hard; roots, fine and medium-sized, are mostly concentrated along the edges of the peds, covered with black skin; gravel and crushed schists constitute 10–20 % of the horizon; clear wavy boundary.

Bsg, 45–70 cm—wet; polychrome, the matrix consists of a combination of brownish–yellow (10YR 6/6) and yellowish–brown (10YR 5/8) spots, interspersed with layers of dark reddish–brown material (5YR 3/4); sandy loam; weak medium subangular blocky structure; plastic; compact; single thin humus-clay coatings; few fine roots; the number of fragments of schist increases with depth, passing into the solid rock, gravel and boulders constitute about 50 % volume of the horizon.

Fig. 4.18 The profile of Podzol/Spodosol under the shade of monate cloud forest in Oaxaca (photo by P. Krasilnikov). See text for explanation

These soils are characterized by an exceptionally low base saturation (3–7 %) in the mineral horizons and low pH values in all the horizons (between 3 an 4 in water extraction). The clay minerals include illite, kaolinite and gibbsite. For details see Álvarez-Arteaga et al. (2008). The profile is shown in the Fig. 4.18.

The soils affected by permafrost were not described in Mexico until now, though their presence is strongly suspected. According to the results obtained by the geocryology specialists (Heine 1994), the permafrost can be found at the highest peaks of the Transmexican Volcanic Belt. The discontinuous permafrost was reported at some of these peaks such as Pico de Orizaba, Popocatépetl and Iztaxíhuatl at the altitudes over 4,600 m. Special research is needed to confirm the presence of Cryosols/Gelisols in Mexico and to record their properties.

Albeluvisols, a group of soils with a bleached albic horizon that has tonguing in the underlying horizon, is a soil taxon, which coincides with the periglacial areas of the last glaciations in Eurasia and North America. The presence of deeply penetrating tongues of whitish material is usually explained by past cryogenic cracking of the soils (Driessen et al. 2001). In the USDA Soil Taxonomy, these soils are classified as Glossic Great Groups of Alfisols, mainly as Glossudalfs. It seems that it is one of the few taxonomic groups absent in Mexico, because in the periglacial zone of the last glaciations in the mountains of Mexico (Heine 1994), the volcanic sediments and the climate do not favour very strong leaching that is needed for the formation of such soils.

A special group of soils poorly reflected in world soil classifications is the group of hydrothermally altered soils. Though they are commonly regarded as poorly developed from the pedological point of view, their special mineralogical composition determines their particular properties, for example, the presence of free sulphuric acid (e.g. Krasilnikov et al. 1995). In Mexico, hydrothermal alteration is widespread phenomena, especially in the Transmexican Volcanic Belt, and such soils should be given a special attention.

4.16 Conclusions

Mexico is characterized by high heterogeneity of the soil mantle. It is a result both of the diversity of habitats with different soil-forming factors and of the activity of geomorphological processes. The latter fact determines broad development of shallow and underdeveloped soils, which form mainly due to intensive erosion. According to the calculations of INEGI, the most abundant soils in Mexico are Leptosols (shallow soils both on silicate rocks and limestones), covering 28.3 % of the national territory, followed by Regosols (Orthents) that occupy 13.7 %. The next in area group is Phaeozems (mainly Udolls) that occupy 11.7 % of Mexico, then Calcisols (Calcids) with 10.4 %, Luvisols (Alfisols) with 9.1 %, and Vertisols with 8.6 %. The other soil groups cover much smaller areas.

The extent of the scientific study of different soil groups does coincide neither with the territory that they occupy nor with their significance for agriculture. Since the major centers of soil science in Mexico are located in Mexico City and the State of Mexico, the most important research works have been done in the Transmexican Volcanic Belts, and the most studied soils are Andosols/Andisols, Vertisols, and Solonchaks/Salids. For the future the researchers should concentrate their attention on the less studied but more abundant soils, especially shallow and immature soils, with an emphasis on their degradation and erosion. Another priority should be the study of urban soils with an emphasis on their hydrological and sanitarian functions.

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Geographical Regionalization of the Mexican Territory

5

5.1 Soil Regionalization as a Scientific Task

The soil geography is one of the most important subdisciplines of soil science from the theoretical and practical sense (Ferreras-Chasco and Fidalgo-Hijano 1991). The theoretical goal of the geography of soils is to understand and explain the relationships of the distribution of soils and their properties on the surface of the Earth. The practical application of this subdiscipline includes soil mapping for the inventory of soil resources, the interpolation of spatial data, and land use planning and land management.

The regionalization of soils is one of the main objectives of soil geography (Dantin-Cereceda 1922; Glazovskaya 1984) that has both theoretical and practical importance. Theoretically, you can find regional rules for the distribution of soils in space. For practical work, soil regionalization forms the basis of the activities of management, conservation, and restoration of the soil resource (Dobrovolski and Urusevskaya 2004). Historically, soil regionalization was proposed in the beginning of the twentieth century in Russia and Western Europe (Dantin-Cereceda 1913; Prasolov 1922). In the Russian view, the regionalization was largely a climatic division, while the European concept also included other environmental factors. In Russia, the regionalization of the country's soil was essential for soil studies and land use planning because of the great extent of the national territory. In the United States, the first work on soil regionalization was published by Wolfanger (1930), who divided the entire country mainly in two areas of Pedalfers, soils which dominate the process of translocation of aluminum and iron, corresponding to moist areas, and Pedocals, soils of arid areas with accumulations of calcium carbonate and soluble salts in the profile. Pedalfers occupy the eastern part of the continental US and pedocals, the west. According to Wolfanger, the limiting factors for agricultural development are different in the two areas; in the zone of Pedocals the arid climate limits the development of crops, while in the areas of Pedalfers soil properties such as acidity, Al toxicity and the presence of plinthite are limitations. Although the work of Wolfanger was very general and reflected more the division of the US to climatic zones, he also proposed to develop more detailed soil regions.

Soil regionalization occupies a specific place in the theory of soil geography. All the pedogeographic studies can be divided into three main approaches: statics, dynamics and structural (Krasilnikov 2011). Each of these approaches has its own theoretical foundations, research methods and terminology. The static approach deals with the spatial distribution of soils from the point of view of state factor theory: the spatial distribution of the soil is explained in terms of spatial distribution of soil-forming factors (Yaalon 1971; Arnold 1994). Although considered vertical processes in the soil profile, the lateral processes of material transport in any form are not taken into account (Pennock and Veldkamp 2006). Another approach is based on the concept of lateral transport of solutions and solid materials that cause the difference in the composition and properties of soils. Geochemical flows of various scales are considered in terms of landscape geochemistry (Glazovskaya 1984), and transport of solid material along the slopes in terms of soil geomorphology (Birkeland 1999). Although the concept may be applied at various scales (Glazovskaya 1984), it is usually used for describing solute and solid material transport along a slope in the scale of a soil catena, rather than an area encompassing thousands of kilometers. Finally, the structural approach in soil geography focuses on the arrangement of soils in space, with little or no attention to the genesis. Examples of this research are the theory of the pattern of soil cover or soil landscape analysis (Fridland 1974; Hole and Campbell 1985) and pedometrics methods such as the study of pedodiversity (Ibáñez et al. 1995). The work of a soil geographer is seldom restricted to one of these approaches. In the majority of the studies, several approaches are used in combination. For example, we can study the spatial arrangement of soils and then interpret the results using state factor theory and/or lateral transport of matter.

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This combined approach helps us, inter alia, dividing the pedospere into regions with more or less uniform internal pattern of soils.

Soil regionalization is a procedure that is mainly based on the static concept of management of soils in space, although it is necessary to take into account the dynamic and structural concepts. The grouping of soils in the regions is based on the uniformity of soil combinations in the region that implies a relative uniformity of soil-forming factors (Hudson 1992). The soil, like a mirror, reflects the factors of its formation, so there is always some relationships among the topography, geology, climate, vegetation, and soil, and thus soil regionalization usually complies to natural areas in general. For this reason, the soil regions are commonly delineated by the boundaries of the climatic, physiographic, or biogeographic regions. The most traditional regionalization in soil geography is to outline the zones, provinces, and regions according to climatic conditions. This does not mean that climate is more important than other components of the environments, but the distribution of climates is a regular and predictable factor. However, the regionalization based only on climate is not perfect. Several authors showed that both topography and parent materials could affect the spatial distribution of soil practically in any scale (Arnold 1994). Also the climatic conditions may be very variable in relatively short distances. In a mountainous system, one should take into account the climatic gradient rather than characterizing the climate of the area with the average values of temperature and precipitation. The regionalization of soils based on bioclimatic regions was developed for the relatively flat areas with gradual climate transitions; this situation is almost nonexistent in Mexico. In the Russian system of regionalization, the mountains were considered as unique with a complex altitudinal distribution of soils (Dobrovolski and Urusevskaya 2004). Mountainous areas defined as soil regions are often defined as an area with a regular gradient of climate and related ecosystems. However, some mountain systems have an even more complex mosaic of climates, where some slopes are dry and the others are wet, with their own altitudinal gradients. It is also important to take into account the lithologic diversity, because the variation in parent material can completely change the soil pattern, especially if the parent materials have particular properties, such as volcanic ash or limestone (Fridland 1974; Steila 1989).

5.2 Soil Regionalization of Mexico

Soil regionalization is difficult in Mexico due to the high variability of its topography and climates. The complexity of the landscape of the country and the extent of the coasts result in the existence of numerous climatic gradients: altitudinal gradients, gradients of aridity/humidity due to the proximity of the sea, and the presence of the "geographical shadows".

The complexity of the topography, climates, and soils in Mexico did not permit the development of a system of regionalization of the country until now. Also the traditional way for representing data on any of the natural resources in Mexico is the representation of data by administrative units (states), which is logical from the standpoint of natural resources management. Curiously, the soil regionalization for Mexico was published only by Russian authors within the zoning of the soil cover of the world (e.g., Glazovskaya 1984). In accordance with the soil zoning proposed by this author, the most extensive northern part of Mexico belongs to the California–Mexican desert region of reddish-brown, gray-brown, and mountain cinnamon soils, which is a part of a bigger North American desert soil sector of brown desert-steppe, reddish-brown desert, mountain gray-cinnamon, and cinnamon soils. The extreme south of Mexico belongs to the Central American soil region of mountainous humus ferralitic, fersiallitic and siallitic soil, and Andosols, which is a part of the Pacific humid tropical soil sector. This region is divided into two subregions: the western mountainous (Southern and Eastern Sierra Madre and the Mesa Central Plateau) and the eastern flatland (Yucatan). This regionalization was made on the basis of general considerations, because the data on the soils of Mexico were insufficient for successful geographical analysis; for example, the extension of "cinnamon soils" (Xerolls/Kastanozems) and "ferralitic soils" (Oxisols/Ferralsols) was strongly overestimated (Krasilnikov 2011). The disadvantage of the scheme was also the use of original authorial terminology that was not accepted internationally. Thus, this regionalization scheme was only of historical importance.

Evidently, for Mexico, a successful scheme of soil regionalization should be based not only on the major climatic gradients, but also on the topography and lithology (Cuanalo de la Cerda et al. 1989). Turning to the empirical data on the pedogenetic factors in Mexico, we should first take into account the general distribution of climates in the country. Although Mexico is an extensive country that stretches for more than 2,000 km from north to south, the sums of temperature do not change regularly in the latitudinal direction, and depend mainly on the elevation (see Chap. 3). The distribution of precipitation is of major importance. It affects the soil moisture regime and, thus, the whole pathway of pedogenesis. There are two areas of arid moisture regimes in the north-east and north-west of the country based on the estimates of climatic parameters and surface runoff. These arid regions are separated by a relatively wet mountain range, the Sierra Madre Occidental.

A small area of dry soil is found in the Northwestern Yucatan Peninsula, as well as sporadically in all the valleys of mountain systems. Virtually, the soils of the entire territory of the major mountain systems of Mexico (Sierra Madre Oriental, Sierra Madre Occidental and Sierra Madre del Sur, Transmexican Volcanic Belt) have ustic, and in places perudic, soil moisture regimes. We proposed dividing the whole territory of Mexico into mostly arid (and semiarid) and mostly humid (also subhumid and extrahumid) zones with relevant types of soil formation (Krasilnikov 2011). In addition, taking into account an important role of specific parent materials, it makes sense to separate the zone of pedogenesis in volcanic ashes (Transmexican Volcanic Belt), and the zone of limestone pedogenesis (Peninsula of Yucatan and Sierra Madre Oriental). Thus, there are three major soil zones in Mexico: arid, humid, and lithology dependent (Fig. 5.1).

The general division of the Mexican territory into three major districts of arid, humid, and lithology-dependent pedogenesis is supported by the data on the mineralogy of soil clays (e.g. García-Calderón et al. 2005; Graham and Franco-Vizcaino 1992; Dubroeucq et al. 1992; Ducloux et al. 1995; Dudek et al. 2006). Although the publications are not very abundant, they give evidence of the dominance of smectite and palygorskite clays in the soils of the arid district, halloysite, kaolinite, and gibbsite in the humid district, and allophane, halloysite, and smectite clays in the volcanic areas.

On the lower level, the regionalization of Mexican soils should be also done taking into account both climates, topography, and lithology. Our proposal was to relate soil regions with physiographic provinces, because the latter represent areas with the same type of relief and are affected by the same gradient of atmospheric flow (Krasilnikov 2011). Each province has its own mosaic of landscapes that depends on a whole set of physiographic factors. There are several schemes of physiographic regionalization of the Mexican territory (Instituto de Geografía 1992). The most accepted division actually includes 15 physiographic regions (Quiñones 1987); this scheme is recognized by INEGI (Fig. 5.2). A recently published book on soil geography of Mexico also uses this division (Krasilnikov 2011). The latter source gives the following division of Mexican territory into pedogeographic regions. The regions where vertical zonality is of major importance are marked as "mountainous regions", and those where the lithology is more significant include the name of the dominant parent material.

1. Arid and subarid regions
   - 1.1. Mountainous region of Baja California with poorly differentiated (Regosols and Cambisols/Orthents and Cambids), sandy (Fluvisols and Arenosols/Fluvents and Psamments), and shallow soils (Leptosols/Lithic groups of Entisols and Inceptisols).
   - 1.2. The region of Sonorian Lowlands with calcareous (Calcisols/Calcids), swelling, and shrinking soils (Vertisols), and saline soils (Solonchaks/Salids).
   - 1.3. The region of the Lowlands and Uplands of the North with calcareous (Calcisols/Calcids), shallow (Leptosols and Lithic Great Groups of Entisols and Ustepts), and humus-enriched soils (Kastanozems/Ustolls).
   - 1.4. The region of Great Plains of Northern America with humus-enriched (Kastanozems and Chernozems/Ustolls and Udolls) and calcareous (Calcisols/Calcids) soils.

Fig. 5.1 The division of the Mexican territory into three major soil zones, where *yellow*—arid zone, *green*—humid zone, and *purple*—lithology-driven zone

Fig. 5.2 The division of Mexican territory into physiographic/soil regions: *1*—Baja California, *2*—Sonorian Lowlands, *3*—Sierra Madre Occidental, *4*—Lowlands and Uplands of the North, *5*—Sierra Madre Oriental, *6*—Great Plains of Northern America, *7*—Pacific Coastal Plain, *8*—Central Mesa, *9*—Northern Coastal Plain of the Gulf of Mexico, *10*—Transmexican Volcanic Belt, *11*—Sierra Madre del Sur, *12*—Southern Coastal Plain of the Gulf of Mexico, *13*—Yucatan Peninsula, *14*—Ridges of Chiapas and Guatemala, *15*—Central American Cordillera (modified after Krasilnikov 2011)

1.5. The region of Central Mesa (Tableland) with humus-enriched (Phaeozems, Kastanozems/Udolls, Ustolls), hardpan (Durisols/Duric Great Groups of various Orders) and calcareous (Calcisols/Calcids) soils.

2. Humid, subhumid, and extrahumid regions.

2.1. Mountainous region of Sierra Madre Occidental of texturally differentiated (Luvisols/Udalfs) and humus-enriched carbonate-free soils (Phaeozems/Udolls).

2.2. The region of Pacific Coastal Plain of poorly differentiated (Regosols, Arenosols, and Cambisols/Entisols and Udepts) and calcareous humus-enriched (Kastanozems/Ustolls) soils.

2.3. The region of the Northern Coastal Plain of the Gulf of Mexico with swelling and shrinking (Vertisols) and humus-accumulative carbonate-free (Phaeozems/Udolls) soils.

2.4. The region of the Southern Coastal Plain of the Gulf of Mexico of hydromorphic (Histosols, Gleysols, and Fluvisols/Aquents and Fluvents, Stagnosols/Epiaqualfs, and Epiaquepts) swelling and shrinking (Vertisols) and texturally differentiated tropical soils (Acrisols/Ultisols).

2.5. Mountainous region of Sierra Madre del Sur of texturally differentiated tropical soils (Acrisols, Alisols/Ultisols, and Kandic Great Groups of Alfisols), humus-accumulative carbonate-free soils (Phaeozems/Udolls, Umbrisols/Dystrudents), and poorly differentiated soils (Regosols, Cambisols/Ortents, Ustepts).

2.6. Mountainous region of the Central American Cordillera of texturally differentiated tropical soils (Acrisols, Alisols/Ultisols, and Kandic Great Groups of Alfisols) and shallow soils (Leptosols/Lithic groups of Entisols and Inceptisols).

3. Lithogenically driven regions.

3.1. Mountainous region of the Transmexican Volcanic Belt of volcanic ash soils (Andosols/Andisols), humus-accumulative carbonate-free soils (Phaeozems/Udolls), texturally differentiated (Luvisols/Alfisols), and swelling and shrinking soils (Vertisols).

3.2. Mountainous region Sierra Madre Oriental of humus-enriched shallow soils on limestone rock (Rendzic Leptosols and Phaeozems/Rendolls), texturally differentiated (Luvisols/Alfisols), and poorly differentiated soils (Cambisols/Ustepts and Udepts).

3.3. The region of Yucatan Peninsula of humus-enriched shallow soils on limestone rock (Rendzic Leptosols and Phaeozems/Rendolls).

3.4. Mountainous region of the Ridges of Chiapas and Guatemala of texturally differentiated soils (Acrisols, Luvisols/Ultisols and Alfisols) and shallow soils (Rendzic Leptosols and Phaeozems/Rendolls).

Evidently, the proposed regionalization is not perfect. First, the characteristic of the soils of each region, and especially the information about their spatial distribution is not complete yet, and thus it is difficult to say that we have an entirely clear understanding of the soils mosaic of the country. Second, the limits of the regions are imprecise, because the distribution of soils does not necessarily correspond to the limits of actual landscapes, and additional research is needed to specify the borders of the regions. However, for the first approximation these regions may serve as a basis for the characteristics of soil distribution in Mexico.

5.3 The Soils of Baja California Peninsula

5.3.1 Topography

The physiographic region of Baja California (INEGI 1995, 2001) is located in the northwestern part of Mexico. It is a long wisp of land of about 1,250 km, which stretches for more than 9° of latitude in the direction from N–NW to S–SE between the coordinates 32°32′04″ and 22°51′16″ N and 117°07′28″ and 109°54′14″ W (Fig. 5.2).

The spine of the Baja California Peninsula is formed by a system of blocks of 48–96 km wide, which reaches altitudes above 3,000 m in the northern part and gradually decreases to 500 m north of La Paz in the southern part of the peninsula (Raisz 1964). The region, due to complex topography, may be divided into the following subregions: Sierras de Baja California Norte (or Sierra de Juárez), the Viscaíno Desert, and Sierra de la Giganta. The first subregion has the highest elevations and the most abrupt escarpments. The topography is created by tectonics rather than by planation processes. The Viscaíno Desert is an extensive, slightly graded flatland composed mostly of eolian deposits. Finally, the Sierra de la Giganta is a mountainous system with developed debris cones and inclined flat plains in the toeslope of the mountains.

5.3.2 Geology

The geologic history of the Peninsula of Baja California is complex (López-Ramos 1982). The most ancient rocks detected were formed in upper Paleozoic epoch, mostly during the Carboniferous period. There are marbles, sandstones, and other metamorphosed sedimentsry rocks that occur mainly in the northeastern part of the peninsula. Other ancient rocks include plutonic rocks of the Triassic and Jurassic periods with various grades of metamorphism that are located at the very north of the region. Also these rocks are accompanied by metamorphic rocks of sedimentary origin. A little bit younger series of rocks formed mostly during the Jurassic and Cretaceous are of pyroclastic origin. The composition of these tuffs and breccias varies widely from basalts to dacites; they are commonly altered by hydrothermal processes, especially at the contacts with the plutonic rocks. The major event in the geologic history of the region is the intrusion of an enormous granitic batholite during the Cretaceous period that created the crest of the whole mountainous system of the peninsula. Most of this initial mountainous system was planated by erosional processes, which produced extensive terrigenous clastic rocks. The residual parts of that mountainous system can be found now as single small ranges mostly buried by alluvial and pediplains in the eastern part of the peninsula. In the Paleogene period, the territory suffered strong tectonic subduction movements (Frizzell 1984). The most tectonic activity occurred during the Miocene epoch, when the Pacific and the North American plates separated from one another. This catastrophic event, to a great extent is responsible for the topography of the western part of Mexico and resulted in the separation of Baja California from the main land and the formation of the Gulf of California (the Cortés Sea). The entire appearance of the region was created by this event. The tectonic movement crumpled the rocks forming high mountainous ranges along the peninsula. Tectonics are active and result in the slow horizontal drift of the peninsula from the continent to the west, and in a vertical uplift. Apart from the slow drift, earthquakes are common, as well as volcanic activity. There were two peaks during the intensity of volcanism in the region during the Cretaceous time. The first one started in the Miocene and produced andesitic, dacitic, and rhyolitic rocks; and the second one between the Pliocene and Quaternary produced mainly basalts and andesitic basalts. The Quaternary deposits are represented mostly by marine and alluvial sediments. The tectonic uplift results in the exhibition of littoral zone, extensive sandy plains of the Viscaíno Desert, and the Magdalena flatland, which emerged from the sea and were partly reworked by the wind. Alluvial sediments are restricted mainly to the closed valleys.

5.3.3 Hydrology

The Peninsula of Baja California is generally poor in water resources, since virtually all the streams are nonperennial. The main rivers serving as reservoirs of water are the Tijuana River, Carrizo Creek and Ensenada Creek in the north, and the creeks San Lazaro, Arroyo Grande and Cajoncito in the south. The rest of the peninsula depends on groundwater as the only source of supply for agricultural and urban areas. The water quality varies from fresh to salty due to high evaporation rates that cause increased salinity of the aquifers.

In many areas, the groundwater resources are being overexploited, resulting in seawater intrusion in some aquifers (Maya et al. 2011). Consequently, agricultural soils are affected by salinization due to the poor quality of irrigation water.

The peninsula has a well-defined watershed that divides all the basins to the Gulf of California and the Pacific Ocean. The catchments are bigger on the Pacific slope of the peninsula, except in the extreme southern part of the region, where the situation is reversed.

5.3.4 Climate

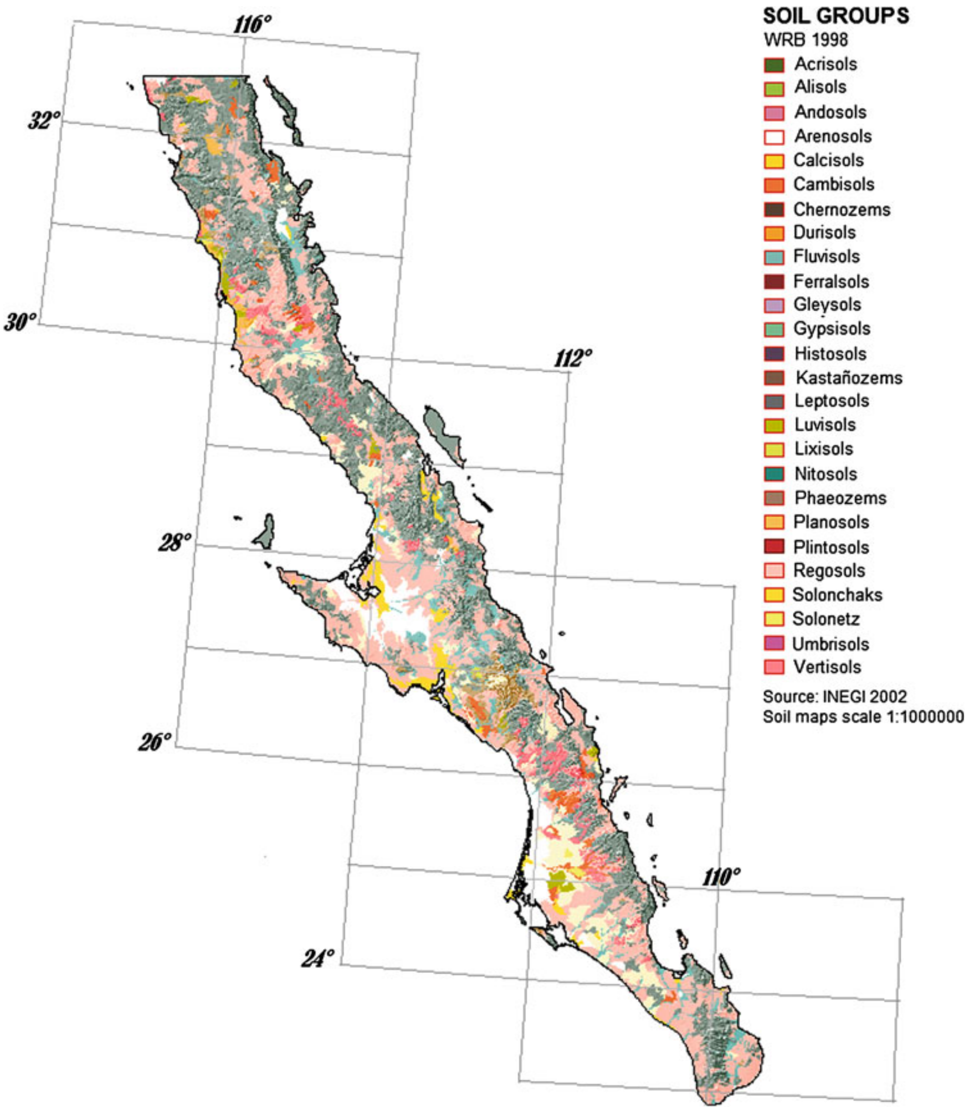
The region is located within the subtropical high atmospheric pressure zone with the exception of the extreme south that crosses the Tropic of Cancer. The common feature of the whole region is the aridity of the climate, but the variation in climate is great because of the latitudinal extension of the peninsula, climate variation with elevation, and different effect of water bodies on the eastern and western sides (of the Pacific Ocean and the Gulf of California). Thus, the climates vary both along and across the region. The driest areas are located in the very north of the region and in the Viscaíno Desert, where the annual amount of precipitation is less than 100 mm. The northwestern part of the region is the only part that has a Mediterranean climate.

The south has tropical and subtropical semihumid climates and an annual precipitation up to 700 mm.

The temperature depends both on the latitude and altitude. In the northern part, the mean annual temperature ranges about 17 °C at sea level, while in the tropical south—about 23 °C. At the elevations over 1,500 m above sea level, the temperatures are in the range 11–13 °C. The effect of the Pacific Ocean is important for understanding the climate of the region. The California Current carries cool water from the depths of the sea and thus creates low clouds and fog, forming a barrier and producing a temperature inversion, where the temperature abnormally increases with elevation. In contrast, the Gulf of California is a relatively shallow warm water body. Thus, the Gulf-oriented coast is warmer, especially in summer: the difference in the mean air temperature at sea level between the Pacific and the Gulf-oriented coasts may reach 6 °C (Garcia and Mosiño 1968).

5.3.5 Vegetation

The variety of climates is reflected in diversity of vegetation. According to Wiggins (1980), there are eight phytogeographic districts within the Peninsula of Baja California. The first includes the chaparral of California. It covers the Pacific coastal plain and the foothills of the Sierras Juárez and San Pedro Martir. This district is intermediate between a typical shrubland and xerophilous forest, with representative species such as chamise (*Adenostoma fasciculatum*), white stick (*Arctostaphylos oppositifolia*), spin (*Aesculus parryi*), and wild rose (*Rosa minutifolia*). The arboreal vegetation includes several oak species: *Quercus agrifolia, Q. dumosa,* and *Q. engelmannii*. The second district that includes conifer forest is located in the Sierras Juarez and San Pedro Martir. The forests are formed by xerophilous pine species, such as *pinus quadrifolia* that is common in Sierra Juarez and *P. jeffreyi* that predominate in the highlands of San Pedro Martir. Other trees found in this forest are *P. murrayana*, sweet pine (*P. lambertiana*), white fir (*Abies concolor*), and poplar (*Populus tremuloides*). The third district is microphyllous desert, located to the east of the Sierras Juarez and San Pedro Martir, below 1,000 m asl. The dominant shrub is creosote bush (*Larrea tridentata*), and other species include cacti *Opuntia cinerea,* ocotillo (*Fouqueria splendens*), donkey grass (*Ambrosia* spp.), ironwood (*Olneya tesota*), and white torote (*Bursera microphylla*). The fourth district of the Viscaíno Desert is characterized by the association Agave-Ambrosia. Also in this district there are extensive areas without any vegetation at the sea coast, where evaporates accumulate. The fifth sarcocaulous desert district is characterized by the presence of bushes with thick, fleshy stems, mainly *Bursera* and *Jatropha* association. Among the cacti one can see cholla (*Opuntia cholla*), cardon (*Pachycereus pringlei*), nopales (*Opuntia spp.*) and jasmine (*Ferocactus spp.*). The sixth district of the flatland of Magdalena includes a shrubland with a variety of life forms, from columnar cacti such as cardon (*P. pringlei*) and sweet pitaya (*Lemaireocereus thurberi*), to several species of torote (*Bursera*) and legumes such as mesquite (*Prosopis articulata*) and palo verde (*Cercidium floridum*). The seventh district, Sierra de la Giganta is characterized by the dominance of legumes and shrubs (*Lysiloma spp., Acacia spp., Cercidium microphyllum* and *Prosopis spp.*). Finally, the eighth arid-tropical district is located at the extreme south of the peninsula, where in the lowlands there are bush species with cardon (*P. pringlei*) and *Jatropha spp.*, while in the mountains there are tropical deciduous forest, and oak and oak-pine forest. The mangroves occupy minor areas along the coasts.



Source: INEGI 2002
Soil maps scale 1:1000000

Fig. 5.3 The soil map of the Baja California physiographic region. Reproduces with a permission of INEGI

5.3.6 Soils

The Peninsula of Baja California has rather variable soil-forming conditions with the potential for high soil diversity. First, there is a wide range of parent materials, including sedimentary, igneous, and metamorphic materials of various mineral compositions. Second, there are several important climatic gradients determined both by latitude and by the altitude and the presence of the cold California Current. However, the diversity of soils in the region is low (Maya et al. 2011) due to the aridity of the climate and erosional processes, largely driven by tectonic activity. However, there are differences in the soils of the region. For example, in the subregion Sierras de Baja California Norte at the highest elevations under the most humid climates of the peninsula, the pedogenesis is more advanced than in the arid central and southern parts. As evidence of better soil development is the abundance of Mollisols/Phaeozems that are absent in the southern part of the peninsula.

The soil map of the region (Fig. 5.3) shows that the majority of the area is represented by weakly developed soils.

According to the calculations of Maya et al. (2011) made on the basis of the INEGI soil maps,[1] the two most widespread soil groups in the region, occupying over 20 % of the area each, are sandy weakly developed soils (Arenosols/Psamments) and shallow soils (Leptosols/Lithic Great Groups) (Fig. 5.4c). Sandy soils are located mainly in the

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[1] The maps of the scale 1:250,000 were used for calculations. Although INEGI provided the synthesis of the geographical information, including the total areas occupied by different soil groups, the initial calculation was done on the basis of administrative units (states) that did not correspond with the limits of the physiographic units

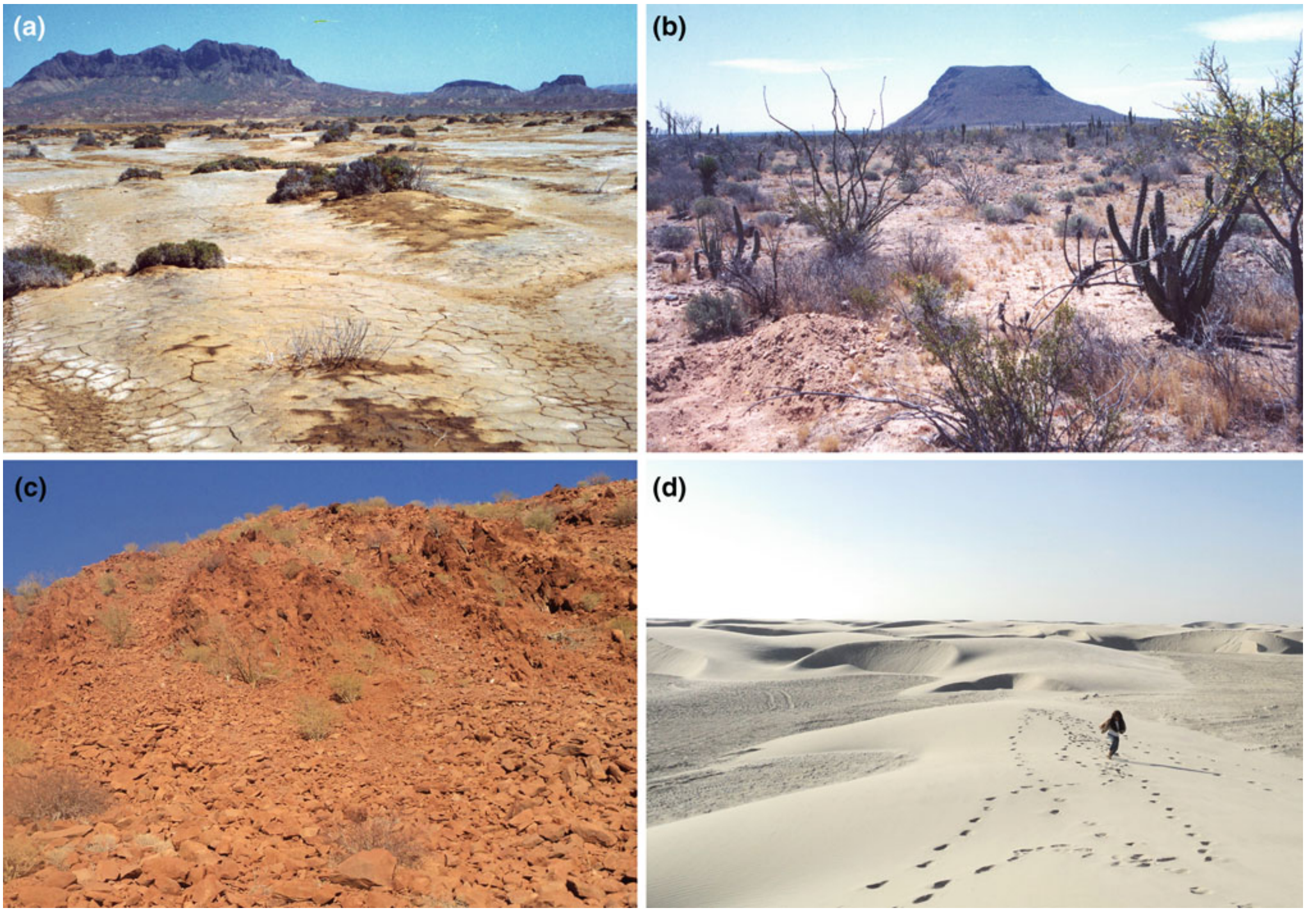


Fig. 5.4 Typical landscapes of the physiographic region Baja California: **a** Solonchak/Salid, Bahía Tortugas, Baja California Sur; **b** Landscape with Regosols/Orthents with surficial accumulation of stones (*yermic* horizon—desert pavement, Vizcano, Baja California Sur; **c** Landscape with shallow soils in Bahía de los Angeles in the north of Baja California; **d** Sandy dunes, Guerrero Negro, Baja California Sur (photos by C.O. Cruz-Gaistardo)

Vizcaino Desert and in the Magdalena flatland. Both of these areas are formed by broad plains that emerged from the sea floor. In the case of the Vizcaino Desert, sandy soils are basically formed by wind action (Fig. 5.4d). Shallow soils are widely represented in the mountain ranges that cross the entire peninsula.

These most abundant soils are followed by immature soils (Regosols/Orthents) and alluvial soils (Fluvisols/Fluvents). Immature soils are well represented in the foothills of mountain ranges, where the soils also receive materials constantly transported by the slope processes. Most of these soils are shallow and have high mineral skeleton content. The alluvial soils found in the region form both in fluvial and marine sediments. The marine sediments found along the entire coastal line of the peninsula have poorly developed soils. Inland alluvial soils consist of material transported from the upper reaches of the river and are found mainly in the channels of the main streams.

The next abundant soil group includes desert soils enriched with calcium carbonate (Calcisols/Calcids). These soils occupy about 11 % of the area of the region, and are found mainly in the foothills of the eastern part of Sierras de Baja California Norte, the western footslopes of the Sierra de la Giganta and the southern part of the Magdalena flatland. Soils with strong textural contrast (Planosols/Argids) occupy about 8 % of the area and occur in the north and in some small coastal plains and in a few intermountain valleys of the Sierras de Baja California Norte. Soils rich in humus (Phaeozems/Mollisols) cover slightly more than 7 % and are found in plain areas and on the mountain hillsides, mostly in the north of the peninsula. In the south they occur in the oasis, and under the pine-oak forests of the Sierra de la Laguna. Salt-affected soils (Solonchaks/Salids) are well represented in the plains of evaporation of the Vizcaino Desert. They are also found in other locations where seawater intrudes and represent a total area of more than 4 % of the region. Poorly developed soils (Cambisols/Cambids) are not very common; they cover slightly more than 2 % of the total area of the region. They are mainly associated with other soils. Shrinking and swelling soils (Vertisols), water-saturated soils (Gleysols/Aquents), and soils with gypsum accumulation (Gypsisols/Gypsids) hardly occupy 1 % of the region area together. Vertisols are distributed chiefly in the valleys of the Sierra de la Giganta. Flooded soils are found mainly in the coastal areas, including mangroves. The soils with gypsum are located on the island San Marcos and are important commercial deposits of gypsum.

5.3.7 Soil Use, Degradation and Management

The entire zone to the southeast of Tijuana and east-southeast of Ensenada is one of the most important wine regions of the country. The Mediterranean climate, the presence of irrigation water and soil properties provide excellent conditions for grape and olive tree cultivation.

In the southern part of the peninsula, the most important agricultural region is the Valle de Santo Domingo. It is an area of irrigated agriculture of about 130.760 ha, situated in the scrub desert, which was opened for production in the 1940s in an attempt to boost the economy of the region (Maya et al. 2011). The main crops were cotton and wheat, and the zone was flourishing for several decades until several irrigation wells were exhausted. Currently, the land is used mainly to grow alfalfa, oranges, beans, peas, and corn. The abandonment of the land in this region has led to wind erosion problems and even the formation of active dunes. In general, deflation is the most active soil degradation process in the region. The wind promotes the constant removal and deposition of sediments, resulting in little soil development due to instability and poor establishment of vegetation. This process is particularly significant in the Vizcaino Desert and the region bordering the Pacific Ocean on the Plains of Magdalena.

The other important agricultural region is the Vizcaíno Valley. It was opened for production at the same time as the Valle de Santo Domingo. It is much smaller (about 8.660 ha), and soils are sandy and have natural limitations of high salts and sodium saturation, which are characteristic for the soils in this region. The main crops in this valley are wheat, cotton, corn, beans, grapes, dates and alfalfa using drop irrigation systems.

5.4 Sonorian Lowlands

5.4.1 Topography

This region is shared between Mexico and the State of Arizona (USA); in the northwestern part it borders the Peninsula of Baja California, in the east with Sierra Madre Occidental and in the south with the Pacific Coastal Plain. This physiographic unit consists of two main parts. The first is the Colorado delta, and the second is the San Felipe desert. The Colorado delta is a flat fluvial plain formed by fine sediments of this river. Much of the desert consists of low parallel hills consisting of fault blocks, oriented roughly from NNW to SSE, separated from each other by broad valleys (Solís-Portillo and Venegas 2011). The breadth of these valleys filled with alluvial and eolian deposits increases to the west toward the Gulf of California.

5.4.2 Geology

The geological structure of the region is variable; there are rocks and sediments of different ages from Precambrian epochs to recent alluvial sediments. The dominant rocks are those formed before the Cenozoic epoch. In the east, these are covered with later volcanic sediments. The Precambrian rocks are represented by the most ancient geological formation in Mexico (approximately 1,700–1,800 Ma), called the Bamori formation that includes mainly metamorphic rocks such as gneiss, amphibolites and schists. These rocks are located near Caborca in the Sonora State. Also there are sedimentary Precambrian and Paleozoic rocks in the same area represented by limestones, dolomites, and sandstones, which partly superpose the metamorphic formation. The Mesozoic epoch left various rocks mainly of sedimentary origin, both of marine and continental genesis, such as limestones with coal layers and clastic sediments. The accumulation of continental clastic rocks was provoked by the fall of a big tectonic block (Gastil et al. 1975), where later several kilometers of sediments accumulated due to intensive erosional processes during the Mesozoic epoch. Also in the Sonorian Desert there are volcanic andesitic rocks and intrusions of granites and diorites. In the Cenozoic epoch, the most important geological event was the activation of the San Andrés fall, the separation of the Baja California peninsula in the Miocene, and the increase in volcanic activity. This epoch produced many volcanic and pyroclastic rocks mostly of an acid composition. The surficial sediments in the lowlands are mainly recent Quaternary alluvial and eolian deposits.

5.4.3 Hydrology

The water flow of major importance for the region, though not the most affluent one, is the Colorado River that comes from the north. Its head waters are located in Wyoming, USA, and only its delta is situated in Mexico. Its total annual water flow is 103.31 millions of m^3, but only 2.5 Mm^3 are available for the use in Mexico (Solís-Portillo and Venegas 2011). Most of this water is used for irrigation purposes. The water quality is poor, because the river is strongly contaminated with fertilizers and salts before it enters Mexico. The river transports a huge amount of solid particles that contribute to the gradual growth of the delta and to a continuous accumulation of sediments on the irrigated soils.

The other important rivers include the San Ignacio, Concepción, and Bamori. The River San Ignacio starts at the ridge El Tordillo at an altitude of 1,120 m and falls into the Gulf of California. It transports 41.54 Mm^3 of water annually. The river Concepción starts at the ridge Las Veredas at an elevation of 2,000 m; it has a complex watercourse and even has different names at different parts of its flow. It transports annually 132.76 Mm^3 of water. The basin of the river Bamori is considered to be the driest catchment in the country, because it includes the Altar desert. However, due to the extension of the basin, the annual water transport is 52.96 Mm^3. The main water use is for irrigation, followed by household and livestock use.

5.4.4 Climate

The region, together with Baja California, has the most arid climate in Mexico. In the system of Köppen modified by Enriqueta García (1973) they are all characterized as “very dry”, that means that the total annual precipitation is less than 400 mm all over the region with the mean annual temperatures ranging from 18 to 26 °C. The region is located outside the tropics, and thus the difference between the winter and summer temperatures is wide, over 14 °C. Very hot climate with a summer maximum of precipitation describes the coastal southern part of the region. The mean temperatures of the hottest month (July) range between 31 and 35 °C. Near the city of San Luis Río Colorado, the climate is similar but the maximum of precipitation corresponds to the winter period. The largest portion of the region has a slightly cooler climate with a maximum precipitation in summer. The mean annual temperature varies between 19 and 21.5 °C, and the precipitation roughly falls in the range between 50 and 300 mm.

5.4.5 Vegetation

Dry climate determines the desert character of the vegetation. The major part of the natural vegetation of the region is represented by xerophilous matorral vegetation with various life forms like succulents, shrubs, ephemera, etc. The most abundant species throughout the region are ironwood (*O. tesota*), creosote bush (*Larrea tridentata*), and hump (*Simmondsia chinensis*), and the representatives of the genera *Ambrosia*, *Fouquieria*, and *Cercidium* (Solís-Portillo and Venegas 2011). The most abundant vegetative community is so-called microphylous shrubland. These plants grow mainly in the dry streams and in stony habitats. The other common species for the region are ocotillo (*Fouqueria splendens*), several cacti species of the genus *Opuntia*, and *Ferocactus acanthodes*. The latter prefers low hills, and shallow, very stony soils. On the floodplain, mostly those of Colorado River, there are southern cattail (*Typha domengensis*), reed (*Phragmites australis*), various willows (*Salix* spp.), arrow-weed (*Pluchea sericea*), and Palmer’s grass (*Distichlis palmerii*).

5.4.6 Soils

The most typical soils for the region are Calcisols/Calcids (Figs. 5.5; 5.6a); these soils may be regarded as “zonal soils” for the entire region (e.g., Krasilnikov 2011). These soils form in arid climates if calcium carbonate can readily form due to soil water infiltration and evaporation. These soils lack humus-enriched topsoil because of the low biological productivity of arid regions and poor potential for microbial transformation of organic matter. See Chap. 4 for the detail on the genesis of these soils.

However, the distribution of calcium-carbonate-enriched soils is not very extensive because of the high proportion of young alluvial and eolian sediments, heavy clays, and the development of salinization, i.e., the factors that determine the development of intrazonal and azonal soils. The young alluvial sediments are very common in the Colorado River delta. These sediments are layered and the vertical distribution of clay and organic carbon is irregular in these soils. The pedogenetic processes do not exhibit themselves due to the young and dynamic sedimentation. These soils are classified as Fluvisols/Fluvents. Some of the soils that are subject to prolonged irrigation with muddy waters have a topsoil horizon of sediment accumulation; in the WRB system these soils are Irragric Anthrosols, and in the USA taxonomy they are likely in the Fluvents Suborder. Sandy soils occur in the dune fields, which occupy extensive areas along the coast in the Sonorian Desert and at the wings of the Colorado River delta. The entire delta of the Colorado River that belongs to the Mexicali municipality is strongly affected by salinization. Arid conditions cause intensive evaporation that result in the uplift of soluble salts with capillary water. The process is promoted by high anthropogenic mineralization of the irrigation water that comes from the strongly fertilized fields of the USA. The soils with high soluble salts content are classified as Solonchaks in the WRB system. In the US Soil Taxonomy, these soils are partly included in the Suborder of Salids. If groundwater is close to the surface and is the main source of salts, the soil should be classified as Halaquepts. These saline soils with the water table close to the surface are common in the

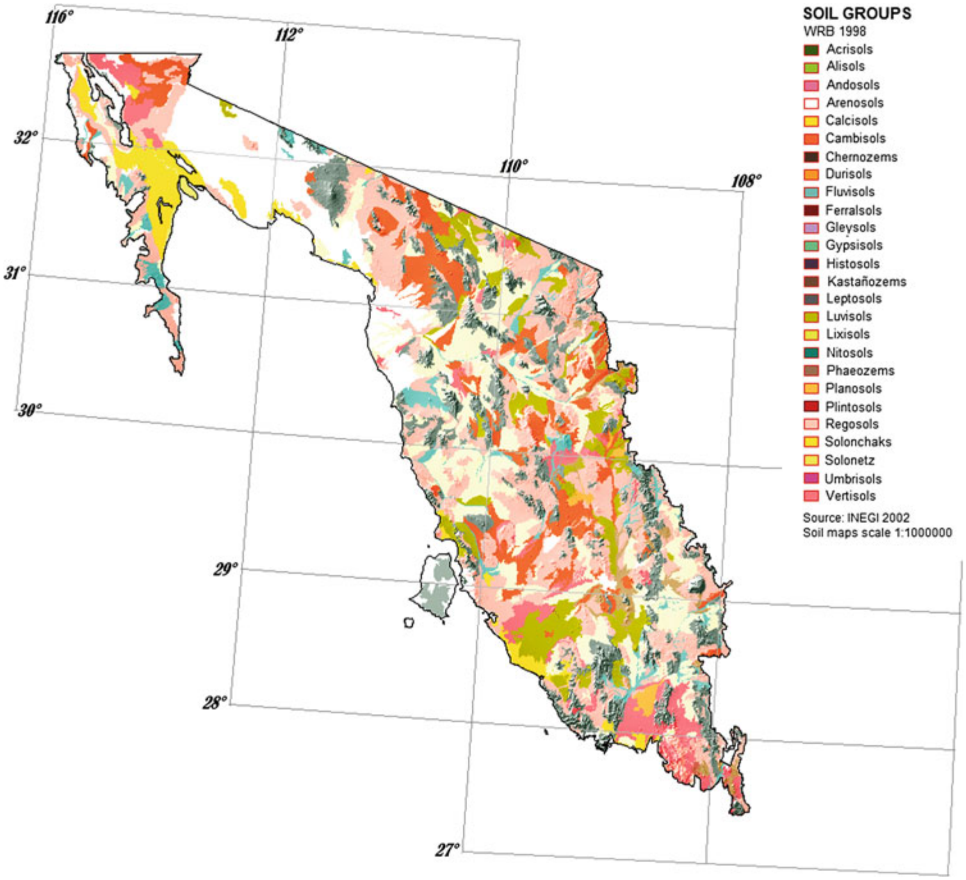


Fig. 5.5 The soil map of the Sonorian Lowlands physiographic region. Reproduced with a permission of INEGI

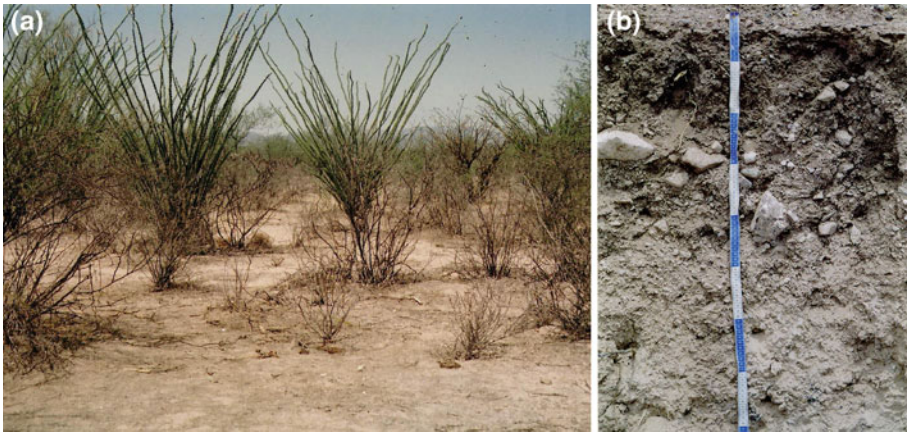


Fig. 5.6 Typical landscape and soils of the physiographic region Sonorian Lowlands: **a** landscape on Calcisols/Calcids in Batobabi, Sonora; **b** Calcaric Epileptic Phaeozem (Episkeletic)/Lithic Calciustoll of clay texture, with desert pavement, La Matanza, Sonora (photos contributed by Jose María Solís-Portillo)

region with the most evident example in the famous Laguna Salada.

The soils formed in the smectitic clays commonly show the evidence of swelling and shrinking. The majority of clayey sediments in the region are of marine origin, and the majority of that has a significant proportion of smectite. These soils are classified as Vertisols, and their distribution is related to marine sediments, including certain parts of the delta of Colorado River.

In the small mountainous portion of the region called Sierra del Pinacate, there are shallow and very stony soils (Leptosols/Lithic Groups of various Orders). This territory is a naturally protected area. In places, desert soils in deep loose sediments have no significant concentrations of calcium carbonates or soluble salts, and are classified as Regosols and Cambisols/Orthents or Cambids. These soils are common in the vicinity of Hermosillo. In the same area, soils are with a subsurface horizon enriched with clay: Luvisols/Argids. These soils are believed to have formed in more humid epochs or due to other mechanisms than clay illuviation. The same Hermosillo area is one of the most humid places within the region and has more developed soils than areas with humus-enriched horizons, especially if these soils form in creeks and valleys. These soils are classified as Phaeozems/Xerolls (Fig. 5.6b).

5.4.7 Soil Use, Degradation, and Management

Although the climatic conditions hardly favor the development of agriculture, the region of Sonorian Lowlands is one of the important agricultural areas in the country, partly because of the technology transfer from the USA. Crop production is mostly dependant on irrigation. The main nodes of agricultural production are the delta of the Colorado River and in the vicinity of Hermosillo—Miguel Alemán. In the delta of the Colorado River agricultural production is concentrated on wheat, cotton, and alfalfa production. Practically, all the water of the Colorado River is used for irrigation, thus strongly affecting wetland ecosystems once existent in the delta (Luecke et al. 1999). The main degradation process in the area is intensive salt accumulation that is almost inevitable due to the irrigation by strongly mineralized water. The other node is located near Hermosillo that also uses irrigation. The main crops grown in the county are wheat, safflower, chickpeas, corn, and other grains. Also, the main perennial crops are grapes, citrus, alfalfa and walnuts, plus vegetables. The current trend in this activity is geared toward the replacement of traditional crops by those linked to foreign markets and offering higher returns, such as vines and vegetables. The livestock is also important for the region, with a definite preference to cattle and hogs. Some extreme habitats, like sandy soils, are used as pastures for goats.

5.5 Lowlands and Uplands of the North

5.5.1 Topography

The region of the Lowlands and Uplands of the North is a relatively flattened area wedged between two great mountainous systems of the Sierra Made Occidental and Sierra Madre Oriental. This region is divided between three states, Chihuahua, Coahuila, and Durango, and also extends deep into the territory of the USA (INEGI 2003). In topography, it is similar to the Central Mesa (Tableland) that is located to the south. This province is characterized by the predominance of plains covered by thick layers of alluvial materials, as well as the existence of isolated hills formed by sedimentary rocks of marine origin and outcrops of igneous rocks. The mountains here are low and steep, oriented roughly from NNW to SSE. The large plains filled with alluvial sediments that separate mountain ridges have traditionally been called "bolsons" (pockets). In the northern part of the region, in the vicinity of Ciudad Juarez, there is one of the largest dune fields in the country. In the southern part of the region, there is a big subregion called Laguna de Mayran (or Bolson de Coahuila), a huge dried lake.

5.5.2 Geology

The territory of the region consists mostly of rocks of sedimentary origin, both marine and continental ranging in age from Paleozoic to Quaternary (INEGI 2003). The Paleozoic metamorphic rocks are exposed in small areas scattered throughout several areas in the region. The most typical rocks are the Mesozoic limestones. These rocks have been affected by intense folding (anticlines and synclines) and tectonic faults, as well as by intrusions related to them. The orientation of the folds is east–west in the southern portion of the region, and northwest–southeast in the northern portion, and the mountains are also oriented preferentially in these directions. The Cretaceous sediments include mainly continental deposits such as conglomerates, sandstones, and lutites. There are also intrusive bodies and lava flows in the portions corresponding to the steep volcanic mountains in the center and north of the region. The ages of these rocks range from Triassic to Quaternary. The intrusive bodies are commonly exposed to the surface due to weathering and erosion of the inclosed ancient sedimentary rocks. Alluvial deposits are the most recent ones and consist of the debris of all the rock present in the region.

5.5.3 Hydrology

The major portion of this region is part of the Conchos River Basin, a tributary of the Rio Grande. The other part includes common endorheic basins or hollows, some of them with salt accumulations, and some with temporary lakes. In the central part of the region there is a big Mapimí Bolson. In the southern part of this region lies the Laguna de Mayran, or Bolson de Coahuila and then more to the south lies the ancient lake region of the Viesca bolsons.

5.5.4 Climate

The climate of the province is characterized as arid and semiarid (INEGI 2003). The annual amount of precipitation varies from 125 to 400 mm with an expressed summer maximum. The latitudinal zonality results in the differences in the mean annual temperatures between the northernmost portion of the region and its southern part. In the north, the mean temperatures are in the range 12–18 °C, while in the south (Laguna de Mayran) it is 20–22 °C. The region is closed by the mountains from the effect of the sea; in winter cold air comes from the northern part of the continent, thus the climate shows certain continental features. The difference between the summer and winter temperatures is very high; in the southern part of the region (in Torreón) the mean temperature of the coolest month is 0 °C, and of the hottest month 40 °C.

The winds are rather common in this region, provoking dust storms, which limit the visibility to a few kilometers. The winds mostly have a southern direction, and their velocity varies from 20 to 44 km/h. This phenomena leads, on the one hand, to strong deflation of the soils and salt transport, and, on the other hand, to the accumulation of eolian deposits such as dune fields.

5.5.5 Vegetation

The natural vegetation is represented by desert microphyllous matorral with such dominant species as creosote bush (*Larrea tridentata*), mesquite (*Prosopis spp.*), yuccas (*Yucca spp.*) with some ocotillos (*Fouquieria spp.*) at the outcrops of limestone rocks. In the coarse alluvial sediments, one can find in some areas an almost undisturbed desert rosetephylous matorral with agaves and cacti (*Agave lechuguilla* and *Opuntia spp.*). In the areas with saline soils the matorral vegetation is mixed with halophytic communities, and the dominant species is saltbush (*Atriplex* spp.), bush seepweed (*Suaeda nigra*), and Iodine bush (*Allenrolfea* spp.).

5.5.6 Soils

The soils of this region are mainly affected by the processes of calcium carbonate accumulation and salinization. The endorheic catchments serve as geochemical traps for the salts, and thus in arid climates almost all the soils of the valleys (bolsons) have accumulations of calcium carbonate

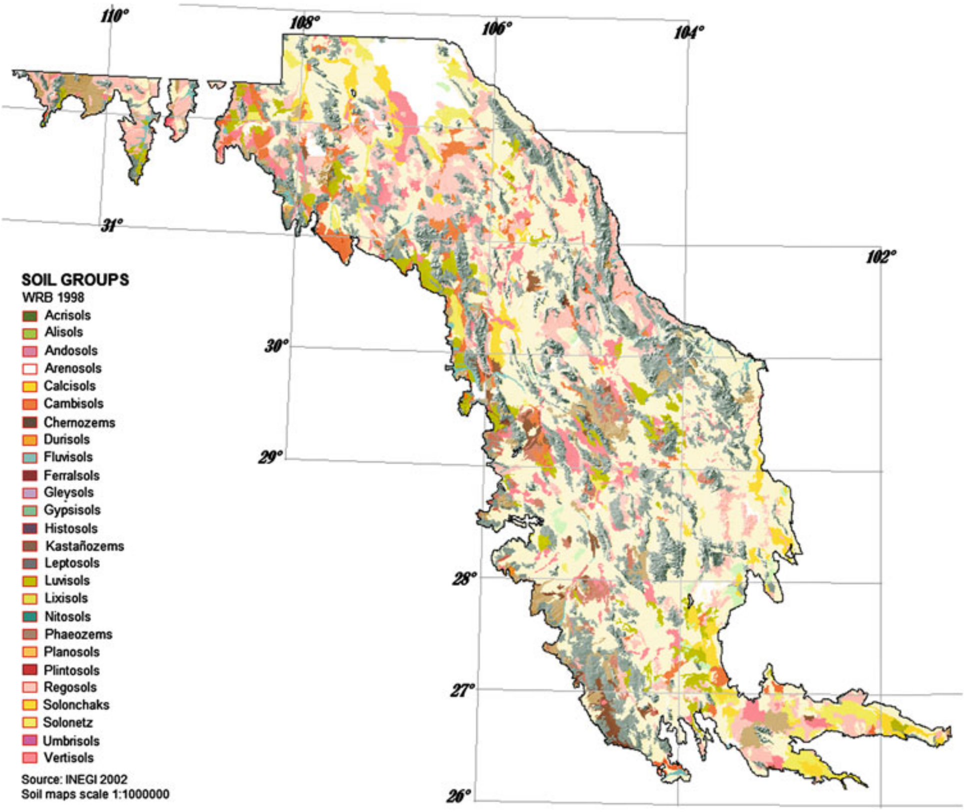


Fig. 5.7 The soil map of the physiographic region of the Lowlands and Uplands of the North. Reproduced with a permission of INEGI

commonly together with soluble salts. Thus, the main soil groups found are soils with carbonates and salts: Calcisols/Calcids and Solonchaks/Salids (Figs. 5.7; 5.8b, d).

All the soils of bolsons form in lacustrine and alluvial sediments, and thus have certain evidences of layering. In the absence of significant amounts of carbonates, salts, or gypsum they are classified as Fluvisols/Fluvents (Fig. 5.8c). In some of the soils of the valleys, the presence of a clay-enriched subsurface horizon has been reported, and these soils are classified as Luvisols/Argids. However, the presence of a heavy-textured subsurface horizon may hardly be attributed to the processes of clay illuviation, present or past. Most probably, the initial difference in the texture of the sediments or selective weathering at the depth of groundwater availability contributed to the formation of these soils.

The soils of the slopes of the hills and mountains are poorly developed. The mountains composed of igneous rocks commonly have very shallow and stony soils that are classified as Leptosols/Lithic groups of Entisols (Fig. 5.8a). The mountains and ridges formed by sedimentary rocks are less resistant to weathering, and deeper soils can occur on their slopes such as Cambisols and Regosols/Cambids and Orthents. The extensive dune fields have undeveloped sandy soils like Protic Arenosols/Psamments.

5.5.7 Soil Use, Degradation, and Management

The agricultural development in this dry region is possible only using irrigation. In such agricultural centers as Ciudad Juárez, the water for irrigation comes from the Rio Grande, and in the inland centers such as Torreón from groundwater resources. The agriculture of the region was previously focused on cotton production. However, the production of cotton has decreased, especially in the endorheic bolsons. The main reason was the scarcity of water and progressing salinization of the soils. In the area of the Laguna de Mayran, the groundwater level decreased 30–120 m during the last 50 years due to overexploitation of water.

Agriculture now centers around cattle breeding, principally dairy races of cows like Holstein. Vast areas are occupied by alfalfa plantations. The other important crops for the region are wheat, sorghum, fodder corn, and mellow.

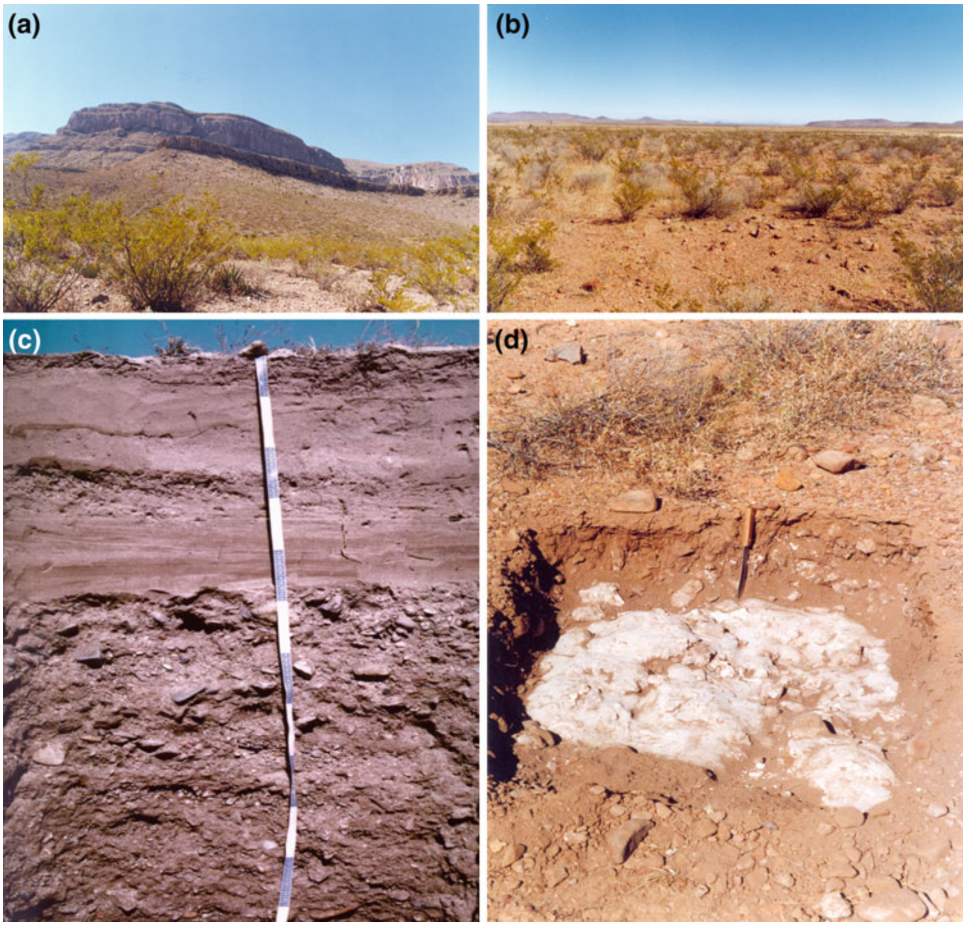


Fig. 5.8 Typical landscapes and soils of the physiographic region Lowlands and Uplands of the North: **a** Landscape with shallow soils, Sierra La Amargosa, Chihuahua; **b** Landscape with Calcisols/Calcids, Cerros blancos, Chihuahua; **c** Fluvisol/Fluvent in Arroyo Chuviscar, El Chamizal, Chihuahua; **d** Calcisol/Calcid with desert pavement, Cerros blancos, Chihuahua (photos contributed by Jesús Esparza)

Apart from salinization, the important soil degradation process is wind erosion that is active all over the region. The wind action has a negative effect not only because it removes the fertile topsoil, but also because it distributes the salts formed at the surface of numerous dry salted lakes.

5.6 Great Plains of Northern America

5.6.1 Topography

This continental-scale physiographic region extends north to south from the Alberta and Saskatchewan provinces (Canadian) to Coahuila, Nuevo Leon, and Tamaulipas states in Northern Mexico. In Mexico, the limits of the region correspond to 29°53′–24°30′ N and 98°10′–102°35′ W. In its western edge, altitudes reach 500–850 m and 100–400 m in the east, showing a clear inclination from west to east. The most prominent feature of this province is the presence of very flat, wide plains covered with prairie vegetation. In Mexico, however, the relief of the region is complicated by the presence of the outcrops of Mesozoic limestone rocks that form anticline strips oriented from NW to SE direction.

5.6.2 Geology

Geologically, the region of the Great Plains can be divided into two parts. The western part is composed of Mesozoic limestone rock later folded by the Cretaceous tectonic activity; it is the same formation that composes the Sierra Madre Occidental mountains, but the grade of folding is much lower (López-Ramos 1982). The tops of these limestone anticlines are very common in the western part of the region. Partly, they are covered with Paleogene and Neogene marine sediments. The terrigenous Quaternary sediments fill the valleys between these ridges, and the depth of these sediment can be considerable (Valadez-Araiza 2011). Volcanic activity developed in the late Neogene and the beginning of the Quaternary period and produced some olivine basalts, especially in the region Múzquiz—Nueva Rosita.

The eastern part of the region belongs to the Paleogene geosinclinal of the Gulf of Mexico. This part consists of thick packages of lutites and sandstones formed during the Paleocene and Oligocene epochs. Quaternary alluvial deposits are widespread all over the region, forming a cover of varying thickness over the older geological formations.

5.6.3 Hydrology

The hydrology of the region of the Great Plains of North America is complex due to the flow of the rivers. The main stream that determines the water supply of the whole area is the Río Grande and its numerous tributaries. There are seven catchments around this major river, each one corresponding to the important tributaries such as the San Juan, Sosa, Álamo, Río Salado, San Rodrigo, and El Escondido, or to big water collectors. The southern part of the region belongs to the other big basin that corresponds to the major tributary of the Rio Grande, the Conchos River.

Surface water quality is satisfactory in the region; most of the streams have medium mineralization, low sodium content, and a slightly acid reaction. The quality of the groundwater varies depending on the geology and has a wide range of mineralization, sodium content, and acidity. Most of the wells have high amounts of clay particles in the water.

5.6.4 Climate

The climate of the region in general may be characterized as subarid to subhumid. The southern part of the region has the most humid climate with annual precipitation between 600 and 800 mm, and the mean temperature ranges between 20 and 23 °C. In the northern part, the climate is much dryer and the annual precipitation does not exceed 300 mm with a temperature around 20 °C. The difference between the winter and summer temperatures is significant, and the period of frosts varies from 20 days per year in the north to 0 days in the south (Instituto Nacional para el Federalismo y el Desarrollo Municipal 2005). The proximity of the sea and humid winds in the summer result in the major part of the annual precipitation all over the region. In winter, the cold masses of polar air called "nortes" cause an increase in the humidity and rainfalls in the portion of the region that corresponds to the central and northern parts of the Tamaulipas State.

5.6.5 Vegetation

The region belongs to the Xerophytic Mexican floristic district within the Neotropical kingdom. Morphologically, the vegetative communities formed under arid and subarid climates are very diverse, and they are all given a joint common name of xerophyllous shrub vegetation, or matorral (Rzedowski 1983).

Within the region, the dominant plant community is thorn shrub, with the medium height of the trees between

2 and 3 m, and the dominant plant are hackberries (*Celtis* spp.), nopal (*Opunti*a spp.), acacia (*Acacia* spp.), palo verde (*Cercidium* spp.), cenizo (*Leucophyllun* spp.), palo santo (*Porlieria* spp.), castela (*Castela* spp.), manjack (*Cordia* spp.) with frequent mezquite trees (*Prosopis* sp.).

The other common vegetative community is the grassland, both natural and cultivated, with grama (*Bouteloua* spp.). These grasslands are used as pastures.

The next abundant community is the microphyllous shrubland with such plants as creosote bush, algarobilla, tarworts (*Flourensia* sp.), ocotillo, cenizo, and nopal. This community is tolerant to water deficits and soil salinity. On the limestone rocks, the typical community is rosetophyllous shrubland with such plants as agave, spurge, yukka, hechtia, and desert spoon. In the areas strongly affected by salinity the vegetation is represented by halophyllous communities with such plants as dropseed grasses, seepweeds, and saltbush.

Mezquite trees form stands at the alluvial terraces with deep calcareous soils. Furthermore, there are small patches of oak stands in the extreme north of the region and some gallery forests along the more or less permanent river flows.

5.6.6 Soils

The most abundant soils in the region are deep with strong calcium carbonate accumulations (Fig. 5.9). These soils (Calcisols/Calcids or Eutrustepts) occupy around 40 % of the total area of the region (Valadez-Araiza 2011). The extension of these soils in the region might seem strange, because the climatic conditions and the vegetative communities favor more intensive organic matter accumulation. A possible explanation is that some of these soils were classified erroneously, because the color of the topsoil horizon could be masked by calcium carbonate. The

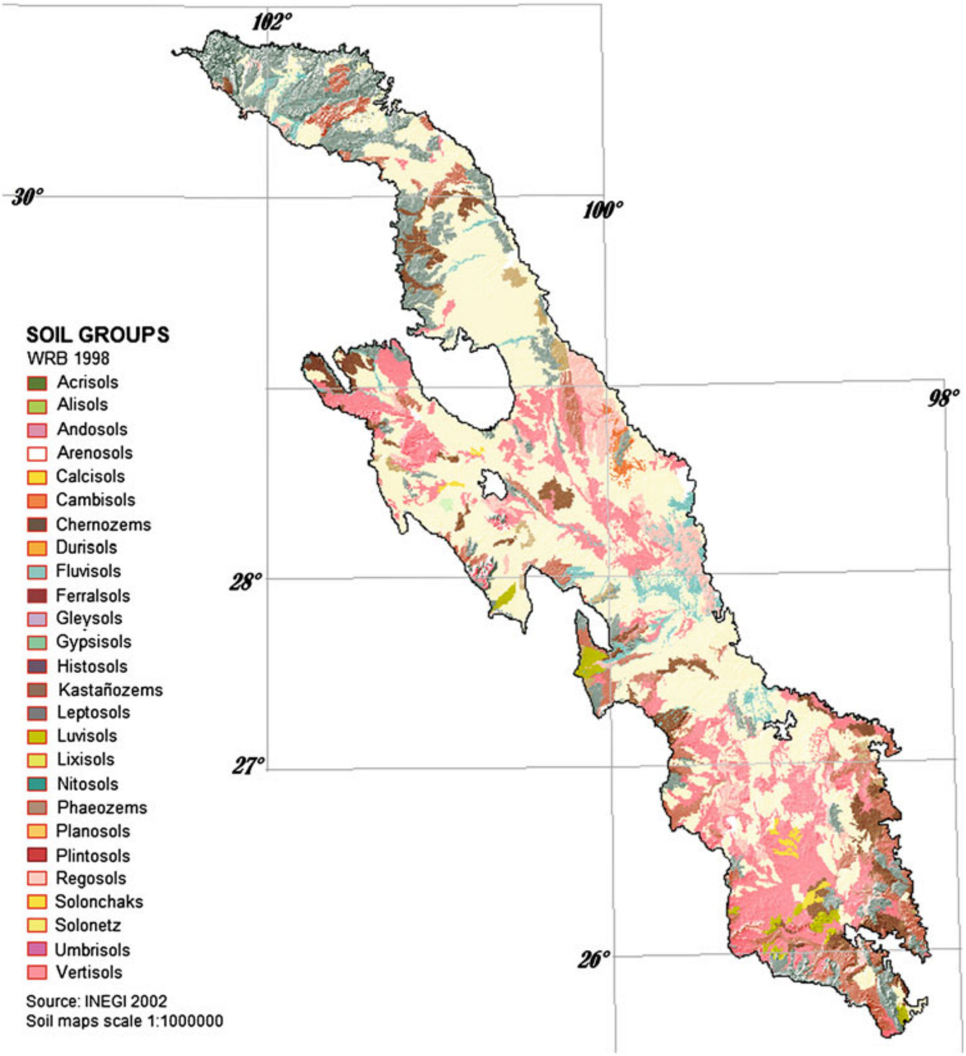


Fig. 5.9 The soil map of the physiographic region of the Great Plains of North America. Reproduced with a permission of INEGI

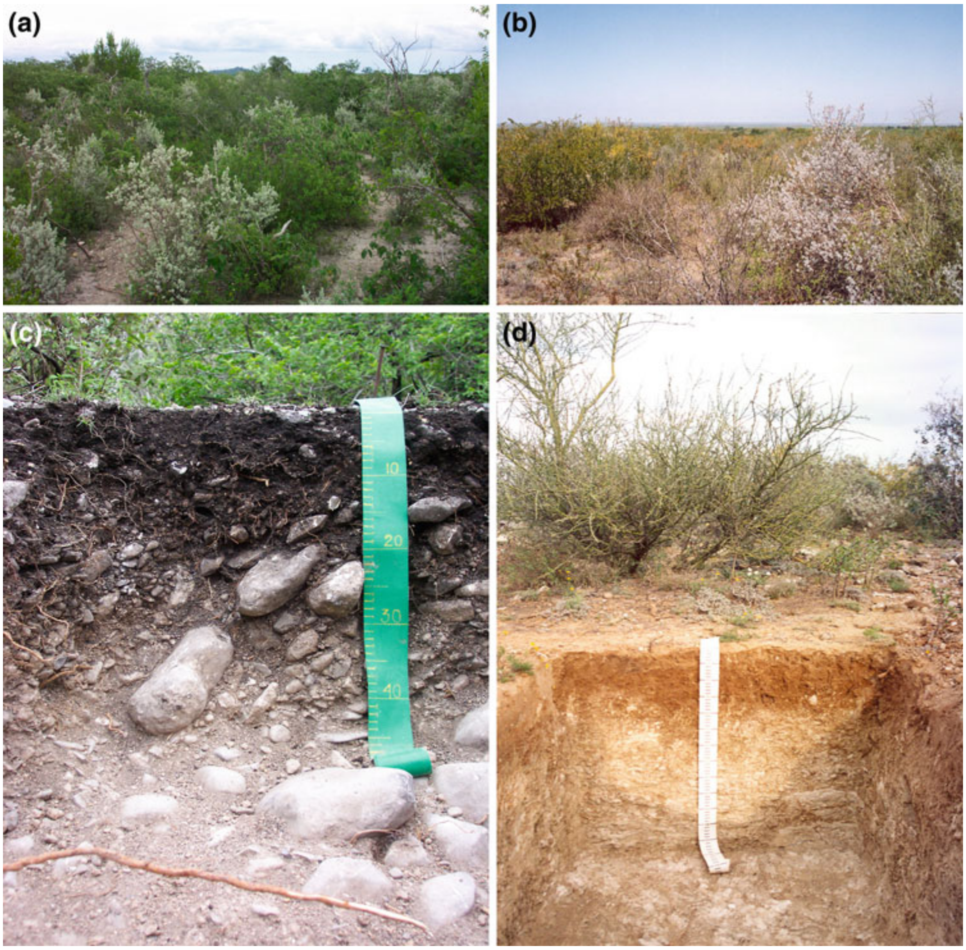


Fig. 5.10 Typical landscapes and soils of the physiographic region Great Plains of North America: **a** Mesa San Isidro, Tamaulipas; **b** La Lajilla, Nuevo León; **c** strongly stony Kastanozem/Ustoll, La Reforma, Tamaulipas; **d** Kastanozem/Ustoll, Presa Loma Larga, Nuevo León (photos contributed by Carlos Alberto Saracco-Alvarez)

classification manuals (Soil Survey Staff 1999; IUSS Working Group WRB 2006) recommend omitting the color criteria for soils rich in calcium carbonate, but the first soil surveyors in the region could make a mistake due to the lack of experience (Cruz-Gaistardo et al. 2006).

The next abundant soil group that occupies about 18 % of the area of the region is Vertisols. These soils are distributed more or less equally in the region, and correspond to the valleys where clayey sediments accumulate. The majority of such soils are found in the ancient marine sediments. The next abundant group includes shallow soils, which are classified as Leptosols/Rendolls and Lithic groups of Entisols. The majority of these soils form on the tops and slopes of limestone ridges. Approximately, the same area is occupied by the soils that exhibit both organic matter and calcium carbonate accumulation: Kastanozems and Chernozems/Ustolls (Fig. 5.10). These soils occur predominately in the southern and southeastern parts of the region. The associated soils that cover much less areas include alluvial soils, saline soils, and some other soils of minor importance.

5.6.7 Soil Use, Degradation, and Management

The main problem for the development of agriculture is the water deficiency; thus, approximately one half of the cultivated fields require irrigation. The rivers that penetrate the region serve as the main sources of water for irrigation. The main crops include corn, sorghum, sunflower, oats, wheat, walnuts, and soybeans. The major part of the rainfed agriculture production is concentrated in the southern part of the region that receives much more precipitation than the rest of the region thanks to its proximity to the sea.

Extensive territories in the region are used for pastures, mainly for cattle and goats. The use of the pastures is intense, and the majority of these are cultivated and fertilized.

Many of the soils (22 %) of the region are shallow or stony, which limits their productivity (Valadez-Araiza 2011). The main soil degradation processes associated with the region are excessive fertilization, physical degradation of the plow layer of the soils due to the use of heavy machinery, and soil salinization. We should note that the intensity and extension of these degradation processes are not very significant in the region.

5.7 Central Mesa

5.7.1 Topography

The Central Mesa, or Tableland is located in the very center of Mexico and includes portions of the states of Zacatecas, San Luis Potosi, Guanajuato, and Durango but also includes small patches of the states of Jalisco, Aguascalientes, and Queretaro.

In the north, this region borders with the region of the uplands and Lowlands of the North at river Nazas. In the south, it borders the Transmexican Volcanic Belt.

The term "tableland" is partially correct, because approximately a half of the province area is nearly flat plains and gentle slopes. However, there are significant disruptions throughout the province such as the steep high mountains located in Guanajuato.

The minimum elevation above sea level in this province is 1,180 m and is located on the Francisco Zarco Dam that receives flow from the Rio Nazas in Durango state. The highest point is Cerro El Zamorano with an altitude of 3,200 m asl located near Columbus, Querétaro. The topography of the Central Mexican Tableland is diverse. It includes arid alluvial flat lands, hills, basaltic table mountains, table mountains with erosional dissection, mountains of various altitudes, plain or eroded slopes, gulleys, and canyons.

5.7.2 Geology

The geological materials are highly variable at the Central Mesa, where limestones, sandstones, conglomerates, alluvial deposits, outcrops of basalts, rhyolites, and sequences of sandstones and lutites occur. The geological history of this region is somewhat similar to the region of the Lowlands and Uplands of the North except it was much less deformed by the tectonic action. The base of the region is composed of Cretaceous limestones and conglomerates. In places, these rocks are exposed to the surface, especially in the northern part of the region, but in the major part of the area they are covered with a thick sheath of Cenosoic sedimentary and volcanic rocks. In the north, the main Palegene rocks are basalt, acidic tuffs, and rhyolites. In the southern part of the region, there is a clear sequence of rhyolites, tuffs in the upper parts to sandstone–conglomerate in the lower parts. The Quaternary sediments are represented mainly by the alluvial deposits that cover approximately one half of the area of the region.

5.7.3 Hydrology

The Central Mesa covers several hydrologic basins. In order of area covered they are streams, lakes, and closed basins of El Salado, the arid and closed-system Nazas-Aguanaval, the Lerma River—Rio Grande de Santiago, the Panuco River that flows to the Gulf of Mexico, and the Presidio-San Pedro basin. The region is dissected with many superficial water fluxes, some of them permanent and others—temporary. The water quality varies among the water fluxes. The northernmost rivers have strongly mineralized water with high calcium and sodium content. The other rivers are less mineralized, and sodium content is generally low.

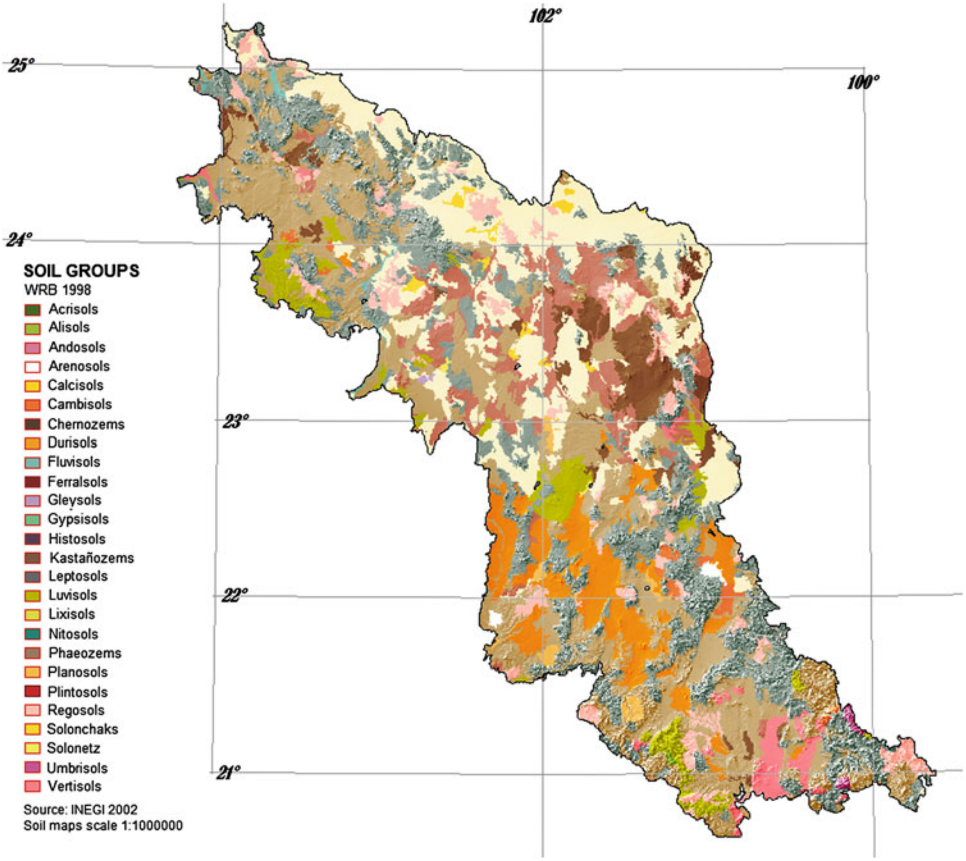
5.7.4 Climate

The climate of the region is semiarid temperate with the majority (over 90 %) of precipitation in summer. The unique feature of the climate of the region is its "inverted zonality": the temperatures decrease and precipitation increases from north to south. This regularity is complicated by the elements of vertical zonality of climatic conditions; generally, the mountains have cooler and wetter climates than the lower flat areas. The difference in elevation results in a sharp contrast between close localities in their climatic conditions. For example, in the very south of the region very cold wet climate of a "mountainous tramp" for cold air borders with warm dry climate in a distance of only 30 km.

The precipitation ranges from 300 mm in the northeast corner to 900 mm in the southern end of the region. The temperature is more uniform, except in the high mountain ranges that exceed 2,000 m asl.

5.7.5 Vegetation

In the northern part of the Mesa, the vegetation consists of rosetophyllous matorrals, with the dominant species such as agave (*Agave lechuguilla*), mariola (*Parthenium incanum*), and yucca (*Yucca gracilis*). At the plain to the north of Miguel Auza, there are spots of halophilous grasslands, extending for many kilometers, which consist of such species as alkali sacaton (*Sporobolus airioides*), Swallen's curly-mesquite



Source: INEGI 2002
Soil maps scale 1:1000000

Fig. 5.11 The soil map of the physiographic region of the Central Mesa. Reproduced with a permission of INEGI

(*Hilaria swallenii*), and blue grama grass (*Bouteloua gracilis*) typical for the zones of salt accumulations in soils. Furthermore, there are arboreal species such as mezquite. Some species are toxic for cattle, such as woolly locoweed (*Astragalus mollissimus*) and garbancillo (*Astragalus wootoni*). In the transition zone between the Central Tableland and the catchments with internal drainage to the north, there are zones of sediment accumulation, where the vegetative community changes radically to matorral with cacti. From the Ciudad de Rio Grande, there are matorrals with cacti, mostly pricky pears, and some mixtures of ocotillos and mariola. To the south of this area toward the city Zacatecas, there are extensive areas with natural grasslands. The most abundant weeds of the grasslands are cobblers peg (*Bidens* spp.), tufted lovegrass (*Eragrostis pectinacea*), and Indian paintbrush (*Castilleja arvensis*). The forest vegetation is present on the slopes of the few mountains that are found within the region and consist typically of pine and oak species.

5.7.6 Soils

The most important soils of the region are Phaeozems/Udolls that occupy about 25 % of the total area and Calcisols/Eutruserts, which occupy more or less the same area (Fig. 5.11). The next abundant group that occupies about 17 % of the area are shallow soils: Leptosols/Lithic subgroups of the Enthisols Order. The distribution of these soils is geographically determined: the humus-rich soils form in the humid south part of the region, the calcium-carbonate-rich soils are found in the subarid northern part of the region, and the shallow soils occupy the slopes of the mountains and hills formed by rock outcrops.

The other soils commonly found in the region include humus-enriched soils with calcium carbonates accumulations: Kastanozems and Chernozems/Ustolls (Fig. 5.12). Totally, these soils occupy more than 12 % of the total area of the region. Geographically, they represent a transition from Calcisols to Phaeozems (from Eutrustepts to Udolls) along a gradient of increasing amounts of precipitation. The other important group is Durisols/Durustepts that cover about 7 % of the region. The genesis of this soil group is related to an ancient flood plains, where cementation with opal occurred due to the long effect of silica-rich groundwater. The soils with the evidence of clay illuviation are not very common in the region: they occupy about 3.5 % of the area and occur mainly on the slopes of the mountains Santa Rosa and Sierra de Lobos.

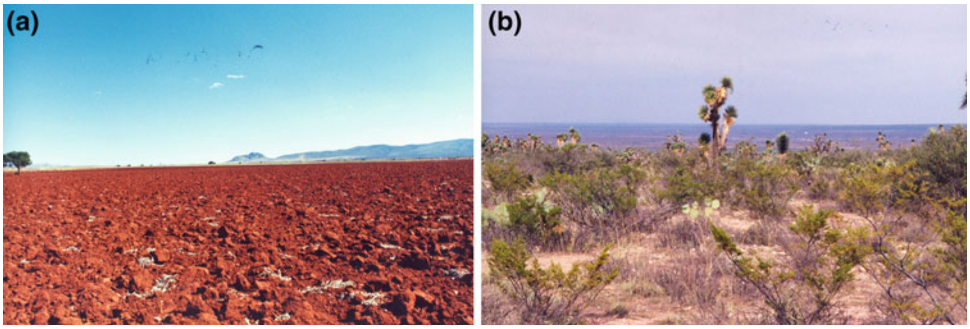


Fig. 5.12 Typical landscapes of the physiographic region Central Mesa: **a** Landscape with Phaeozems/Udolls in red-colored sediments, Mina de Proaco, Zacatecas; **b** Landscape with shallow soils on limestone (Rendzic Leptosol/Rendoll), Cerrito del Agua (photos contributed by María Guadalupe Durón Ruiz-Esparza and David Blanco-Corona)

5.7.7 Soil Use, Degradation, and Management

In its driest part of the region, rainfed agriculture is not very profitable and the crops are limited to corn, beans, and wheat. The yield is commonly low. Irrigation is a good option for these dry areas for increasing the productivity. The water is pumped from the wells and then distributed by gravity. In the middle part of the region, where the amount of the rainfalls is higher, both rainfed and irrigated field are productive. The common crops in this portion of the region are chile, vineyards, alfalfa, squash, tomatoes, and other vegetables. In the most humid part of the region, rainfed agriculture produce very high yields of fodder oats, pumpkin, maize, and beans.

The main degradation process for the region is extensive rill erosion. Although the topography of the region is not very steep, the alternating dry and wet seasons lead to the washing of soil particles in the beginning of the rainy season. In the northern dry part of the region, in places, salinization may be a dangerous tendency.

5.8 Sierra Madre Occidental

5.8.1 Topography

The physiographic region of the Sierra Madre Occidental is a huge mountainous system oriented along the western coast of Mexico. It stretches from north to south from 31°21′49'' to 20°47′27'' and from west to east from 111°13′01'' to 102°18′00'' covering an approximate area of 362,180 km^2. The range runs north to south, crossing eastern Sonora, western Chihuahua, Sinaloa, Durango, Zacatecas, Nayarit, Jalisco, Aguascalientes, and Guanajuato. It is characterized by abrupt topography with steep slopes and deep canyons. The escarpment is oriented to the west, while the inland slopes are gentler. The elevations vary at short distances, and within just a few kilometers the range of altitude may be from 100 to more than 3,000 m asl. The highest peak in this mountainous system is Cerro Mohinora with an altitude of 3,300 m asl. The region possesses the most picturesque canyons in the country.

5.8.2 Geology

The base of the mountainous system consists of ancient rocks that are buried by the more recent volcanic activity (Herrera-Pedroza 2011). The oldest formation consists of Proterozoic gneisses and amphibolites and of marbles, sandstones, and other metamorphosed sedimentary rocks formed during the Paleozoic epoch. These rocks are found in the northern part of the region below a thick package of igneous rocks. These ancient sediments are exposed by deep canyons. The basement of the southern part of the region includes a series of Mesozoic sedimentary rocks such as limestone, conglomerates, sandstones, and lutites. There are few exposures of these sediments. The morphology of the region is formed by a thick cover of igneous rocks that extruded starting from the upper Cretaceous period to the Quaternary period and was also broken and folded by tectonic activity related to the major tectonic block movements and the separation of Baja California from the mainland. There were five principal stages of magmatic activity in the region. The first stage is associated with the formation of effusive and plutonic rocks in the upper Cretaceous period and in the Paleocene. The second stage occurred in the Eocene, when an increase in volcanic activity resulted in the formation of andesitic rocks and minor patches of dacites and rhyolites. The next stage, most probably associated with the major volcanoes eruptions of Katmai type that occurred with two maximums in early the Oligocene and early Miocene, resulted in the deposition of siliceous ignimbrites. The fourth stage includes the extrusion of andesites and basalts that followed the formation of ignimbrites; these rocks are mostly found in the southern part of the mountainous system. The fifth stage includes the most recent volcanic episodes that occurred during the late Miocene, Pliocene, and in the Quaternary period and that accompanied the separation of Baja California from the continent. The tectonic movements were active during the whole Cenozoic epoch and resulted in the formation of numerous fractures and faults that formed river canyons. Abrupt topography and active tectonics result in the poor development of recent Quaternary deposits that are limited to the alluvial sediments of narrow valleys.

5.8.3 Hydrology

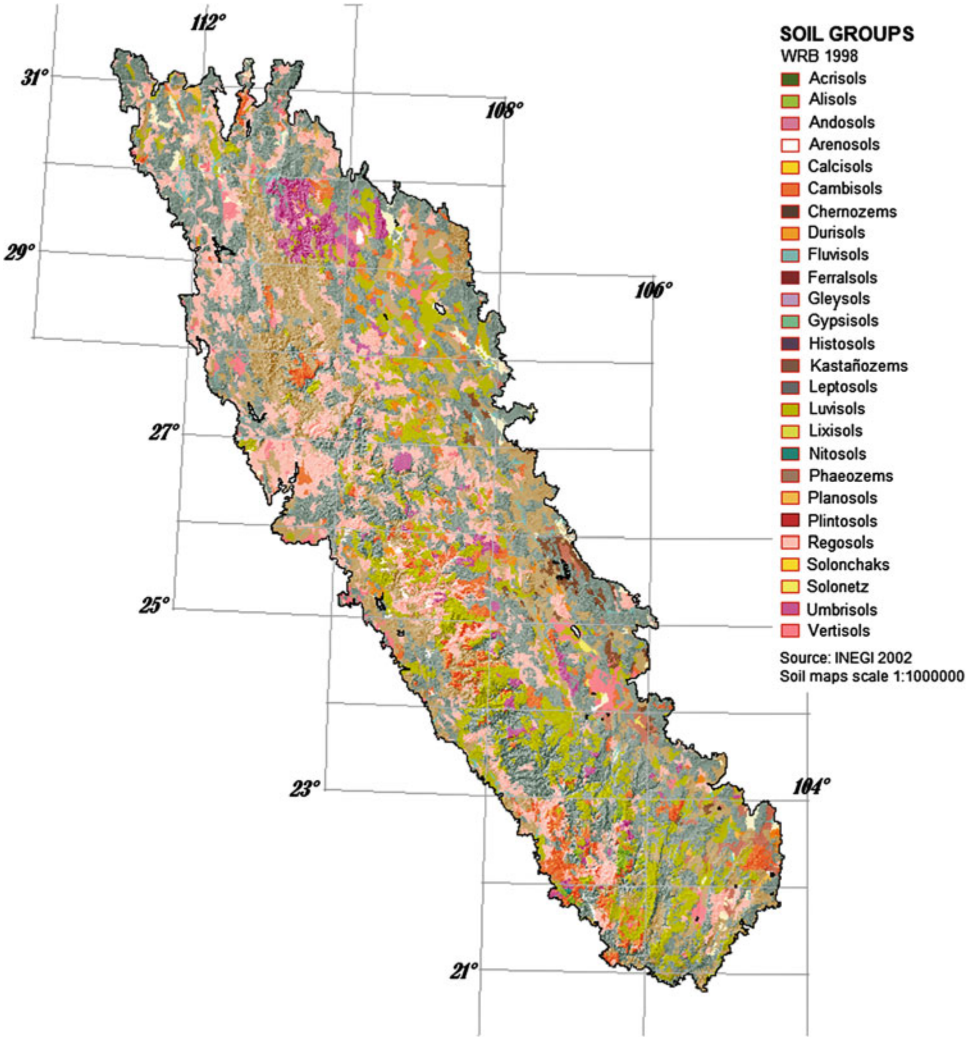
Water drains from the Sierra Madre Occidental both to the Pacific Ocean and to the basin of the Gulf of Mexico. Flows that run to the Pacific include the Yaqui and Fuerte Rivers, the largest in the region, in the north, the Rio Grande de Santiago in the south, and numerous minor flows between them. The basin of the Gulf of Mexico is represented by the Conchos River that drains the eastern part of the region. The Nazas and Aguanaval Rivers drain the territory in an endorheic basin.

5.8.4 Climate

In general, this region is considered to be humid. However, there is a variety of climates here, from tropical and temperate humid to temperate subarid. The general regularities of climate distribution are the following: in the altitudinal distribution there is a gradient from the north to the south of increasing mean annual temperatures. The amount of precipitation depends mainly on the orientation of the slope either to the ocean (humid climates) or to the inland area (dry climates). The altitude strongly regulates the climatic conditions. With increasing elevation, the temperature decreases and the amount of rainfalls increases. The difference in elevation determines the contrast in climatic parameters at short distances. Also the configuration of the slopes matters, because many canyons serve as traps for humid and cold air. As a result, the amount of precipitation varies in a broad range, with the lowest values of 400–500 mm of annual rainfall on the inland slopes facing the region of the Uplands and Lowlands of the North, and the highest values of about 2,000 mm of annual precipitation on the elevated marine slopes in the northern part of the region. The mean annual temperatures range from 8 °C in the crest of the northern part of the range to 26 °C in the southern valleys. The extreme temperatures are even more impressive; the summer temperature may rise up to 40 °C in the inland toeslope of the range, and drop down to −20 °C in the winter in the northern highlands.

5.8.5 Vegetation

The vegetation of the region is regulated by its latitudinal and altitudinal dimensions. The northern part at lower elevations has vegetative communities similar to those of the Sonorian Lowlands, i.e., xerophyllous shrubland. Similar communities occur in the whole inland area of the region bordering the Lowlands and Uplands region of the North. However, these communities are commonly richer than the bordering regions due to higher amount of precipitation. With increasing elevation, these xerophyllous communities are replaced by tree stands and mountain meadows. The slope oriented toward the ocean is much wetter and thus has forest vegetation from the lowest elevations. Forests compose the major part of the vegetative communities of the Sierra Madre Occidental; the region contains about two-thirds of the standing timber in Mexico. At the lowest elevations, the vegetative communities on the marine side are commonly represented by tropical deciduous forest. Immediately above the shrublands or tropical deciduous forests, there is a narrow belt of oak forests; it is a rich community with the most common species represented by Emory oak or bellota (*Quercus emoryi*), Mexican blue oak (*Q. longifolia*), and Arizona oak (*Q. arizonica*). The upper belts include the famous pine-oak forests. Within the Sierra Madre Occidental pine-oak forests there are 23 different species of pine and about 200 species of oak, including such species as Apache pine (*Pinus engelmannii*), Durango pine (*P. durangensis*), egg-cone pine (*P. oocarpa*), and pino chino (*P. herrerae*). The uppermost positions, commonly above 2,000–2,100 m asl, are occupied by mixed coniferous forests. The stand is composed mainly representative by fir, pine, and Douglas fir species. These trees have high commercial value and thus the forest has been logged in the last several decades. Most of the broadleaf trees present in this



Source: INEGI 2002
Soil maps scale 1:1000000

Fig. 5.13 The soil map of the physiographic region of Sierra Madre Occidental. Reproduced with a permission of INEGI

forest are winter-deciduous like Gambel oak (*Quercus gambelii*), capulin or wild cherry (*Primus serotina*), ash (*Fraxinus papillose*), and aspen (*Populus tremuloides*).

5.8.6 Soils

The three most abundant soil groups in the region of Sierra Madre Occidental are humus-enriched soils (Phaeozems/Udolls), shallow soils (Leptosols/Lithic groups of Entisols), and underdeveloped soils (Regosols/Orthents) (Fig. 5.13). In the pedogeographical context, the first group represents the "zonal" soils of the region, or perhaps better stated the prevalent vegetative community of the region, namely the tropical deciduous, oak, and pine-oak forest. The other two groups are "azonal" soils that reflect poor soil development due to continuous erosion on steep slopes. The distribution of soils greatly depends on the parent rock. Shallow soils are found mainly on solid volcanic or plutonic rocks that weather slowly; thus, the erosion rate is greater than the formation of the fine earth material. Ignimbrites, which have the features both of lavas and pyroclastic sediments, weather much easier, and most of the deep soils form in these parent rocks.

The humus-enriched soils under the coniferous forest can be acid, and are classified as Umbrisols/Dystrudepts. Furthermore, under the shade both of the coniferous and tropical semideciduous forests the soils may have intensive water percolation, and thus clay illuviation occurs. The soils with textural differentiation are widespread all over the region,

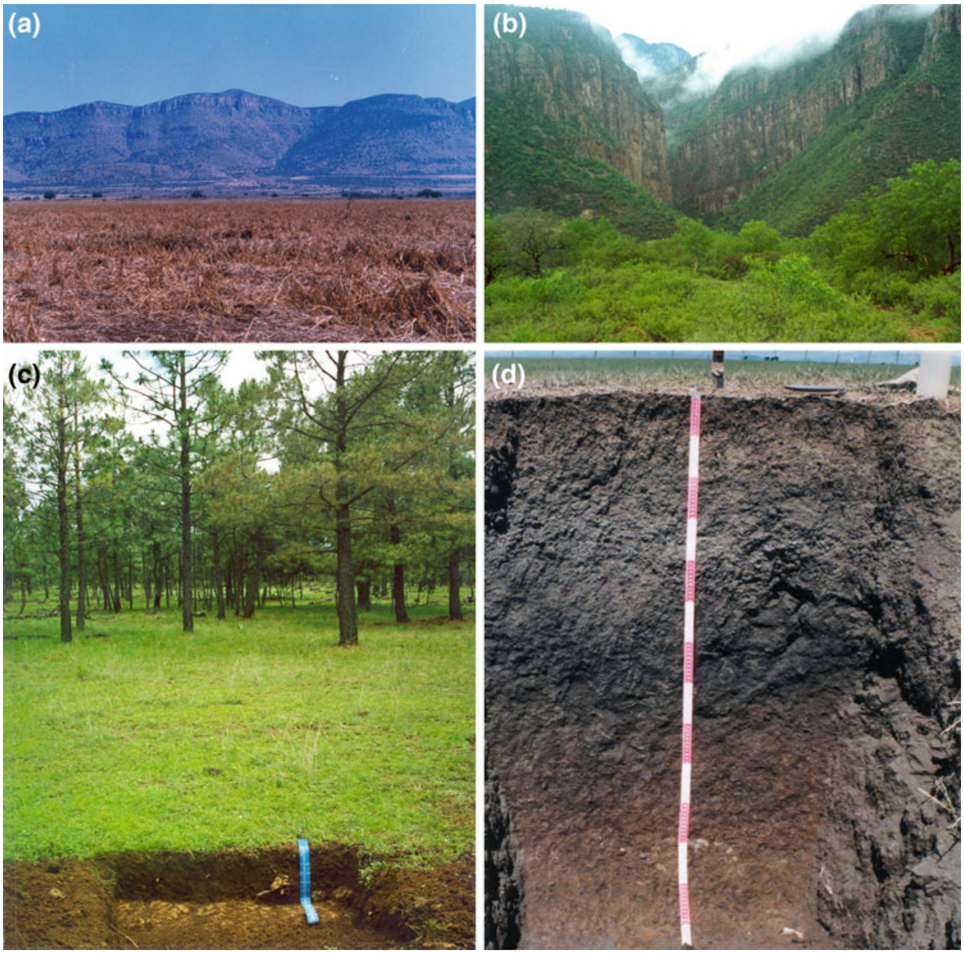


Fig. 5.14 Typical landscapes and soils of the physiographic region Sierra Madre Occidental: **a** valley with Vertisols, Villa Montemorelos, Durango; **b** Mountainous landscape with Calcisols/Eutrudepts, El Mezquital, Durango; **c** Humic-Umbric Luvisol (Epileptic)/Lithic Haplustalf, Mesa El Sargento, Durango; **d** Mesotrophi-Humic Vertisol/Ustert, Lago Bavícora, Chihuahua (photos by Carlos Omar Cruz-Gaistardo)

though they do not occupy large areas. Most of these soils are base-saturated (Luvisols/Alfisols), but in the southern slopes of the mountainous system some base-poor tropical soils (Acrisols/Ultisols) occur. A number of typical "dryland" soils are located along the eastern arid slope of the mountainous system and in some dry valleys. These soils include Calcisols/Eutrustepts, Vertisols, Solonetz/Natrustalfs, and Kastanozems/Ustolls (Fig. 5.14). Minor areas of immature alluvial soils (Fluvisols/Fluvents) occur in the valleys.

5.8.7 Soil Use, Degradation, and Management

The main occupation of the region is logging and agriculture. In most places the agriculture is rainfed, or irrigation irregularly in case of emergency. The main crops are corn, oats, and pumpkins. The use of irrigation broadens the number of crops produced, especially in the inland side of the region. Irrigated areas produce corn, beans, chile, alfalfa, grapes, peaches, sugarcane, mango, avocado, sorghum, guava, potatoes, peanuts, and some vegetables. Extensive territories are also used for pastures.

The most dangerous soil degradation process in the region is water erosion that is especially severe on steep slopes under cultivation with crops such as corn or overexploited pastures.

5.9 Pacific Coastal Plain

5.9.1 Topography

This region is constituted by an elongated narrow coastal plain about 60–70 km wide. It is characterized by an almost plane relief formed by large floodplains, lakes, and swamps aligned parallel to the coast. The major part of this region is covered by alluvium deposited by rivers flowing into the sea from the Sierra Madre Occidental. In the northern part of the region, there are ridges interspersed with plains, while in the south there are valleys and flood plains.

5.9.2 Geology

The geological basis of the coastal plain was formed by extrusive igneous rocks of the same period as the volcanic rocks of the neighboring region of the Sierra Madre Occidental, mostly in the Eocene epoch. Later, they have been buried with Neogene and Quaternary deposits such as alluvium, lacustrine, and marine sediments, consisting of sands, gravels, silts, and clays.

The origin of this narrow band of coastal plain is related to marine transgressions that occurred during the Quaternary and that continued along the late Pleistocene and Holocene. According to Contreras (1988) during the last glaciations, approximately 18,000 years ago, there was a rise in the sea level, and the water covered all the plain. The period between 4,750 and 3,600 years BP is critical to its development when the neotectonic movements uplifted the region. Since that time, a regression of the sea started that continues until now. Thus, the majority of the surface deposits are rather young, and almost all of them have marine or alluvial origin. Furthermore, there are some eolian sediments represented by coastal dunes.

5.9.3 Hydrology

All of the rivers running from the region of the Sierra Madre Occidental pass through the Pacific Coastal Plain. The major deltas of the rivers are those of the Yaqui, Mayo, and Fuerte in the north and the Rio Grande de Santiago in the south. At the early stages of the sea regression, the Santiago and the San Pedro Rivers converged before flowing into the ocean near the bay of Boca de Camichín, and about 500 years ago the Santiago River separated from the San Pedro River and moved to the south forming a new delta (Romo and Ortiz 2001). The dynamic character of the rivers increases the risk of floods. In the last five decades, there have been changes in drainage patterns of the lower courses of the rivers Santiago, San Pedro, and Acaponeta, resulting from the construction of levees to protect the main towns settled on the banks. Furthermore, the hydroelectric projects Aguamilpa, San Rafael, and El Cajon on the Santiago River, the channel of Cuautla and some works on the aquaculture and fisheries allowed greater control of floods (García-Sancho et al. 2009).

5.9.4 Climate

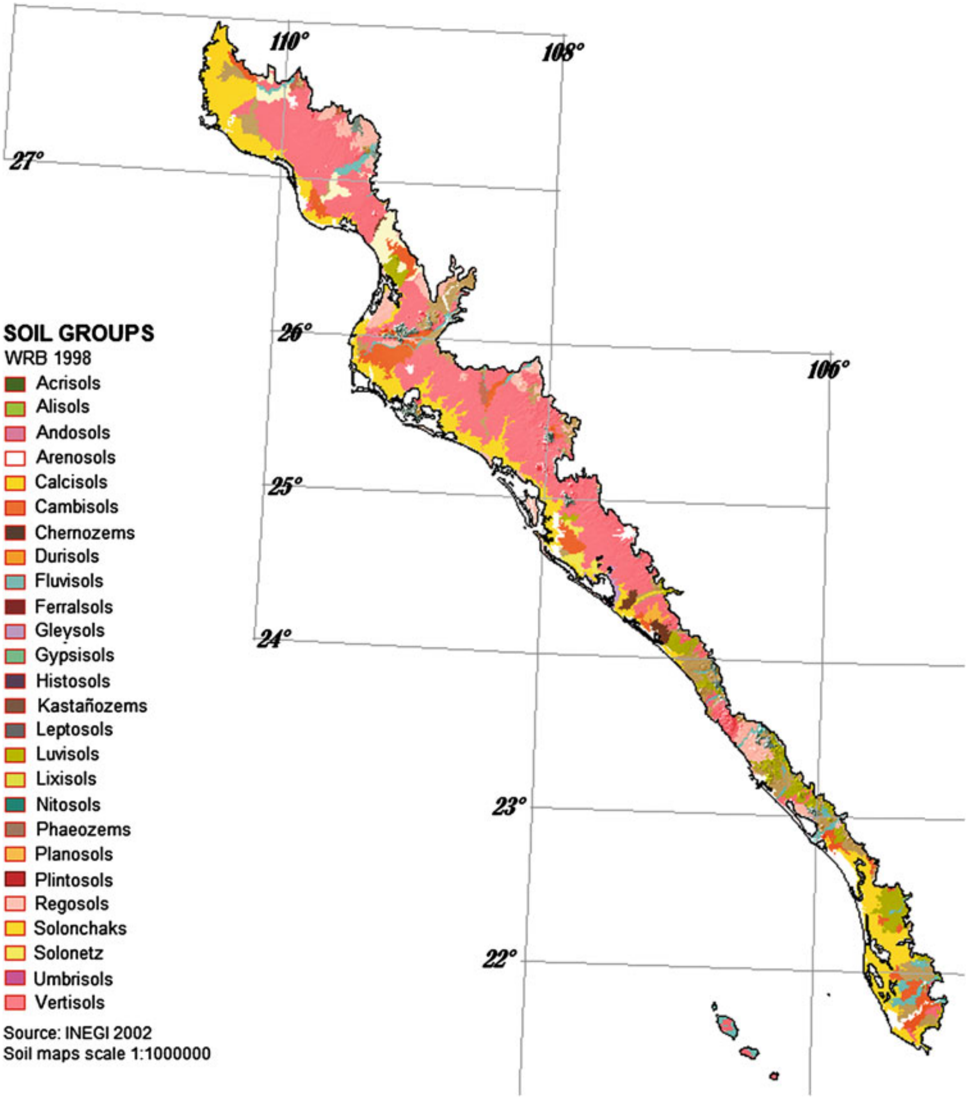
In general, the climate of the region may be characterized as subarid in the northern part at the border of the Sonorian Lowlands and as subhumid in the southern portion. The temperature is higher than 20 °C throughout the region. Relative aridity of the coastal plain with numerous river streams illustrates the regularity common in the coastal mountainous systems, where the humid air discharges with rains at certain elevations, and the air cools and thus its relative humidity increases. Low calescent coastal areas heat the air and decrease its relative humidity, thus the air masses pass by without any rainfall. However, permanent breeze, the proximity of the groundwater, and the abundance of surface fresh water make the climatic conditions of the region comfortable for ecosystems and for humans.

5.9.5 Vegetation

The landscapes of the region are represented by deltas (floodplains), wetlands (mangroves, coastal lagoons and estuaries) and coastal bars adjacent to the coast (García-Sancho et al. 2009). The first ecosystem to be mentioned is tropical deciduous forest, where the arboreal floor is represented by the species of the genera *Bursera*, *Cyrtocarpa*, *Picus* and *Psidium*, and the thorn scrub floor with such representative species as capulin (*Ehretia tinifolia*), honey mesquite (*Prosopis juliflora*), majagua (*Hibiscus pernanbucensis*), gray nicker (*Caesalpinia bonduc*), soldierbush (*Tournefortia densijhra*), and Cuban tangle (*Stegnosperma cubense*). These vegetative communities are commonly found at the uplifted parts of the alluvial deltas. The same positions are also occupied by palms (*Orbignya guacoyule*) and semideciduous tropical forest with dominant species in the arboreal floor of the genera *Bursera*, *Ficus*, *Acacia*, *Ayenia*, *Calliandra* and *Salvia*. The low coasts are characterized by mangrove vegetation represented by the species white mangrove (*Laguncularia racemosa*), red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*) and buttonwood (*Conocapus erectus*). Furthermore, at the coasts one can find halophytic communities with such species as sea-oats (*Uniola pittieri*), southern sandspur (*Cenchrus echinatus*), goat's foot (*Ipomoea pes-caprea*), and shoreline purslane (*Sesuvium portulacastrum*). At the bare coastal beaches and dunes, the latter two species plus combtop muhly (*Muhlenbergia pectinata*), occur.

5.9.6 Soils

According to the recently published data (Bojórquez et al. 2006–2008) the main soil groups in the region are Cambisols/Udepts and Fluvisols/Fluvents with inclusions of other less abundant soil groups (Fig. 5.15). According to the data of the above-mentioned authors there are three plain levels. At the lowest coastal plain, there are tide flooding



Source: INEGI 2002
Soil maps scale 1:1000000

Fig. 5.15 The soil map of the physiographic region of the Pacific Coastal Plain. Reproduced with a permission of INEGI

plain, parallel bars, beaches, and coastal dunes. At this level, the soils are the least developed, and the dominant soil groups are Regosols/Orthents, Fluvisols/Fluvents, and Arenosols/Psamments (Fig. 5.16b, d). In the areas affected by saline groundwater there are Solonchaks/Halaquepts. The second level has mainly Cambisols and Gleysols/Inceptisols that are more developed than the soils of the lower coastal areas. Commonly, these soils have accumulations of organic matter on the surface and alteration of minerals in the profile. The upper level soils are represented mainly by Phaeozems/Udolls and Ustolls under the shade of deciduous and semideciduous tropical forests. These soils have thick A horizons and brownish B horizons (Fig. 5.16c).

5.9.7 Soil Use, Degradation, and Management

The agricultural production of the region is concentrated mainly in the river deltas. The valleys of Yaqui and Mayo are situated in the northern part of the region, near the Obregon City. The main crop is wheat, also cotton and vegetables are cultivated. Irrigation is a common practice for agriculture. The water is pumped from deep wells, and the water quality is satisfactory. Apart from agriculture, the local population practices aquaculture and fisheries.

The degradation processes are related to the destructive effect of the rivers and the risk of floods. Some of the challenges of actual land management in the region include

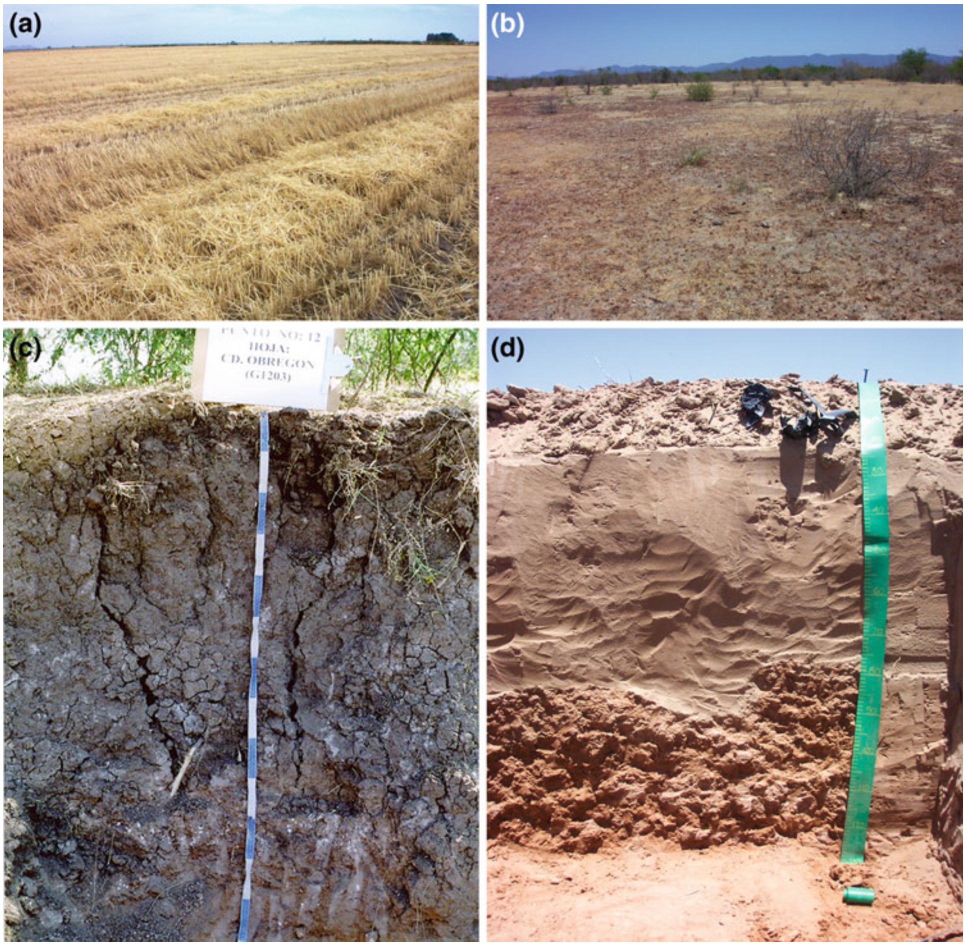


Fig. 5.16 Typical landscapes and soils of the physiographic region Pacific Coastal Plain: **a** Agricultural field on Vertisols, Sinahuiza, Sonora; **b** Semiarid landscape on stony immature soils (Cambisols/Ustepts), Francisco Sarabia, Sonora; **c** Haplic Vertisol (Calcaric, Chromic)/Haplustert, Navojoa, Sonora; **d** Haplic Regosol (Arenic, Thaptoluvic)/Ustipsamment, El Refugio, Sinaloa (photos contributed by Carlos Alberto Saracco-Alvarez)

current changes in the coastline, the intensification of the processes of channel erosion, and accumulation of sediments in the coastal lagoons of the coastal system, and changes in salinity patterns and mangrove plant communities (Bojórquez-Tapia et al. 1997) (Fig. 5.16).

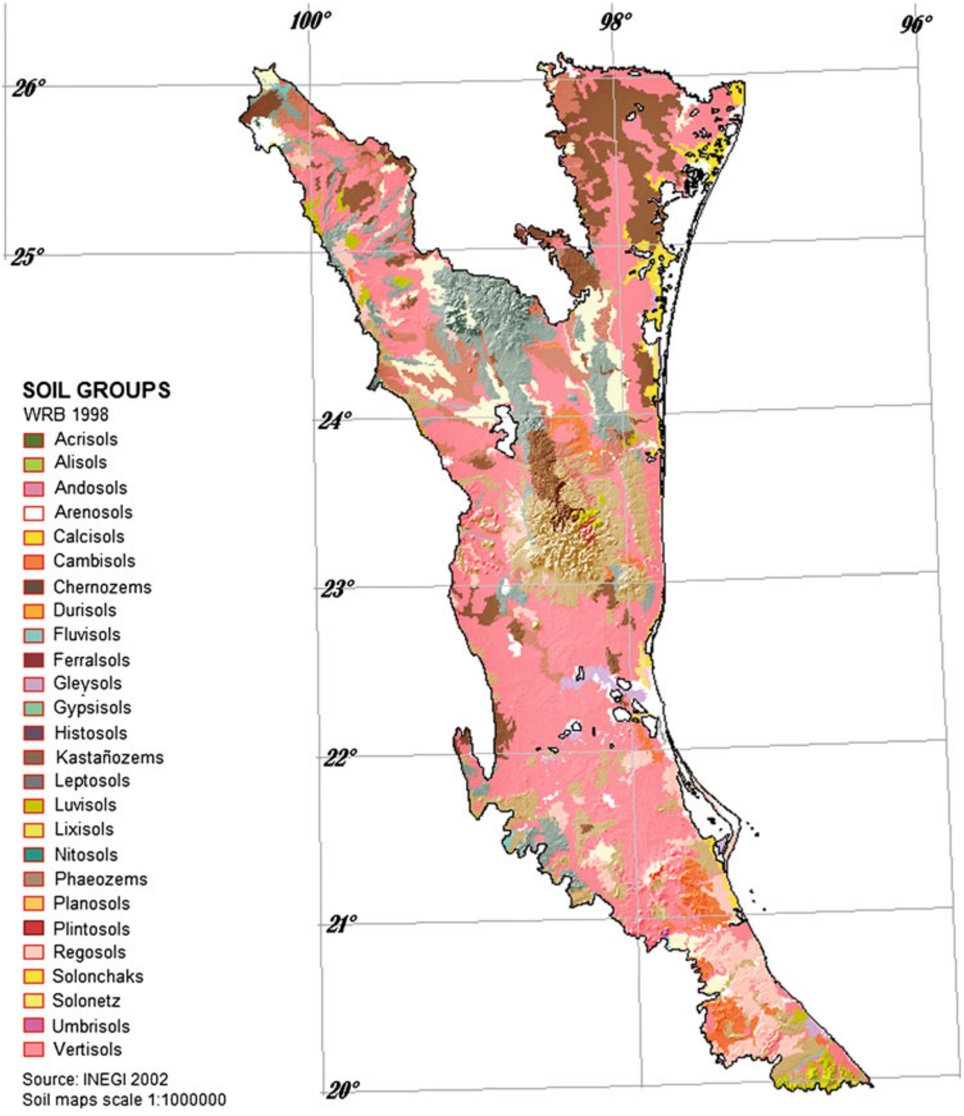
5.10 Northern Coastal Plain of the Gulf of Mexico

5.10.1 Topography

This region stretches along the Gulf Coast from the Rio Grande near the city of Reynosa in the Tamaulipas State to the mouth of the river Nautla in the Veracruz State. It borders with the region of the Great Plains of North America in the north, with Sierra Madre Oriental in the west, with the Gulf of Mexico in the east, and the Transmexican Volcanic Belt in the south. In Mexico, this region partly covers the states of Tamaulipas, Nuevo Leon, San Luis Potosi, Hidalgo, and Veracruz. It is a flat area with insignificant inclination: the highest point of the western border of the region is located in the Monterrey area (500 m asl), and the lowest—near Reynosa (150 m asl). However, there are also single mountainous ranges, the Sierra de San Carlos and Tamaulipas, with extreme elevations up to 1,400 m asl. The eastern border corresponds to sea level. The whole region slowly uplift during the whole Cretaceous epoch. Abundant forms of relief in this area are so-called *tapones* that look like chains of hills or single hills, which are not important topographically, but are of major economic importance, because these structures correspond to important deposits of petroleum.

5.10.2 Geology

This uplifted area is generally characterized by a sequence of marine sediments with the age increasing with distance from the present coastal line. The most ancient rocks are found at the highest elevations. The Sierra de San Carlos with peaks of 800–1,000 m asl up to a maximum of 1,400 m asl is composed of consolidated Cretaceous limestones intruded by intermediate igneous rocks. The Tamaulipas range resembles the Sierra de San Carlos in



Source: INEGI 2002
Soil maps scale 1:1000000

Fig. 5.17 The soil map of the physiographic region of the Northern Coastal Plain of the Gulf of Mexico. Reproduced with a permission of INEGI

geological structure, but the intrusions are acid. Clay marine sediments of the Upper Cretaceous age are found in the vicinity of Ciudad Mante and Monterrey. In the southern portion of the region, west of Tamiahua and extending north to Ciudad Victoria there are clays, sands, and conglomerates formed during the Miocene and Oligocene epochs. Closer to the coast, there are calcium carbonate-rich sands, clays, and lutites of Pliocene and Quaternary age. The most recent sediments are represented by the actual beach deposits and coastal dunes.

5.10.3 Hydrology

The tectonic uplift of the territory results in a somewhat paradoxical situation with the rivers of the region. Although the region is plain, the rivers penetrate deeper into the sediments due to stream-channel erosion and do not deposit sediments in the flood plains. The rivers that flow into its coast, the such as Bravo, Soto La Marina, Tamesí, Panuco, Tuxpan, Cazones, Tecolutla, Nautla, and others, do not deposit alluvium in its territory. The water of the rivers of the region is of poor quality due to the contamination by the petroleum industry, sugar production, increasing urban waste, and excessive fertilization of agricultural fields. Groundwater is widely used in the region, but the quality of the water derived from the wells is also not very good due to high mineralization.

5.10.4 Climate

The precipitation falls mainly in summer, except for the uplifted parts (400–500 m asl), where the precipitations

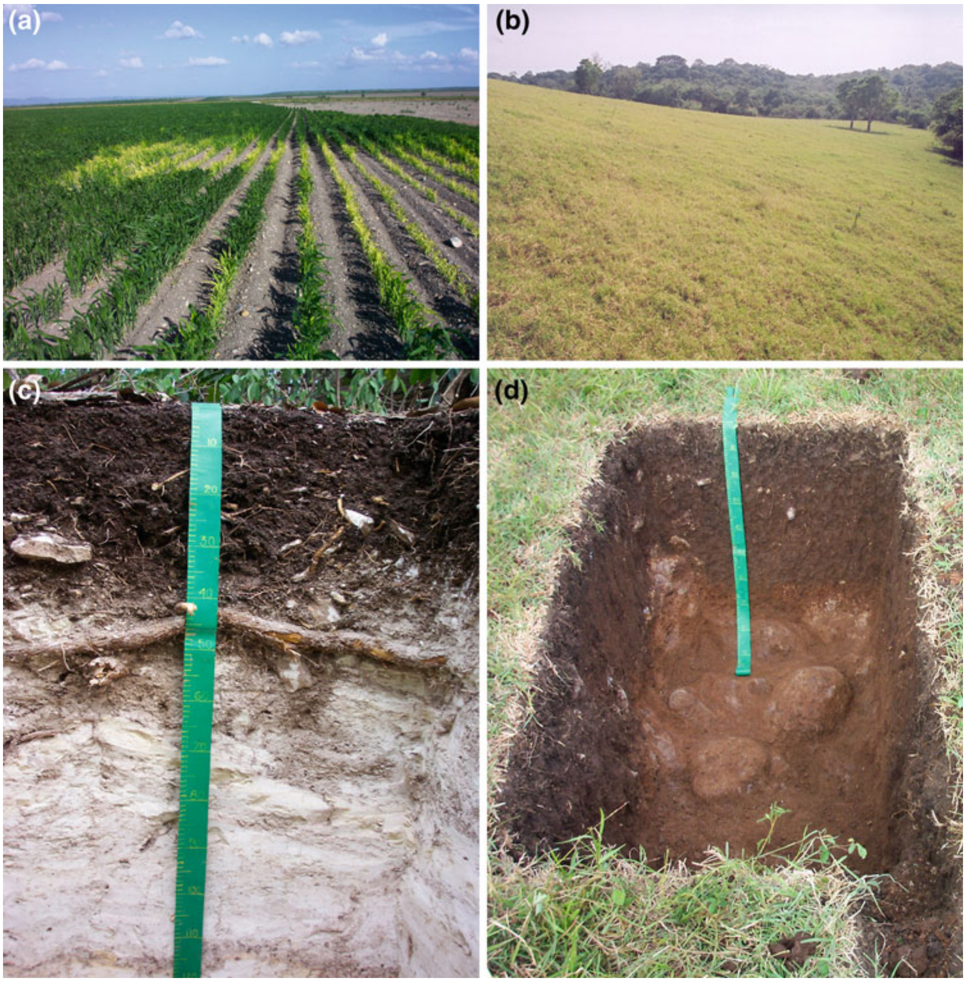


Fig. 5.18 Typical landscapes and soils of the physiographic region Northern Coastal Plain of the Gulf of Mexico: **a** Agricultural fields on Vertisols, Nicolás Bravo, Tamaulipas; **b** Pastures on underdeveloped calcaric soils, Paso de Lorenzo, Veracruz; **c** Clayey Chernozem/Udoll, Arroyo los Coyotes, Tamaulipas; **d** Stony clayey Phaeozem/Udoll, El Aquichal, Tamaulipas (photos contributed by Enrique Hernández, Héctor Tello-Taracena and Rafael Vicente-Aguilera)

occur all the year long. At the Northern Coastal Plain, the annual precipitation ranges from 1,500 (Tamasopo) to 3,000 mm (Xilitla), with relatively uniform mean annual temperatures in the range of 22–24 °C. The dominant climates are classified as subtropical subhumid; only in a northern area the climate is subarid.

5.10.5 Vegetation

The vegetation in the northern part is represented by low mountain scrub and thorn scrub communities. Further to the south, there are humid tropical forests rich in arborous species such as red cedar, oaks, walnut, and vast areas of grasslands. At higher elevations, there are some oak forests, and even higher there are pine-oak and pine forests.

5.10.6 Soils

The most abundant soils of the Northern Coastal Plain are Vertisols, Fluvisols/Fluvents, Gleysols/Aquents and Aquepts, and Solonchaks/Halaquepts (Fig. 5.17). Vertisols occupy flat areas with clayey marine sediments. Their distribution also depends on topography: in places they are present only in local depressions, whereas in the slightly undulated areas the soils do not have enough clay to exhibit the evidences of the cycles of shrinking and swelling. On the slopes of the hills, there are abundant humus-enriched soils with only weak evidence of *vertic* properties. Depending on the presence of secondary carbonates these soils are classified as Vertic Phaeozems or Chernozems/Udolls (Fig. 5.18). The abundance of loose sediments with high contents of calcium carbonate lead to the formation of soils with poorly pronounced morphology. These soils are commonly classified as Regosols and Cambisols/Orthents and Eutrudepts. Extensive areas close to the coastal line are occupied by poorly developed sandy soils in marine, alluvial, and eolian sands. These soils are classified as Fluvisols and Arenosols/Fluvents or Psamments dependenting on the presence of layering in the sediments.

5.10.7 Soil Use, Degradation, and Management

The region makes a major contribution to the agricultural sector in the country. Rainfed agriculture is dominant and is achieved by planting in short cycles, especially in the spring–summer period. The main crops include corn, beans, sorghum, paddy rice, coffee, oranges, mangos, bananas, pineapples, sour lemons, tangerine, papaya, grapefruit, plums, almonds, and coconut fruit, as well as rubber hevea, vanilla, green chile, potatoes, and watermelon. Irrigated agriculture has not reached significant importance in the region, primarily due to the favorable climate, which can obtain high yields with low investment. The main irrigated crops are sorghum, corn, peas, watermelon, okra, squash, melons, and sunflowers. One of the most important commercial crops in the region is sugar cane.

Cultivated pasture is developed throughout the region. The grassland species commonly seeded in the pastures are African star (*Cynodon nlemfuensis*), guinea (*Panicum maximum*), jaragua (*Hyparrhenia rufa*), and pangola (*Digitaria eriantha*).

Soil degradation processes include erosion that occurs in the slightly undulating landscapes. Soil and groundwater contamination by pesticides and fertilizers are also common problems.

5.11 Southern Coastal Plain of the Gulf of Mexico

5.11.1 Topography

This region comprises the coastal regions of Veracruz and Tabasco states where deep alluvial soils abound. In Veracruz, the northern part of the coast has hilly topography, but south of this state and Tabasco becomes increasingly flat. East of Tabasco is a large floodplain swamp. In contrast to the Northern Coastal Plain, the Southern Coastal Plain of the Gulf of Mexico is dominated by alluvial sediments of the most important rivers of the country. The plain is very low and there are vast areas periodically flooded by seawater. The mineralogical composition of the materials forming the plain is dominated by primary silicates and swelling minerals. The alluvial plain is narrow at the north with an important long area of coastal dunes near the Veracruz port. This region is characterized by low, almost flat, relief, with altitudes below 100 m, which are cut by wide valleys, resulting from the accumulation of large river deposits in different media, such as the lakeside, and coastal marsh.

A major physiographic discontinuity, the Sierra de los Tuxtlas volcanic area, interrupts this region on the coast. Some geographers prefer considering it an enclave of the Transmexican Volcanic Belt. The Sierra de los Tuxtlas consists of numerous small volcanic apparatus and big volcanoes of San Martin at 1,658 m and Watcher of Santiago, 800 m asl. Lake Catemaco, 9–10 km in diameter, also located in this volcanic portion of the region is the largest caldera in the country.

5.11.2 Geology

Like a big portion of the Mexican territory, the region of the Southern Coastal Plain of the Gulf of Mexico has Mesozoic (Upper Cretaceous) limestones at its base (López-Ramos 1982). However, these rocks are practically never observed at the surface, because they are covered with a thick layer of more recent marine and coastal sediments. The older part of such sediments may be found in the contact zone of the region with more uplifted areas such as the Sierras of Chiapas and Guatemala and Sierra Madre del Sur. These Paleocene deposits are layers of clastic (shale-sandstone) outcrop in the south portion of the region, overlying the Upper Cretaceous carbonate rocks. The region is a sedimentary plain whose origin is closely related to the regression of the Atlantic Ocean that started in the Palocene period and thus provoked the accumulation of terrigenous sediments in coastal environments. The sequence of the sediments of increasing age along the gradient from the coast to inland areas shows that, like the northern part of the coastal plain, the southern part also is a product of a prolonged uplift. However, this uplift was much less pronounced and thus the inclination of the plain is also less than in the northern part of the plain. Continuous rejuvenation of the coastal platform has allowed subsequent erosion of the Cenozoic marine deposits, which currently have little elevation over the area. The Pliocene and Quaternary deposits occupy the major part of the area of the region, among them the swamp, alluvial, coastal marsh, and lacustrine sediments.

The volcanic enclave Los Tuxtlas consists mainly of alkaline magmas erupted by the volcano San Martín Tuxtlas; the age of effusive rocks varies from Oligocene–Miocene to Holocene (López-Ramos 1982). Volcanic ashes, including recent ones, represent the surface sediments. The latest eruptions of the volcano were recorded in 1664 and

1793 (Nelson and González-Caver 1992), which resulted in the presence of poorly weathered ashes on this territory.

5.11.3 Hydrology

Although the relief of the region is flat, the drainage of its major portion is satisfactory, and the drainage density is medium to high. Numerous rivers cross the region draining into the Gulf of Mexico, including one of the biggest river systems in the country Grijalva-Usumacinta. The other major rivers in the region include the Papaloapan and Coatzacoalcos. The rivers transport and deposit significant amounts of fine particles, thus contributing to the alluvial sedimentation. In places, the net of the streams cannot drain the territory efficiently, and shallow lakes like Machona, Mecoacan, Sitio Grande, and El Rosario form. The most evident example of insufficient drainage is the presence of extensive wetland areas in the Tabasco State, the famous Pantanos de Centla.

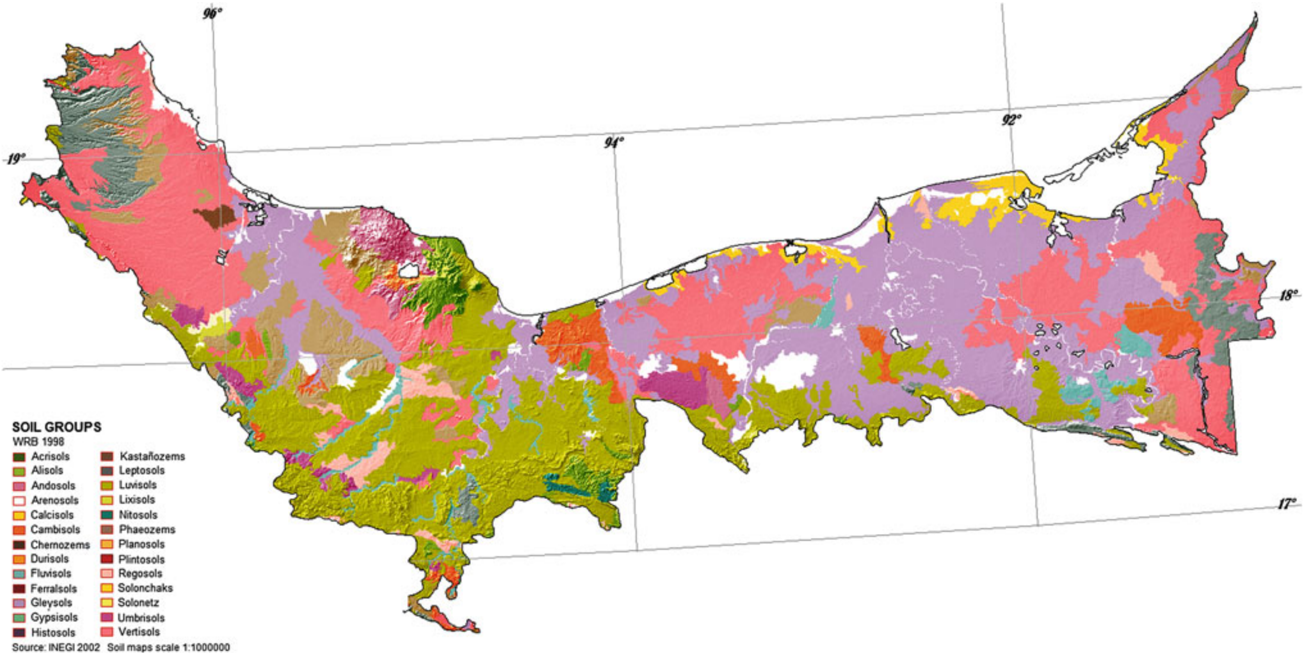
In the volcanic portion of the region, the rivers are small and of a mountainous type. The biggest lake is Catemaco, its pothole has a volcanic origin.

5.11.4 Climate

The Southern Coastal Plain of the Mexican Gulf is one of the hottest and most humid places in Mexico. The climate is characterized as hot and very hot, with mean annual temperatures as high as 24–26 °C. Although precipitation is high everywhere, serious differences exist in the amount of precipitation between even close parts of the region. Due to a well-known phenomena discussed in the Sect. 5.9 of this chapter, the coastal areas of flat tropical coastal plains receive less precipitation than more remote areas, especially the slopes of the mountains. Thus, in places the immediate coastal areas receive 1,500–2,000 mm of annual precipitation, whereas the zones in the proximity of the mountainous slopes of inland regions receive more than 4,000 mm of precipitation per annum. As a result, the areas close to the coast, for example those located between the cities of Coatzacoalcos and Veracruz, are classified as "subhumid". The exception is the uplifted volcanic area of Los Tuxtlas located at the coastline that receives about 4,700 mm of annual precipitation. The rainy season occurs in the region in late summer through autumn. Strong tropical showers are common causing serious floods.

5.11.5 Vegetation

At the Southern Coastal Plain the natural vegetation is represented by tropical rain forests with high diversity vascular plant species, and by various wetland communities, including mangroves. In the unique natural protected area of Pantanos de Centla, due to continuous or prolonged flooding of the territory, the plant communities are



Source: INEGI 2002 Soil maps scale 1:1000000

Fig. 5.19 The soil map of the physiographic region of the Southern Coastal Plain of the Gulf of Mexico. Reproduced with a permission of INEGI

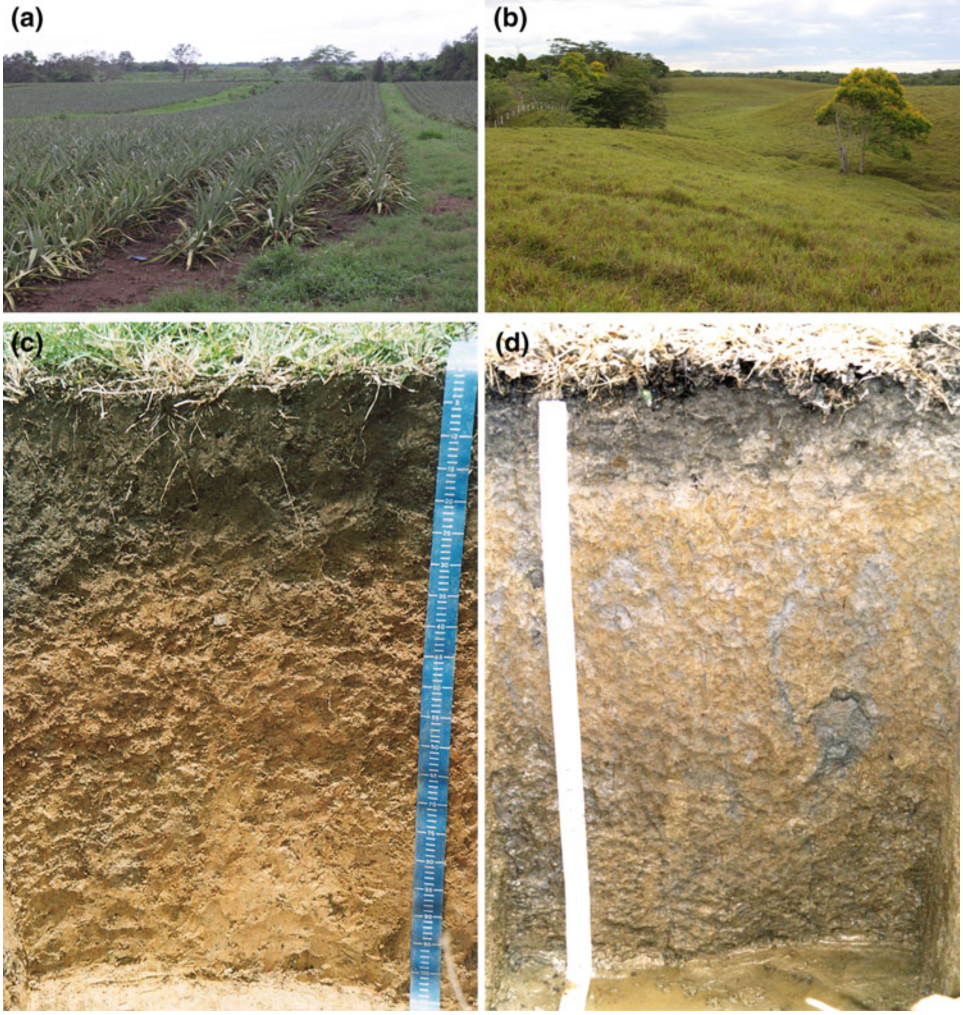


Fig. 5.20 Typical landscapes and soils of the physiographic region Southern Coastal Plain of the Gulf of Mexico: **a** Agricultural fields on Luvisols/Udalfs, Tuxtepec, Oaxaca; **b** Pastures on Luvic Phaoezems/Argiudolls (**c**), Rancho Villacantares, Acayucan, Veracruz; **d** Clayey Gleysol/Aquent, Miguel Hidalgo, Tabasco (photos contributed by José Trejo-Mata and Wendy Cantarell)

primarily aquatic and hygrophilous: reeds (tulars), flood meadows and sparse woody mangrove-like vegetation (Palma-López et al. 1985). The tropical rain forests are known for their high biological diversity. In the National Park Los Tuxtlas, the vascular flora includes 943 species of plants, 545 genera, and 137 families. The families with the greatest number of species are *Orchidaceae*, *Polypodiaceae*, *Asteraceaea*, *Leguminosae* and *Rubiaceae*. The most diverse genera are *Epidendrum* (*Orchidaveae*), *Ficus* (*Moraceae*), *Peperomia* (*Piperaceae*), *Psychotria* (*Rubiaceae*) and *Eupatorium* (*Asteraceae*) (Ibarra-Maríquez and Sinaca 1987). The natural vegetation is mostly replaced by agricultural fields.

5.11.6 Soils

Hot and humid tropical climate is conducive to the development of strongly weathered tropical soils, such as Acrisols/Kandiudults and Plinthisols/Plintudults (Fig. 5.19). The majority of these soils are found at some distance from the coast, because their formation requires some tens thousands of years for the development (Targulian and Krasilnikov 2007), and thus they occur on the higher and older sea and alluvial terraces (Ortíz-Pérez et al. 2005). High amounts of precipitation and somewhat impeded drainage in many places result in the broad development of hydromorphous soils, such as Stagnosols/Aqults and Gleysols/Endoaquents (Fig. 5.20). The most extensive area of soils affected by excessive groundwater is the flood plain Pantanos de Centla. This flat plain, close to the complex delta of Grijalva and Usumacinta rivers, is the only place in Mexico where extensive areas of organic soils (Histosols) exist (Palma-López and Cisneros 1997). The zone close to the coastal line, flood plains, and recent river terraces commonly have young immature soils, such as Fluvisols/Fluvents, Arenosols/Psamments, and Cambisols/Udepts. The area in the vicinity of the young volcanoes has soils with weakly weathered volcanic glass. These soils may be included in the specific taxa of volcanic soils, Vitric

Andosols/Vitrands (Sommer-Servantes et al. 2003). The other soils are classified as relatively immature soils formed in pyroclastic sediments: Tephric Cambisols/Vitrandic Dystrudepts.

5.11.7 Soil Use, Degradation, and Management

The Southern Coastal Plain of the Gulf of Mexico is one of the most important zones for tropical fruit production in Mexico. The main products are pineapples, banana, cacao, papaya, sugarcane, coconut, and many others. Cattle breeding is also popular in the region. The extensive production of tropical fruits and especially of sugarcane resulted in deforestation and a loss of biological diversity. The establishment of national parks and reserves partly helps to preserve the natural heritage of the tropics, but the agriculturalists slowly penetrate into these protected areas, because almost no legal mechanisms exist to prevent reclaiming the protected areas. Deforestation usually results in the quick development of water erosion and to the loss of upper soil layers.

The other degradation process important for the region is petroleum contamination. The region is the main center of petroleum production in Mexico and thus pressure from human activities of the ecosystems and soils is also great. Although the petroleum company tries to avoid contamination of the natural ecosystems, some unpleasant accidents are inevitable, especially in the coastal zones.

5.12 Sierra Madre del Sur

5.12.1 Topography

The Sierra Madre del Sur is a mountainous region stretching along the southern pacific coast of Mexico. In the north, it borders the Transmexican Volcanic Belt (TMVB), in the east the Southern Coastal Plain of the Gulf of Mexico with the Ridges of Chiapas and Guatemala and the Central Cordillera, and in the south and in the west the Pacific Ocean. It includes partly such states as Oaxaca, Guerrero, Michoacán, Colima, Jalisco, and Nayarit. This region, considered to be the most complex and least understood of the country, owes much of its particular features to the proximity of the Cocos Plate, one of the active tectonic plates of the lithosphere (Centeno-García 2004). This major tectonic plate determines the predominantly east–west orientation of the mountain ranges in this region, in contrast to the northern part of the country. The continental mountain ranges of the Sierra Madre del Sur have altitudes that in places exceed 3,500 m asl, and the highest point reaches 3,703 m above sea level. These mountain ranges are dissected by deep river canyons that play an important role in the intense erosive processes. The mountains rise steeply very close to the coastal line, leaving practically no space for the development of a coastal plane. The highest mountains are concentrated in the eastern part of the region in the Oaxaca State. The same portion of the region has the most complex topography. Between the high ranges facing the Pacific Ocean and the Gulf of Mexico, there are dry valleys with a system of ridges of lesser elevations.

To a great extent, the relief of the region has been formed by neotectonic activity that started in the Miocene period. Thus, its structural–geomorphological expression reflects the coexistence of ancient tectonic styles, transformed by the active neotectonic style, and composed of groups of blocks which are differentially displaced both vertically and horizontally (Krasilnikov et al. 2011). Weathering and planation processes modified the topography of the region, but still the tectonic nature of the landscapes is evident.

5.12.2 Geology

From a structural–geological and geomorphological point of view, the Sierra Madre del Sur mountain range is one of the most complex territories of the North American Pacific Rim (Centeno-García 2004). The major part of the mountainous system is composed of metamorphic rocks. A common opinion exists that the three Sierras Madres of Mexico differ in their composition: the Western is composed of igneous rocks, the Eastern one of sedimentary rocks, and the Southern Sierra Madre of metamorphic rocks (López-Ramos 1982). This opinion is true to a great extent, though significant exceptions exist. There are extensive inclusions of rocks of other origin in each of the mountainous systems. The geological structure of the ancient system of Sierra Madre del Sur was formed by the following sequence of geological materials. The first structure to form was the so-called "Oaxaquia" Proterozoic paleocraton, an ancient continent composed of gneisses and amphibolites. The next step was the formation of the Paleozoic metasedimentary and igneous rocks, followed by Mesozoic metasedimentaries, metamorphosed volcano-sedimentaries, granitoids, and serpentines. In the Cretaceous period two series of rocks formed: quartz-feldspathic ortogneisses and serpentines, diorites, gabbros, lutites, and sandstones. Apart from the mostly metamorphic rocks, there are extensive inclusions of sedimentary rocks, for example, of limestones that constitute a big part of Sierra Mixteca. The Quaternary sediments are represented by deposits in the toeslope positions and the alluvial sequences of sediments that are common in all the valleys in this mountainous system.

5.12.3 Hydrology

The largest river system in the region is the Tepalcatepetl; another important system is the Balsas River, one of the seven largest in the country. In the eastern part of the region, the major tributaries of Papaloapam and Tehuantepec rivers originate. On the southern slopes of the region, a number of short rivers drain to the Pacific Ocean. Few of them, like the Armory, the Coahuayana and Papagayo originating north of the boundary of the Coast Range and the Atoyac flow from the Central Valley of Oaxaca. A number of streams are flowing to the basin of the Gulf of Mexico from the northern range Sierra Norte de Oaxaca. The streams starting in the mountains commonly have water of good quality.

5.12.4 Climate

The region possesses a wide range of climates. The variation of climate of the region is due to its complex topography and the air circulation related to the Pacific Ocean and the Gulf of Mexico. At the Pacific slope of the mountainous system, the climates are characterized as hot subhumid, with increasing elevation they alter to temperate humid and cold subhumid. In the inner part of the system the climates are hot arid and subarid. On the escarpment oriented toward the Gulf of Mexico, the climates are cold and temperate extrahumid at higher elevations and hot humid at lower altitudes. The dynamics of precipitation is more or less similar all over the region with dry winter and rainy summer except the eastern extrahumid escarpment, where the rainfalls are abundant throughout the year.

5.12.5 Vegetation

The variety of climates determines the richness of ecosystems. According to Rzedowsky (1983) the major ecosystems present in the regions are: tropical rain evergreen forest, semidecduous tropical forest, deciduous tropical forest, montane cloud forest, pine and pine-oak forest, and matorral (shrublands). The distribution of these vegetative communities is complex and follows general gradients of climatic conditions. A significant part of the natural ecosystems actually is displaced by arable lands and pastures.

The fir is distributed between 2,500 and 3,000 m asl, where the predominant climate is temperate humid and the dominant species is *Abies hickelli*. The juniper forest occurs

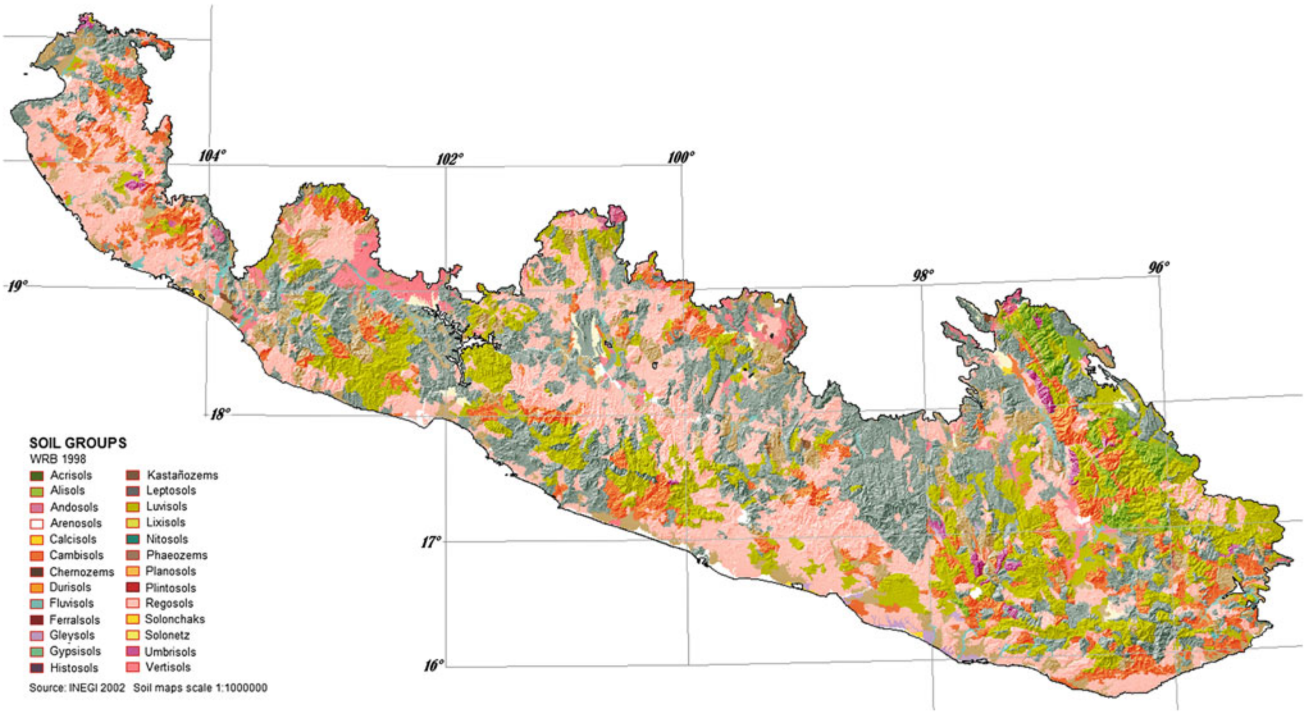


Fig. 5.21 The soil map of the physiographic region of the Sierra Madre del Sur. Reproduced with a permission of INEGI

between 1,800 and 2,500 m asl under semiarid temperate climates with the dominant arboreal species *Juniperus flaccida*. The deciduous forest grows between 600 and 2,000 m where the climate is temperate; it consists mainly of the species of the genus *Liquidambar*, *Platanus* and *Alnus*. The cloud forest is located at the humid slopes and gullies of the Sierra Sur de Oaxaca between 1,000 and 2,500 m asl with frequent fog and drizzle. The trees with heights from 7 to 20 m are represented by numerous species; some examples include *Quercus candicans*, *Pinus patula*, *Liquidambar* spp., *Weinmannia pinnata*, *Ternstroemia sylvatica*, *Persea* sp., *Matudae podocarpus*, *Clethra* sp., and *Saurauia* spp. Epiphytes are the most diverse groups in this type of vegetative community. Variations of this forest are stunted communities established in the peaks of the Sierra Mazatec, Mixe and Juárez at elevations around 2,500 m asl. It consists of trees 4–6 m high with such species as *Weinmannia glabra*, *Gaultheria odorata*, *Lyonia squamulosa*, *Pinus oocarpa*, *Clethra mexicana*. Other variants at lower elevations in the Sierra Juárez and Mexican Mazatec include trees 30–60 m high with such representative species as *Oreomunnea mexicana*, *Quercus candicans*, *Magnolia schiedeana*, *Persea* sp., *Billia hippocastanum*, and *Podocarpus matudae*. Oak forest occupies large areas between 1,600 and 2,900 m asl, in a humid temperate climate. Semideciduous forests grow at the altitudes between 500 and 1,500 m asl on the Pacific slopes of the mountains; the typical arboreal species are *Brosimum alicastrum*, *Enterolobium cyclocarpus*, *Pterocarpus acapulcensis*, *Bursera simaruba*, *Caesalpinia coriacea*, *Ceiba pentandra*, *Cordia aliodora*, and *Ficus* spp. The Sierra Madre del Sur has been ranked as one of the richest floristic regions of the world with a high degree of endemism. The predominant vegetation in the depression of the Balsas and Southeast regions of the province is lowland deciduous forests of oak and pine at the higher elevations, and deciduous forest extending over the entire coast. The province hosts one of the richest floral communities of the world (Rzedowski 1983).

5.12.6 Soils

The sequence of soils generally follows the distribution of climates and ecosystems, but is more complex (Fig. 5.22a, b). In the terms of total areas, the major part of the region is

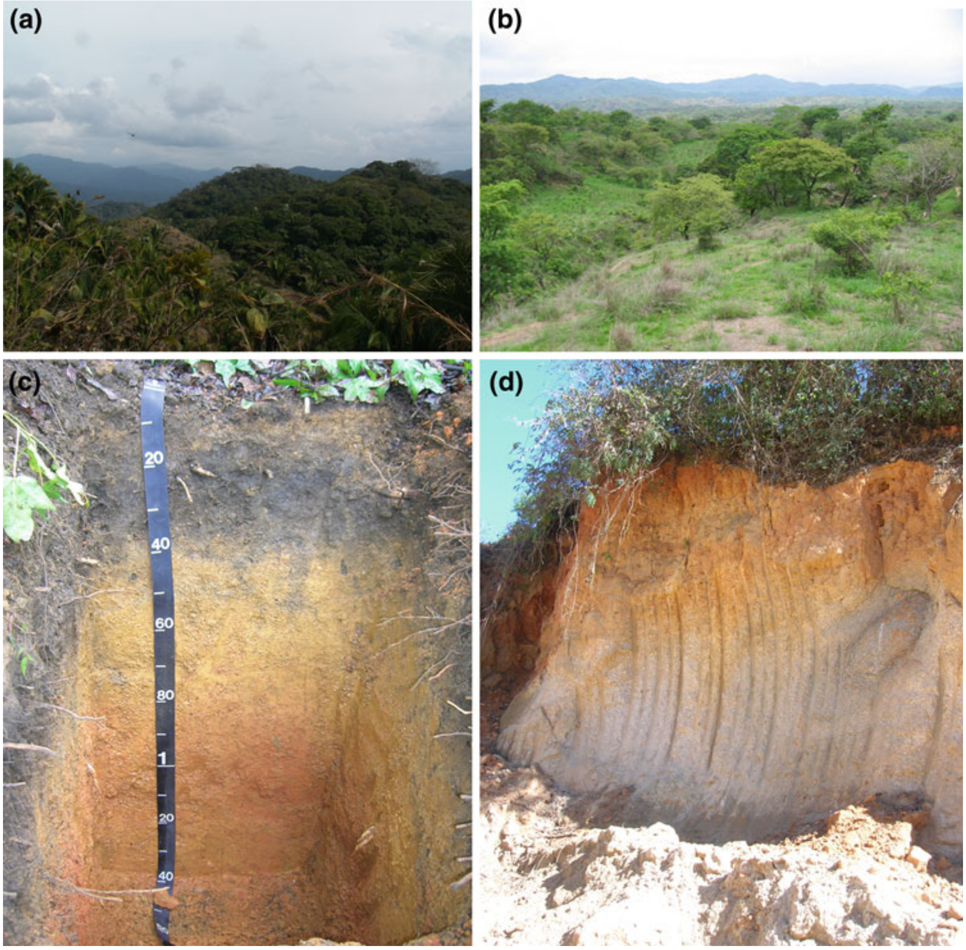


Fig. 5.22 Typical landscapes and soils of the physiographic region Sierra Madre del Sur: **a** High mountainous landscape near Ayutla, Jalisco; **b** Low mountainous landscape near Zacatepec, Oaxaca; **c** Alisol/Udult at the watershed Agua Fría, Juxtlahuaca, Oaxa; **d** Roadcut with a complete weathering profile near Tonala, Jalisco (photo by P. Krasilnikov)

occupied by texturally differentiated soils (Luvisols and Alisols/Udalfs), humus-enriched soils (Phaeozems/Udolls) and brown poorly differentiated soils (Cambisols/Dystrudepts) (Fig. 5.21). The spatial distribution of soils in the region was interpreted in several papers (Krasilnikov et al. 2005, 2009, 2011). In a traverse across the entire region starting from the Pacific slope, each altitudinal belt and ecosystem was characterized by specific soil associations. The lowest zone of xerophyllous deciduous forest has poorly developed soils, Cambisols and Regosols/Dystrustepts, and Othents. The altitudinal belt of semideciduous tropical forests has a complex mosaic of deeply weathered leached soils with expressed clay illuviation (Alisols/Udalfs and Udults) and soils with organic matter accumulation (Umbrisols and Phaeozems/Dystrustepts and Udolls), which vary in the intensity of humus accumulation and leaching of bases. Under the pine and pine-oak forests the dominant soils are Luvisols/Udalfs that are characterized by expressed features of clay illuviation, moderate humus accumulation and relatively high base status (Fig. 5.22c). At the highest elevations under pine stands are Umbrisols/Dystrudents, acid soils with deep humus penetration with no clay illuviation.

The inland slope of Sierra Sur de Oaxaca has a small portion of Luvisols/Udalfs under pine-oak forests at high elevations. The sediments of the valleys are mostly of fluvial origin, and the soils found at the surface form a puzzle of recent poorly developed Fluvisols and Regosols/Fluvents and Orthents and exhumed paleosols. The latter ones are represented with Vertisols and soils enriched with humus and composed partly of expanding clays. The stage of development of the recent surface soils increases from the most arid southern parts of the valleys that are hotter and protected from humid air coming from the Pacific Ocean by the mountain ridge Sierra Sur de Oaxaca, to the northern cooler and slightly warmer part. In the northern part of the traverse, the escarpment oriented toward the Gulf of Mexico is characterized by an extrahumid climate that determines the development of montane cloud forest ecosystems. The soils of the altitudinal belt of montane cloud forests of Sierra Juárez have been described in detail in an earlier publication (Álvarez-Arteaga et al. 2008). Pedogenetically, these peculiar soils show features of podzolization, surface gleying and intensive ferrallitic weathering, and formally are classified as Podzols/Spodosols. At lower elevations, initially occupied by tropical rain forests, the soils are mainly strongly weathered Ferralsols/Oxisols. Due to intensive erosional processes shallow soils are common throughout the region.

5.12.7 Soil Use, Degradation, and Management

Agriculture prevails on flat and slightly inclined areas, focusing primarily on the intermountain valleys and coastal plains south and east of the entity. Representative crops include maize, beans, alfalfa, coconut, pineapple, and banana. In the mountains, coffee growing under the shade of natural vegetation is a common practice. In the intermountain dry valleys previously sugar cane was an important commercial crop, but due to increasing aridization of the climate it is practically absent. Agricultural practices are also carried out on land unsuitable for crop production, which has led to the deterioration and soil erosion over large areas of the region area. At the Pacific slope of the Sierra Madre del Sur, the erosion is especially strong due to frequent hurricanes that cause windfalls and quick formation of gullies. Furthermore, seismically induced landslides cause problems.

5.13 Central American Cordillera

5.13.1 Topography

This region starts at the Isthmus of Tehuantepec and extends to the Republic of Nicaragua through the territories of Guatemala, Honduras, and El Salvador (Ramírez-Cayetano 2011). In the north it borders with the region of the Southern Coastal Plain of the Gulf of Mexico up to the isthmus and the Ridges of Chiapas and Guatemala, in the west with the Sierra Madre del Sur and in the south with the Pacific Ocean. The elevations vary widely from almost sea level at the coast to the altitude of more than 2,000 m. The uppermost peaks of this mountainous system are found further to the south, in Guatemala, where young volcanoes emerge to the altitude of more than 3,000 m asl.

5.13.2 Geology

Despite being a relatively small region, the Central American Cordillera has a very heterogeneous geology. Intrusive and extrusive igneous, sedimentary and metamorphic rocks are located in close association. Sierra del Soconusco, the mountain range that runs longitudinally through the center in a NW–SE direction, is mainly composed of granite intrusive rocks of the Paleozoic era. It is a large igneous batholith that emerged because of the subduction of the

Cocos plate. In most parts of Chiapas, this igneous intrusive body is exposed to the surface, but the territory close to the Tacana volcano is completely covered with extrusive rocks and pyroclastic deposits of young volcanoes, most of which are located outside the Mexican territory. In the northeastern portion of the region, there are Mesozoic sedimentary rocks (sandstone); in the eastern part lies a major area of Paleozoic limestones. Extensive Quaternary alluvial deposits, lake and marsh deposits lie at the coast, from south of the Isthmus of Tehuantepec to the Guatemala border.

5.13.3 Hydrology

The region is divided into two major hydrological units. The first collects the water that goes to the west to the Tehuantepec isthmus and then flows to the Gulf of Tehuantepec in the Pacific Ocean. The Tehuantepec River is 240 km long; the other rivers of the same basin include the Tequisistlán, Perros, Espiritu Santa and Ostuta. Other rivers flow directly to the Pacific Ocean in a southern direction. The most important river among these is the Suchiate with an approximate length of 300 km from its source in the Guatemalan portion of the Sierra Madre de Chiapas until it empties into the Pacific Ocean. The other rivers that fall directly to the ocean are the Tapanatepec, Arenas, La Punta, Sanatengo, Jesus, El Porvenir, San Diego, Pijijiapan, Margarita, Coapa, Novillero Alto, Sesecapa, Cacalutla, Despoblado, Huixtla, Huehuetán, Coatan, Puerto Madero, Cozoloapan, and Cahuacán Rivers. The major lakes include Laguna Superior that covers a significant portion of the Itsmus Plain, Lower Lake Dead Sea Lake, Laguna de Viejo y Temblader and the Laguna de la Joya.

5.13.4 Climate

The major part of the region has hot humid and subhumid tropical climates. In the foothills of the mountains and along the coast the climate is hot and humid, with a mean temperature above 26 °C and annual precipitation above 2,500 mm. In the alluvial zone, starting from Tonala, Chiapas to the border with Guatemala, the climate is slightly drier. Also drier areas with annual precipitation of 1,200–1,500 mm are located at the eastern end of the region, near the central depression of Chiapas. Subhumid

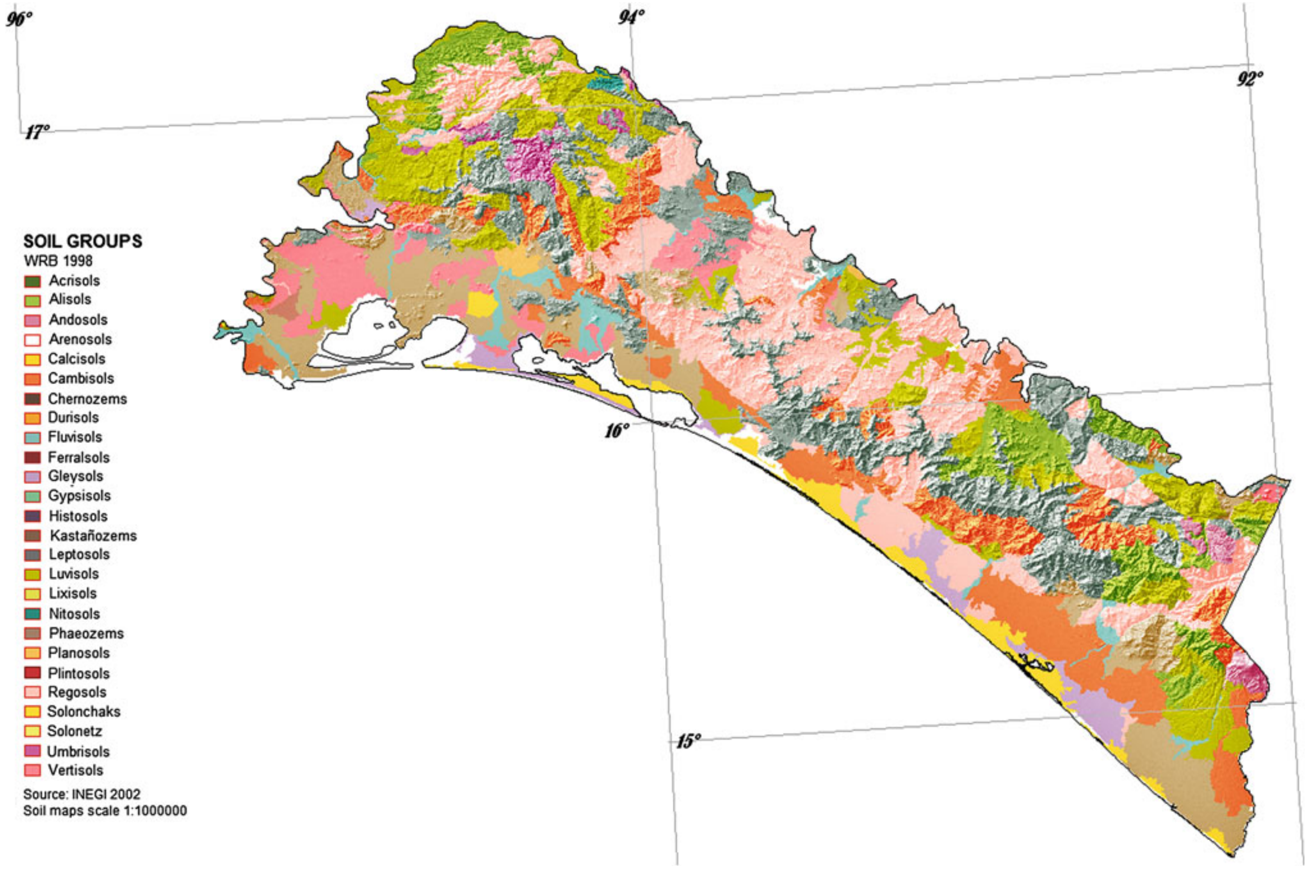


Fig. 5.23 The soil map of the physiographic region of the Central American Cordillera. Reproduced with a permission of INEGI

areas are also linked to the Isthmus of Tehuantepec, where the annual precipitation varies from 1,000 to 1,200 mm. In the mountains, the climate may be much wetter. For example, montane cloud forests form in cool extrahumid conditions of high air humidity and cloud cover most of the year. The altitudinal limit coinciding with these conditions are between 1,000 and 2,400 m asl. Lower mountainous slopes commonly have temperate subhumid climates.

5.13.5 Vegetation

Significant variations in the humid and hot conditions result in the diversity of vegetative communities in the region. Tropical rain forests occupy extensive areas mainly at the foothills of the mountains and parallel to the coast (Ramírez-Cayetano 2011). Recently, large areas of land have been incorporated into agriculture and livestock production; very few primary tropical rain forests can be found. There are relicts of this forest in the coffee groves near the volcano Tacana, near Tapachula.

In the recent past, semideciduous forest existed in all the territory that is now occupied by induced grasslands and plantations (banana or mango). The trees of *Ceiba pentandra* that commonly persists are a reminder of what human activity has destroyed. Tropical deciduous forest form in slightly drier conditions than the communities mentioned above. In the region, some representative species of these ecosystems are copal (*Bursera* spp.) and pochote (*Ceiba parvifolia*). The communities of low thorn forests have a similar appearance to the tropical deciduous forest. The thorn scrub has a lower canopy (<4 m) and branches from the very base; these trees belong mainly to the *Mimosaceae* family. The species typical for the cloud forest in the region are *Liquidambar styraciflua*, *Agnus arguta* and *Quercus* spp. There are also pine and oak forests that commonly occupy the elevations between 600 and 2,600 m asl. These communities form either dominantly oak, pine, or mixed pine-oak stands. At the top of the volcano Tacana, there are high mountain meadows with herbaceous plants and shrubs; the representative grasses are of the genus *Muhlenbergia*, *Trisetum*, *Calamagrostis*, *Agrostis* and some mosses. The savannah in this region is dominated by *Poaceae* grasses

Fig. 5.24 Typical landscapes and soils of the physiographic region Central American Cordillera: **a** Landscape with Acrisols/Udults, Arroyo Nueva Palestina, Chiapas; **b** Landscape with immature soils used for agriculture; **c** Haplic Regosol (Eutric)/Udorthent, Nueva Tenochtitlán, Chiapas; **d** Humic Gleysol/Aquoll, Lago Pampa Castaco in Buenavista, Chiapas (photos by Carlos Omar Cruz-Gaistardo)

(26 species) belonging to the genera *Andropogon*, *Asistida*, *Bouteloua*, *Cenchrus*, *Digitaria*, *Hackelochloa*, *Heteropogon*, *Hyparrhenia*, *Panicum*, *Paspalum*, *Schizachyrium*, *Tharasya*, *Trachypogom* and *Urochloa*, and *Cyperaceae* (11 species) and the genera *Abildgaardia*, *Bulbostylus*, *Cyperus*, and *Rhynchospora*. *Asteraceae* (15 species) and *Fabaceae* (25 species) are also very common. Mangroves are often found in places subject to flooding and therefore under anaerobic conditions. The most characteristic species of mangrove are red mangrove (*Rhizophora harrisonii*) and two species of black mangrove (*A. germinans* and *Rhizophora bicolor*). Popals or marsh vegetation are plant communities that inhabit large areas of freshwater and brackish water marsh. They can be found as pure clusters of red stemmed thalia (*Thalia geniculata*), *Calathea*, and *Heliconia* or mixed with other grasses and sedges.

5.13.6 Soils

The most abundant soils in the region are shallow and undeveloped soils (Leptosols/Lithic groups and Regosols/Orthents) that occur because of erosional processes in this mountainous area (Figs. 5.23, 5.24). The other important soil groups include soils with textural differentiation such as Luvisols, Acrisols and Alisols/Udalfs and Udults, soils with humus-enriched topsoil such as Phaeozems and Umbrisols/Udolls and Dysrudepts, alluvial and coastal sandy soils Fluvisols and Arenosols/Fluvents and Arents and some other groups. A peculiar feature of the region is the presence of tropical soils such as Nitisols/Kanhapludults and Plinthosols/Plintudults. These soils are indicative of the hot tropical climate of the region. However, their limited distribution reflects the youth and high dynamics of the landscapes of the region.

5.13.7 Soil Use, Degradation and Management

About 20 % of the territory of the region is used for agriculture. Although the amount does not seem very high, the development of agricultural activity has strongly affected the natural ecosystems, especially the most fragile tropical rain forest. The absolute majority (around 95 %) of the agriculture is rainfed, and the remainder is irrigated. In the portion that corresponds to the Istmus of Tehuantepec the most important crops are corn, coffee, sorghum, mango, sesame, beans, oranges, agave, and vegetables; significant territories are used for pasture. In the Chiapas state, the most important crops are corn, coffee, cherries, mango, soybeans, beans, oil palm, sesame, sugarcane, cocoa, bananas, and vegetables, also with extensive areas of pastures.

The main negative process that occurs due to the deforestation is the development of gully and rill erosion.

5.14 Transmexican Volcanic Belt

5.14.1 Topography

The Transmexican Volcanic Belt is one of the most characteristic and important regions of Mexico that crosses the country from east to west. It is the cradle of Mexican civilization, where a number of pre-Classical, Classical, and post-Classical cultures developed, and the location of the capitals for both the Aztec empire and the Mexican state—Tenozhitlan, or Mexico City. The importance of volcanic sediments and soils for the development of this civilization is discussed in Chap. 7.

The relief of the Transmexican volcanic belt is mostly mountainous; it was created by numerous volcanic cones. This region has the highest peaks in the country, including Pico de Orizaba (5,610 m asl), Popocatepetl (5,465 m asl), and Iztaccihuatl (5,286 m asl). However, the abundance of pyroclastic sediments forms a very specific gentle topography with almost no angular abrupt forms of relief in the major part of the region. The contrast in the morphology of the relief is evident, for example, at the border between the Transmexican Volcanic Belt and Sierra Madre del Sur. The cones of the volcanoes are separated by gentle valleys, some of them with lakes and rivers.

5.14.2 Geology

The very name of the region indicates that the region has been formed due to recent geological events. According to Demant (1982) the formation of the whole region started due to the relative motions of the North-American and the Carribean plates, and the change in the rotation angle of the Cocos plate in the Oligocene and Miocene periods. These tectonic events started a period of strong volcanic activity in the region that is present even today. The intensive volcanic activity resulted in the formation of both extrusive and pyroclastic rocks all over the region. The same volcano could produce different types of eruptions. Many important volcanic cones such as Popocatepetl or Colima are stratovolcanoes, i.e., have interlayered extrusive rocks and pyroclastic sediments. The composition of the lavas was different in different parts of the region. The western section of the Belt related to the Tepic-Chapala graben has olivine basalts, andesites, and dacites. The other section is associated with the Colima graben, and it is characterized by calc-alkaline volcanic rocks. Finally, the central and the eastern parts of the region are characterized by basaltic and andesitic volcanism with single rhyolite cones. The western part of the region has more volcanic cones (up to 3,000 in Michoacán) because the Earth's crust is much thinner in the western part of the region. All the extrusive products are mixed with and covered by pyroclastic sediments of various ages and compositions. Active volcanoes like Popocatepetl continuously produce volcanic ash that accumulates on the surface even nowadays.

5.14.3 Hydrology

There are many rivers in the trans-Mexican Volcanic Belt that penetrate deeply into the soft ashy sediments. The rivers flow either to the Pacific Ocean or to the Gulf of Mexico due to the transversal orientation of the mountainous chain. The biggest river is Rio Lerma (708 km) that flows into the Chapala Lake and then, under the name Rio Grande flows into the Pacific Ocean. There are many lakes and wetlands in the region that form in the broad and flat valleys. Apart from Lake Chapala, the largest in the country, there are several important lakes in Michoacán state: Pátzcuaro, Cuitzeo, and Zirahuén. Although these lakes are shallow, they are used for fisheries and even serve as sources of water for household use. The other evident example of a system of lakes was in the center of the Valley of Mexico. Only a small portion of the Xochimilco and Chalco lakes persisted, while the major Texcoco lake completely dried. Furthermore, there are some dry lacustrine valleys that partly fill with water only during the rainy season. The biggest valley of this type is Laguna de Totolsingo in Puebla State. The weathering of volcanic ashes produces bases that react readily with carbonate ions. Thus, the waters of the lakes in the trans-Mexican Volcanic Belt have high mineralization and are affected by high sodicity.

5.14.4 Climate

The climate of the region is variable depending on the altitude and orientation of the slopes. The central part of the region has a temperate climate with a maximum of precipitation in the summer. In this continental part of the region, the climate is subarid to subhumid in the valleys but the humidity of the climate quickly increases with elevation. In this region, as in many other parts of Mexico, the rule "dry valleys—humid forested mountains" is quite evident. The winter is usually cold because of "nortes"—cold masses of air that penetrate between the big ranges of the Sierra Madre Occidental and Oriental until they reach the Mexico City. The climate is colder on the slopes of the big volcanoes; the tops of the peaks higher than 4,500 m asl are always covered with snow. The southern slope of the mountain chains is much warmer. The hottest climate is recorded in the western slope of the region in the Presa de Infernillo (Michoacán state), where the deep valley of the Transmexican Volcanic Belt meets the region of the Sierra Madre del Sur. The slopes oriented toward the Pacific Ocean and the Gulf of Mexico show a regular increase in the temperature with decreasing elevation (e.g., see Fuentes-Romero et al. 2004). The amount of precipitation has a maximum at the altitude between 1,000 and 1,500 m asl, where the hot air from the sea discharges the rain.

5.14.5 Vegetation

The region possesses a wide range of vegetative communities, where we note only the most important ones. Oak forests form between 1,500 and 3,000 m asl, on steep slopes, including rock outcrops, under subhumid temperate and tropical climatic conditions. The medium height of the trees varies between 15 and 25 m. The dominant species are *Quercus rugosa*, *Q. laeta*, and *Q. mexican*a, accompanied by the species of the genera *Arbutus*, *Buddleia*, *Alnus* and *Cupressus*. The shrub layer is comprised of different species of the families of *Compositae*, *Labeate*, *Graminae*, and *Leguminosae*. The fir forest forms in the areas with cool climate, usually above 2,000 m asl. The dominant species is fir tree (*Abies religiosa*), which reaches 30 m high. This plant community has an ecotone with the pine forest, so it is common found in belts where *Pinus* species are mixed with fir. On the soils, there are mosses representative of the families *Asteraceae* and *Gramineae*. Montane cloud forest is restricted to the moist slopes oriented toward the Gulf of Mexico. Commonly, they form between 1,900 and 2,500 m asl. Physiognomically it is a dense forest with trees between 15 and 20 m in height, has a low tree layer, and a well-defined shrub layer. The herbaceous layer is lush, with a large number of species. The amount of bryophytes and pteridophytes is high, and there is an abundance of climbing, including *Rhus* sp. and epiphytes of the families *Orchidaceae*, *Piperaceae* and *Bromeliaceae*. Within the tree layer, species include the genera *Quercus*, *Clethra*, and *Prunus*. The mixed forest includes mixed communities of different species of pine, oak, and fir in different proportions, and separating various species is difficult. The pine-oak forest is distributed from 2,800 to 2,950 m asl and grows in temperate and humid conditions. *Pinus* and

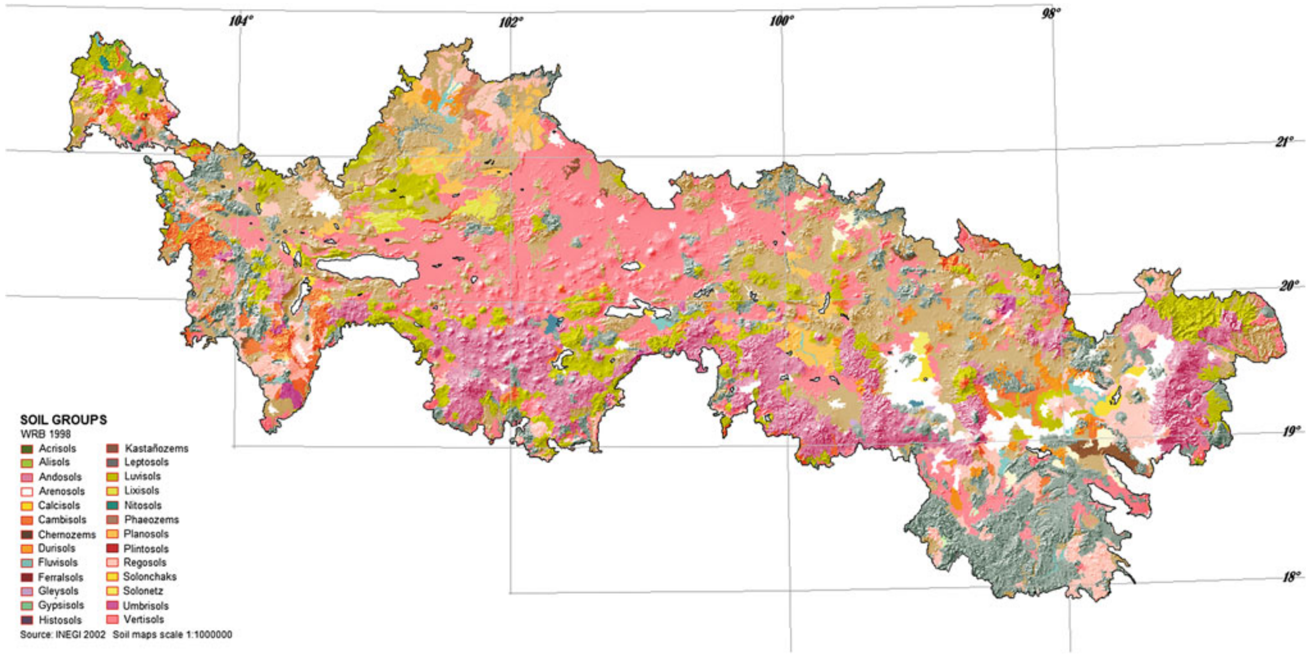


Fig. 5.25 The soil map of the physiographic region of the Transmexican Volcanic Belt. Reproduced with a permission of INEGI

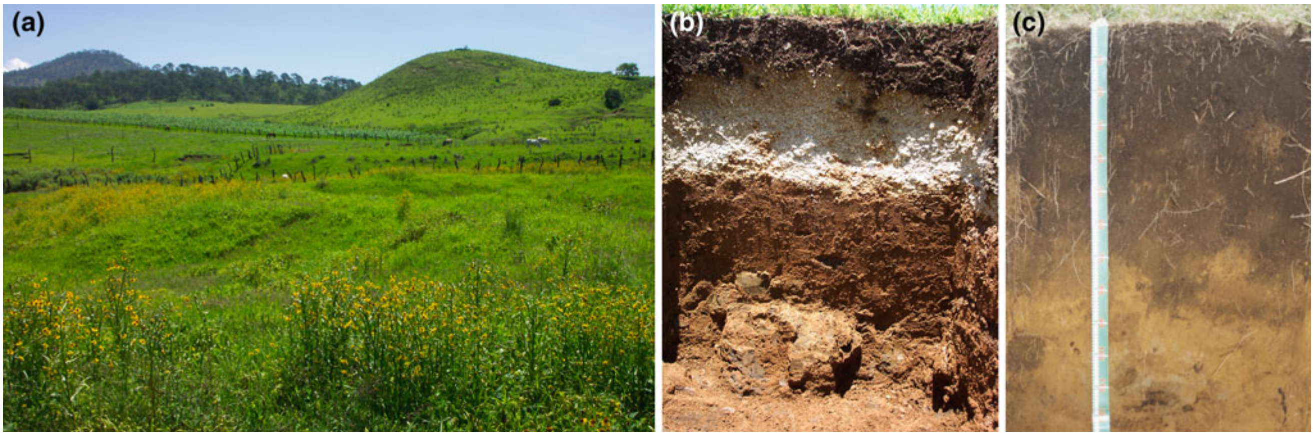


Fig. 5.26 Typical landscapes and soils of the physiographic region Transmexican Volcanic Belt: **a** Landscape with young volcanic soils, La Estanzuela, Nayarit; **b** Young volcanic soils with different ash layers, La Estanzuela, Nayarit; **c** Andosol/Udand, Totutla, Veracruz (photos contributed by Jesús Solano-Ruiz and Carlos Alberto Saracco-Alvarez)

Quercus in this vegetation community are commonly accompanied by the species of the genera *Arbutus*, *Buddleia*, *Alnus* and *Cupressus*. The deciduous forest grows at the altitudes ranging from 1,300 to 1,900 m asl, commonly on shallow and stony soils on hillsides. Some of the representative species are copal (*Bursera fagaroides, Bursera jorullensis, Bursera trimera*), acacia (*Acacia farnesiana*), casahuate (*Ipomoea wolcottiana*), tepehuales (*Lysiloma acapulcensis*), and yellow amate (*Ficus petiolaris*).

The xerophyllous shrublands are communities of temperate climates and thrive in dry plains, hills, and mountains. The dominant life forms in this community are shrubs no more than 5 m high with small leaves, or even spines. Commonly found species include the family of cacti such as nopal (*Opuntia* spp.), others such as powdery mildew (*Zaluzania august*), cat's claw (*Mimosa aculeaticarpa biuncifera*), sangre de drago (*Jatropha dioica*), maguey (*Agave* spp.) and yukkas (*Yucca filifera*). The arboreal species include pepper tree (*Schinus molle*) and mesquite (*Prosopis glandulosa*). Natural grasslands include the representatives of the genera *Bouteloua*, *Andropogon*, *Aristida*, *Cynodon*, *Eragrostis*, and *Stipa*. The high mountain pastures, also called alpine meadow, develop in cold areas above the limit of tree vegetation, at altitudes exceeding 3,000 m. Among the most abundant species are eryngo (*Eryngium bomplandi*), spreading sandwort (*Arenaria lanuginosa*), reedgrass (*Calamagrostis tulecensis*), thistle (*Cirsium nivale*), fescue (*Festuca livida*), Longspur lupine (*Lupinus montanus*), and mountain muhly (*Muhlenbergia montana*).

5.14.6 Soils

Practically, all the soils in the trans-Mexican volcanic belt are derived from the volcanic materials, mostly of pyroclastic materials, because the consolidated extrusive rocks have not had sufficient time for deep weathering needed to produce enough fine earth for deep soils. However, the specific "volcanic" taxa (Andosols/Andisols) do not comprise the majority of the soils in the region (Fig. 5.25). The majority of the soils are too young or too old to be classified as volcanic, though in a broad sense they are all formed in volcanic ash (Fig. 5.26). The majority of the soils of the region are classified as Phaeozems/Udolls and Ustolls. These soils form either in fresh volcanic sediments that accumulated organic matter, but are not weathered enough yet to produce X-ray amorphous constituents (see Chap. 4 for details), or in developed substrates where allophone-like materials already crystallized to form halloysite. The development of Andosols/Andisols after the crystallization of clays in the Transmexican Volcanic Belt leads to the formation of texturally differentiated soils in the watersheds, and of Vertisols in the valleys. Since initially many volcanic soils accumulate organic matter in the topsoils, they are later commonly classified as Phaeozems/Mollisols even if clay illuviation occurs in the profile. Thus, the most abundant soils in the region are Phaeozems/Mollisols, Luvisols/Alfisols, Andosols/Andisols, and Vertisols, all of them representing the same evolutionary sequence. The spatial distribution of soils however, still depends on the climatic conditions and ecosystems: the most weathered and illuviated soils occur in the hottest and the most humid regions. In the subarid central part, the soils commonly have calcium carbonate and even gypsum and soluble salts accumulations, but much depends on the local peculiarities of geochemical fluxes.

5.14.7 Soil Use, Degradation, and Management

The region has a well-developed agriculture. The most traditional crops are corn, beans, chilly, sunflower, and soybeans. At high elevations potatios is successfully grown. In warmer areas, on the slopes oriented toward the Gulf of Mexico and the Pacific Ocean, coffee is grown. In the arid and subarid parts of the region maguey and nopal are important products. The pastures are extensive, they are used mainly for cattle.

The main problem for the region is the development of slope processes. The volcanic soils *sensu stricto* (Andosols/Andisols) are less affected by water erosion than other soils due to their high water-holding capacity, but the same property provokes landslides if these soils are oversaturated. The soils with crystallized clays, such as Luvisols/Alfisols or Phaeozems/Mollisols are easily eroded, and extensive gullies represent an unpleasant common landscape of the region. The arid and subarid territories, especially if water bodies existed in the broad valleys, show evidence of salinization and sodification that may cause local problems with agricultural production.

5.15 Sierra Madre Oriental

5.15.1 Topography

The region of Sierra Madre Oriental is about 1,350 km length and stretches in the meredional direction along the coast of the Gulf of Mexico from the northern border of the country to the border with the Transmexican Volcanic Belt. In the northern and northwestern part it borders with the region of the Uplands and Lowlands of the North, in the west with the Central Mesa, and in the east with the Great Plain of Northern America and with the Northern Coastal Plain of the Gulf of Mexico. The region covers parts of the states of Durango, Coahuila, Zacatecas, Nuevo Leon, Tamaulipas, San Luis Potosi, Guanajuato, Queretaro, Veracruz, Hidalgo, and Puebla.

It is a mountainous region with strongly folded sedimentary rocks, mainly consisting of limestone. In general, the altitudes at the summits of the Sierra Madre Oriental range from 2,000 to 3,000 m asl, but the highest peak Cerro San Rafael, which is located between Saltillo and Ciudad Victoria, reaches 3,713 m asl. The mountainous ridge has a towering cliff on the Northern Coastal Plain of the Gulf, but the transition toward the Central Mesa and the Transmexican Volcanic Belt regions is less steep.

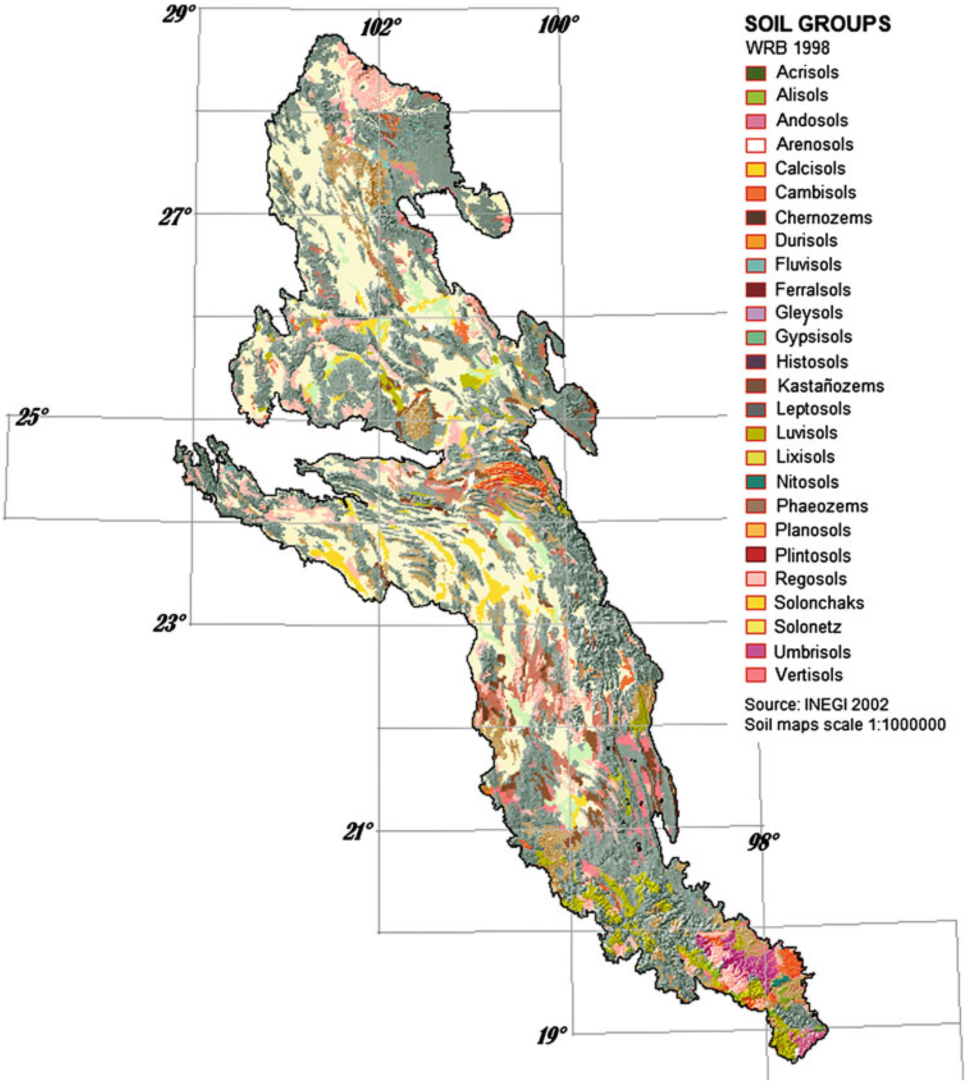


Fig. 5.27 The soil map of the physiographic region of the Sierra Madre Oriental. Reproduced with a permission of INEGI

5.15.2 Geology

The Sierra Madre Oriental is a strongly folded structure derived of marine sedimentary rocks of Jurassic and Cretaceous age. The tectonic deformation that formed the mountainous range occurred in the Eocene epoch during the so-called Laramide orogenetic stage. The dominant material is limestone followed by the sandstones and shales. Common sediments are also represented by the sequences of lutites and sandstones, outcrops of rhyolites, alluvial deposits, and conglomerates. The sedimentary column is about 3,000 m in depth. The Cretaceous sedimentary rocks are the thickest and contain ground water in their karsted units. Due to the abundance of limestone in the region, karst manifestations are common, particularly in the middle and southern portion of the region. Intense infiltration of water into the subsoil has made very extensive cave systems and has also generated copious springs, especially at the foot of the mountain, such as “El Paraiso” located in the vicinity of the Ciudad Mante. These mountains were more eroded than other mountainous systems of Mexico due to erodibility of the rocks that resulted in smoother slopes of the mountains.

5.15.3 Hydrology

Since a significant part of the region has arid and semiarid climates, there is no major drainage network. Furthermore, the hydrographic net is not very pronounced partly due to the effect of karst. For example, some rivers disappear underground and then appear at the toeslope of the mountains on the coastal plain of the Gulf of Mexico. The biggest river, collecting the superficial waters of Sierra Madre Oriental, is Pánuco, which flows into the Gulf of Mexico near the port Tampico-Madero.

5.15.4 Climate

Climates vary over a wide range of temperature and precipitation. The climate is getting wetter and hotter from west to east. The annual precipitation increases from 300 mm in San Luís Potosí to 1,500 mm in Tamasopo, and the mean annual temperature increases from 16 °C in San Luís Potosí to 22 °C mm in Tamasopo. On the slopes oriented toward the Gulf of Mexico, the amount of precipitation is high because of the effect of atmospheric discharge on the cool mountainous slopes. In the inland territories, the climate is dry because the humid air cannot penetrate the high mountains.

5.15.5 Vegetation

Sierra Madre Oriental is the region of a high diversity of flora and fauna with a number of endemic species. The plant communities of the Sierra follow the climate. In the western part of the region there are xerophyllous communities like desert scrub and submontane scrub vegetation. Near San Luís Potosí there are spots of shrub vegetation (matorral) of *Cracicaules* and *Yukka* sp. up to 6 m high. Induced grasslands and microphyllous matorral (shrubland) are found at the slopes, while in depressions there are halophilous vegetative communities. Also in the arid part of the region there are spots of desert microphyllous matorral dominated by creosote bush (*Larrea* sp.) and nopal (*Opuntia imbricate*). In the region between Saltillo and Monterrey there are oak and pine-oak forests. On the eastern slope of the southern part under the subhumid climates there are evergreen tropical forests, while on the western flanks of the Sierra there are deciduous and pine-oak forests. In the mountains is oak forest with endemic *Quercus potosina*. In places, the precipitation and air humidity is sufficient for the development of montane cloud forest, like in the national park "El Cielo".

5.15.6 Soils

The composition and properties of the soils of the region are determined by the abundance of limestone and other calcium-carbonate-rich rocks as parent materials. The main processes of soil formation are carbonate dissolution and in places the accumulation of organic matter. The most abundant soils in the region that occupy almost a half of the total area are Rendzic Leptosols/Rendolls. In the arid western part of the region, Calcisols/Calcids occupy significant areas (22.37 %), because calcium carbonate dissolution and precipitation is a common process in limestone-derived materials under arid and semiarid conditions (Fig. 5.27). The area occupied by other soils is much less than that covered by these two dominant groups. The development of deeper soils is commonly associated with the presence of silicate-containing sediments such as sandstones and shales, (i.e. the materials that can produce significant amounts of fine earth). Among these deep developed soils, the most abundant are the soils with humus-enriched horizon with or without secondary carbonates (Phaeozems, Chernozems and Kastanozems/Udolls, and Ustolls) that occupy about 10 % of the area of the region (Fig. 5.28). Less developed soils (Regosols and Cambisols/Orthents and Ustepts), and soils with textural differentiation (Luvisols/Ustalfs) cover just a few percent of the area. Furthermore, included are soils formed in gypsiferous sediments.

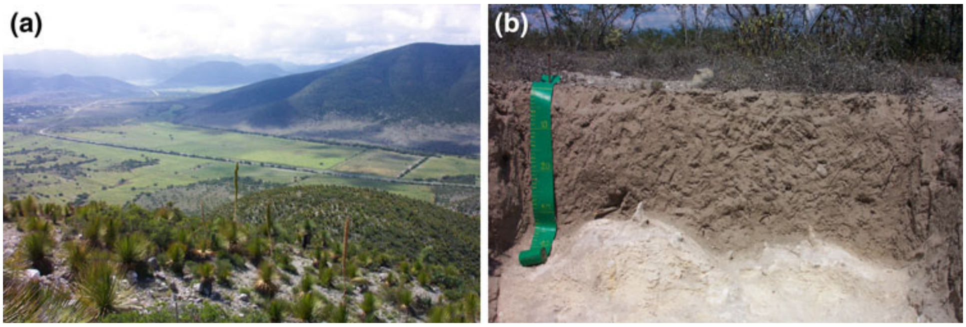


Fig. 5.28 Typical landscapes and soils of the physiographic region Sierra Madre Oriental: **a** Lanscape of the mountainous slopes with Petric Calcisols/Lithic Petrocalcic Calciustepts (**b**), Jaumave, Tamaulipas (photos contributed by Carlos Alberto Saracco-Alvarez and Arnulfo Valadez)

5.15.7 Soil Use, Degradation and Management

Due to the variation in the climatic conditions, there are two major types of agricultural activities in the region: rainfed and irrigated. In the northern part of the region, the irrigated agriculture supports the following crops: corn, beans, sesame, sugarcane, walnuts, oranges, lemons, avocados, soybeans, cotton, and mango. Rainfed crops include maize, beans, lentils, sorghum, chickpeas, and squash, but with low yields that are intended exclusively for consumption. On the hot and more humid side of the mountainous range, rainfed agriculture is developed in portions of the intermountain valleys and plains, on the mountains with steep slopes, convex slopes and limestone with sinkholes, where crop production is dependent on the amount of precipitation that occurs in the summer. Harvests that are obtained from sugar cane, corn, orange, and pasture, are fair to good.

In the inland areas, irrigated agriculture is developed on deep soils in flat areas to produce alfalfa, onions, chile, cabbage, tomatoes, lettuce, corn, oranges, and cabbage. Rainfed agriculture is practiced on the hills, plains and mountains on deep or shallow soils. The crops are oats, oat achicalada, peanuts, pumpkin, barley, beans, chickpeas, corn, and wheat.

The main limiting factor for agriculture is the shallowness of the soils. The degradation problems commonly include karst phenomena and the loss of soil structure that leads to soil compaction.

5.16 Yucatan Peninsula

5.16.1 Topography

The Peninsula of Yucatan is located in southeastern Mexico between 18° and 21°30′ N It borders the Gulf of Mexico in the west and the Caribbean Sea in the east. It is a region of low flat topography with elevations generally below 50 m asl (Bautista et al. 2005). The highest area lies in the center of the peninsula, and elevation decreases east and westward by abrupt steps (Bautista et al. 2011b). The low flat areas exhibit poor karst development, and the older more elevated plains and hills have pronounced karst phenomena. The relief of the region is also formed by tectonic fractures that give rise to aligned hills and dolines.

5.16.2 Geology

From the geological point of view, the Yucatan Peninsula consists of a platform with layers of calcium carbonate rocks. On the surface the age of such rock ranges from the Paleogene to Quaternary. The basement of the platform is Paleozoic, and is covered with a thick package of the Mesozoic and Cenozoic sediments more than 3,500 m thick. The Jurassic sedimentary rocks are covered with the Cretaceous limestones, dolomites, and gypsum. Paleogenic rocks occur across the basement: there are limestones, sandstones and evaporites of the Paleocene and Eocene. During the Eocene, a series of geological events defined the current geomorphology of the peninsula, namely the undulating relief in the south of the peninsula formed due to folding of the recently formed limestone layers. Late Oligocene dolomitic materials were later subjected to severe erosion. During the Miocene and Pliocene, two fracture systems originated, one of them oriented from NE to SW, and another from NW to SE. In the Middle Miocene, the region experienced a collapse that favored the subsequent precipitation of calcium carbonate during the Pliocene, forming the northern portion of the peninsula (López-Ramos 1982; Bautista et al. 2005).

The geological history of the region resulted in the formation of an extensive flat platform almost completely composed of calcium carbonate with minor inclusions of even more soluble evaporates. However, the surface sediments have clay, dust, and sand sufficient to form soils of varying depth. The origin of noncarbonate material may be attributed to either the residual accumulation of materials left after carbonate dissolution or to the accumulation of allochtonous material, including the dust transported across the Atlantic Ocean (Bautista et al. 2011b).

5.16.3 Hydrology

The most remarkable feature of the Yucatan Peninsula is the scarcity of surface drainage, except for the river Champotón and intermittent rivers, Rio Hondo and Rio Bolsa, in the south of the peninsula (Bautista et al. 2011a). The drainage of the region is therefore almost entirely underground. Quick infiltration into the ground water is characteristic for karst topography, where the dominant process is the dissolution of the rocks. Most karsts form in porous highly permeable

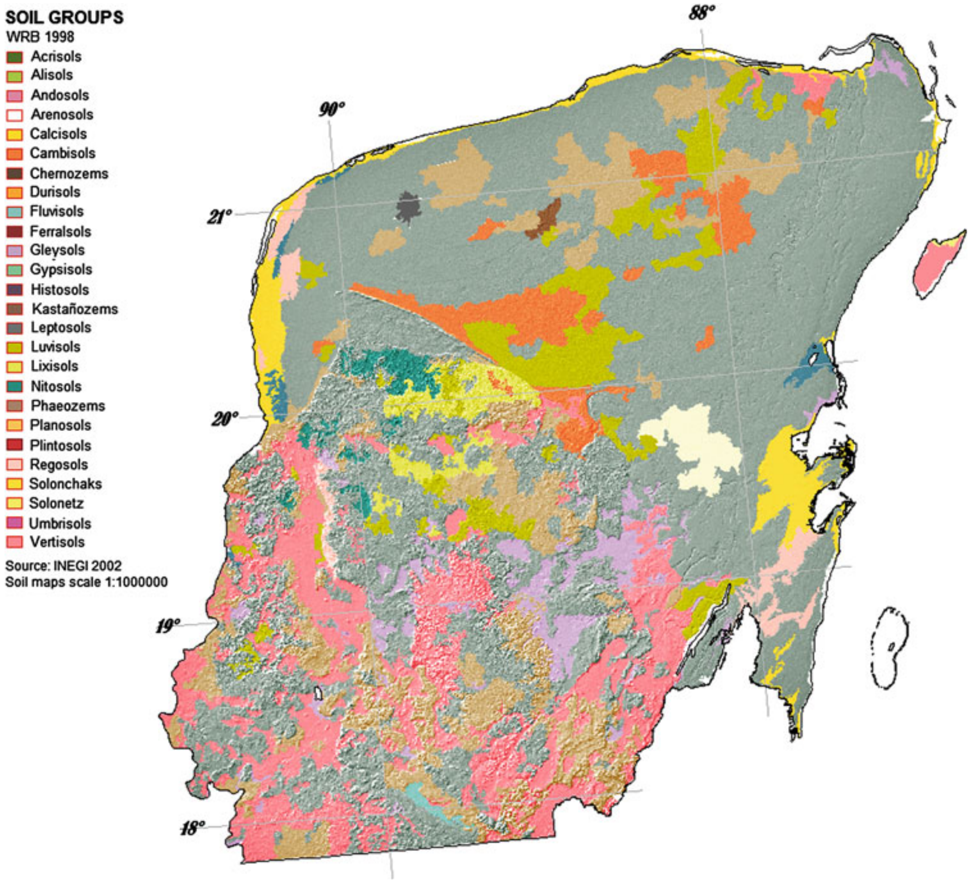


Fig. 5.29 The soil map of the physiographic region of the Peninsula of Yucatan. Reproduced with a permission of INEGI

limestone of the Eocene and Miocene–Pliocene (Bautista et al. 2005). Another tropical karst morphological expression is the formation of dome-like sets of hills. The penetration of water underground leads to the formation of caves. There are several underground caverns in the region, especially in the northern part of the peninsula. High permeability of carbonate rocks and low water table lead to the formation of underground aquifers that are highly vulnerable to pollutants.

5.16.4 Climate

The Peninsula of Yucatan is a flat area with very low elevations above the sea level. This results in a relatively low amount of precipitation in an area that should be much higher under the influence of the Azores-Bermuda high pressure zone (Bautista et al. 2011a). The precipitation generally falls from May to October with more intensity in September mainly as a result of catastrophic events such as hurricanes and tropical storms. Sometimes rainfall occurs in winter because of the "nortes", invasions of cold humid air fronts. The mean annual temperature averages 26° C and the coolest months are December, January and February with the temperatures below 22 °C. In general the climate of Yucatan is warm, but the amount of precipitation varies, especially between the northwestern and the southern parts of the peninsula. The southwest portion of the region has a warm subhumid climate with summer rains, which coincides with the highest altitude of the peninsula (300 m asl). Another area with heavy rain occurs in a band extending northeast to the southwest, from Cancun to the base of the peninsula. The climates with slightly less precipitation are located at the center of the peninsula. The northern coast is the driest area of the Peninsula of Yucatan with a semiarid climate. The annual precipitation is as low as 438 mm in Progreso, Yucatan state, and 377 mm in Faro Triangle, Campeche state (Bautista et al. 2011a).

5.16.5 Vegetation

The Peninsula of Yucatan is recognized as a clearly defined biotic province (Rzedowski 1983), which joins the floristic elements of the Antillean region, Central South, and Southeast Mexico, and a high percentage of endemic species, with a total number of species of plants between 2,200 and 2,400 (Bautista et al. 2011a). The largest area of the

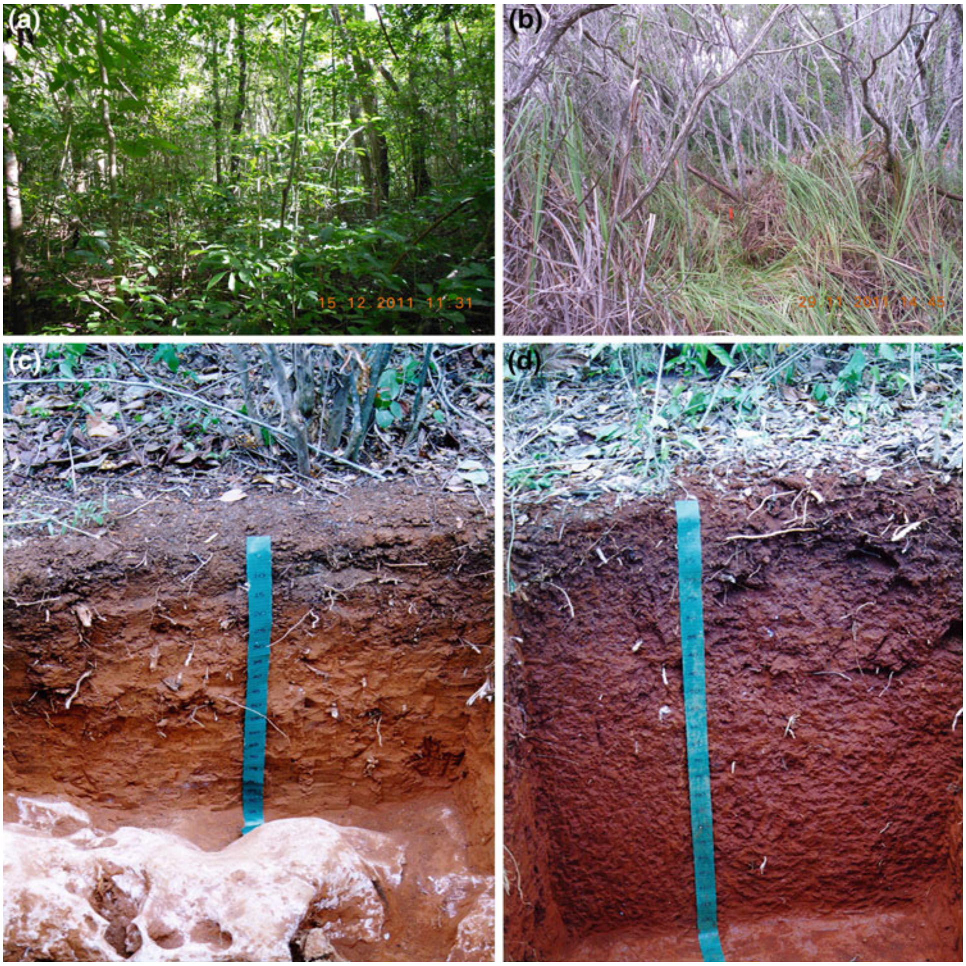


Fig. 5.30 Typical landscapes and soils of the physiographic region Peninsula of Yucatan: **a** Lanscape on shallow soils, experimentsl field, El Tormento, Campeche; **b** Landscape with organic soils in the mangroves of Celestín River, Campeche; **c** Leptic Luvisol/Lithic Hapldalf, Tixcacalcupul, Yucatán; **d** Endoleptic Nitisol/Hapludult, Sabán, Yucatán (photos contributed by Wendy Cantarell and Carlos Omar Cruz-Gaistardo)

region is covered by deciduous and evergreen forests. The tropical rain forest is the is the richest and most complex plant community and is located at the very south of the region, in the most humid habitats. The number of species in the upper stratum of this type of vegetation is very high, and the dominant species are difficult to define. The majority of these trees do not have common names, but they do have common names only in local languages. Epiphytic bromeliads are common, as well as herbs such as *Aechmea* and orchids, lichens embedded in the trunks of trees and woody epiphytes such as *Ficus* spp (laurel). Similar but slightly drier communities form in the south-central Quintana Roo and in a strip at the base of Campeche. This type of vegetation includes trees that exceed 30 m. The most common species in this forest are *Aspidosperma megalocarpon*, *Calocarpum mamosum*, *Cupania glabra, Exostema mexicana*, *Manilkara zapota*, *Pimenta dioica*, *Pouteria unilocularis*, *Pouteria campechanum*, and many others. A medium almost evergreen forest is more widely distributed in the region. It covers most of the state of Quintana Roo and Campeche, and a small portion of the southeastern part of Yucatan. The trees of this community, like those of the tropical rain forest, have buttresses and usually have many epiphytes and lianas (Rzedowski 1983). The trees have an average height of 25–35 m. Among the most abundant species are *Lysiloma latisiliquum*, *B. alicastrum* (ramón), *B. simaruba* (copal), *M. zapota* (sapote), *Lysiloma latisiliqua*, *Vitex gaumeri, Bucida buceras*, *Alseis yucatanensis* and *Carpodiptera floribunda*. Low almost evergreens commonly occupy wetlands. This type of vegetation is characterized by a low tree layer, with average heights between 4 and 7 m. Many species have twisted trunks and branches near the base. The floristic composition is diverse due to environmental variability between the dry and rainy seasons. Among the most frequent species with ecological tolerance to these conditions are *Haematoxilum campechianum*, *Dalbergia glabra*, *Hyperbaena winzerlingii*, *Coccoloba cozumelensis*, *Neomillspaughia emarginata* and *Panicum hampea*. An important feature of the low evergreen vegetation is its density; this boscage is difficult to penetrate, especially in the rainy season, due to the rapid development of herbaceous vines and lianas. The medium semideciduous forest is a dense and closed community. The heights of the trees range between 15 and 20 m, and commonly the upper layer forms a uniform canopy (Rzedowski 1983). This type of vegetation covers the central and eastern portions of the state of Yucatan, the northern part of Campeche and Quintana Roo. Among the most common species are *Acacia pennatula*, *Caesalpinia gaumeri*, *Lysiloma latisiliquum*, *Gyrocarpus americanus*, *Pithecellobium albicans*, *Acacia cornigera*, *Cedrela mexicana* and many others. The low deciduous forest has trees with heights between 8 and 10 m, which lose their leaves for a period of five or more months during the dry season. Among the most frequent tree species are *B. simaruba*, *Coccoloba reflexiflora*, *Piscidia piscipula*, *Nopalea gaumeri* (Cactaceae), *Diospyros cuneata* and *Lysiloma latisiliquum*. A specific type of vegetation may be observed in the state of Quintana Roo: there is a combination of the endemic for Mexico pine *Pinus caribaea* with the savanna grassland species. Mangrove swamps are common along the coasts, and species include the red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*) and buttonwood mangrove (*Conocarpus erectus*). So-called tular is an aquatic plant community, rooted in the bottom of water bodies. This vegetation type is basically made of cattail plants (*Typha angustifolia*) and commonly the reed, *Phragmites communis*. Along the coast there are also grass communities on the coastal dunes. Some of the species include prickly pear (*Opuntia dilleni*), mat (*Abronia maritima*), purslane (*Sesuvium portulacastrum*), uvero (*Coccoloba uvifera*), pepe (*Chrysobalanus icaco*) and others.

5.16.6 Soils

According to Bautista et al. (2011a) the territory of the Yucatan Peninsula is dominated by a combination of shallow soils (Leptosols/Rendolls and Lithic groups), and poorly developed deeper soils (Chromic Cambisols/Ustepts) (Fig. 5.29). The major part of the territory (67 %) is covered with shallow soils on limestone. In the depressions are reddish clayey soils with poor differentiation of horizons. The origin of the fine earth that forms these soils is under question. On the one hand, the weathering of limestones commonly produce residual clayey products, because marine carbonate rocks are commonly contaminated with dust, volcanic ash and other components. The weathing of limestone in the Mediterranean region of Europe produced deep clayey sediments called *terra rossa* (Kubiëna 1970). On the other hand, these silicate and oxide particles could be transported by the wind, especially if we consider the proximity of the volcanic enclave Los Tuxtlas. Dudek et al. (2006) studied the mineralogy of the fine earth fraction in the Yucatan and concluded that the origin of the fine material was volcanic. Bautista et al. (2011a) believe that both mechanisms could contribute to the formation of the fine earth on the peninsula. In any case, there are relatively deep soils in the region (Fig. 5.30), including Gleysols/Aquents in the coastal areas and in the wetlands located close to the coast (about 15.5 %), Luvisols/Udalfs in the karst plains (about 4.5 %), and Vertisols (about 3 % of the total area of the region) in the south and northeast (Bautista et al. 2011b). Furthermore, there are saline soils (Solonchaks/Halaquepts) and organic soils (Histosols) on the coasts.

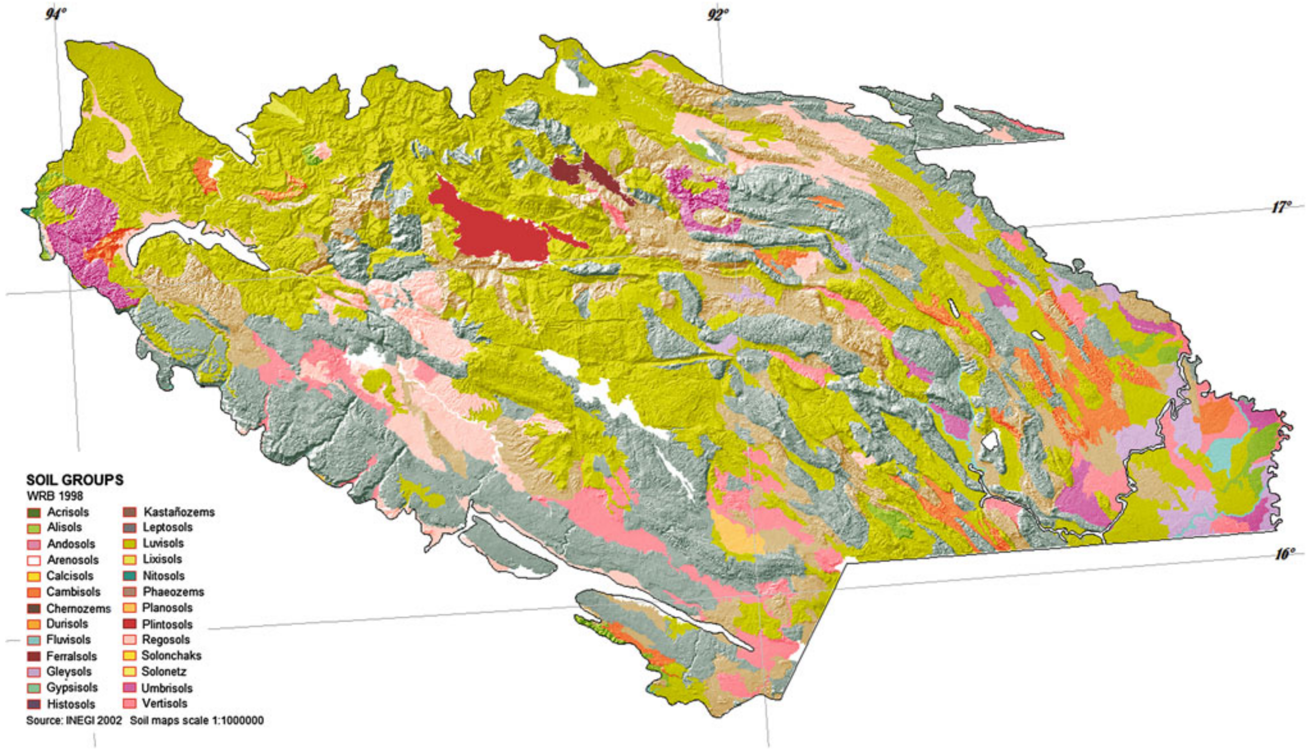
5.16.7 Soil Use, Degradation, and Management

Although the major part of the region is occupied with very shallow soils that seem to be undesirable for agricultural use, there some crop production and pasture on the peninsula. This is not surprising if we remember that this part of the country feeded was home to one of the major classical civilization of Mesoamerica. Among the three states of the region, the Yucatan state has the highest percentage of area occupied by agricultural fields (12 %), with crops such as corn, sisal, oranges, pumpkins, and beans. In the state of Campeche, the agricultural area occupies 1.1 % of the state with maize, sugarcane, rice, sorghum, and beans. Finally, in Quintana Roo agricultural land use occupies only 0.05 % of the state with crops such as corn, beans, rice, jalapeno chile, watermelon, papaya, and sugar cane (Bautista et al. 2011b). The main limiting factor is the volume of soil and close underlying rock. In these conditions, even moderate erosion can be of critical importance. Furthermore, karst phenomena affect the soils.

5.17 Ridges of Chiapas and Guatemala

5.17.1 Topography

This region of the Ridges of Chiapas and Guatemala is formed by folded mountains that consist mainly of Cretaceous limestone and Cenozoic rocks (Zenil-Rubio 2011). The altitude of these folds varies from 200 to 500 m, while the uppermost ridges of this mountainous system range between 1,000 and 2,000 m asl. These elements have been affected by intense fluvial erosion, partly controlled by strike slip fault systems, and are dissected by deep canyons and gorges. In Mexico, this region includes the mountains of the northwestern and northeastern parts of the states of Chiapas and the highlands of the extreme southern part of Tabasco.



Source: INEGI 2002 Soil maps scale 1:1000000

Fig. 5.31 The soil map of the physiographic region of the Ridges of Chiapas and Guatemala. Reproduced with a permission of INEGI

5.17.2 Geology

The geological structure of the region of the Ridges of Chiapas and Guatemala resembles the Sierra Madre Oriental and limestone portion of the Sierra Mader del Sur, the so-called Sierra Mixteca. In fact, it is a continuation of these geological formations; however, due to the discontinuity in their distribution and bioclimatic differences, these physiographic regions are regarded as separate geographic units. The Ridges of Chiapas and Guatemala have a complex pattern of structures formed during the Mesozoic and Cenozoic epochs. There are outcrops of Middle and Late Cretaceous and Cenozoic sedimentary rocks consisting of limestone and dolomite combined with limestone-shale. The sediments have been exposed to the surface because of intensive folding of marine sediments in the Paleocene that formed the Central Massiff of the mountainous system. The next important stage started in the Miocene, and resulted in the uplift of the entire ridge. Further uplift that occurred in the Pliocene–Pleistocene resulted in the emerging of the Istmus of Tehuantepec that connected Mexico with Central America. In the lowlands and flat intermontane valleys, there are recent alluvial sediments. The other important recent geological process is kasrt phenomena that results in the formation of fractures and cavities in the limestone and dolomite.

5.17.3 Hydrology

The region has an impressive network of rivers and lakes formed by several major river systems (Zenil-Rubio 2011). Drainage patterns are mainly subparallel and dendritic type, directly influenced by the relief systems in the form of parallel ridges. The first river system that drains this mountainous region is the Tulijá River in the northwest portion, which rises in the northern slopes of Diamond Knot and empties into the Tabasco flood plain through a canyon near Salto de Agua. The second is an endorheic system of the Lacandon plateau consisting of a number of lakes: Ocotal, Vista, Ojos Azules and Metzabok Naha. The third and most important is that formed by the rivers, Usumacinta and Lacantún. This system has a complicated network of tributaries in the region that forms the border between Mexico and Guatemala and heads out to the coastal plain of Tabasco. In the extreme northwest is the imposing canyon where the river Grijalva flows.

5.17.4 Climate

Generally, the region is characterized by a hot and wet tropical climate. A rainfall gradient runs from SW to NE: the higher rainfall is recorded in the mountainous region

Fig. 5.32 Typical landscapes and soils of the physiographic region Ridges of Chiapas and Guatemala: **a** Landscape on shallow soils, Multajy, Chiapas; **b** Lanscape on hydromorphous soils near the River Usumacinta in Frontera Corozal, Chiapas; **c** Vertisol, Cacada Chentigre in Dolores, Chiapas; **d** Calcic Plinthic Gleysol (Humic)/ Plinthaquox, Agua Azul, Chiapas (photos contributed by Juan Cuenca-Jiménez and Carlos Omar Cruz-Gaistardo)

(3,500 mm of annual precipitation) and decreases gradually toward the coastal plain of the Gulf of Mexico, where just 1990 mm annual rainfall is reported (Zenil-Rubio 2011). The heaviest rains occur in July, August and September, and a relatively dry season occurs during March and April. The relative humidity of the air is 80 % during the entire year. The mean annual temperature is high, with an average of 25 °C at altitudes of less than 800 m asl and 20 °C between 800 and 1,300 m. The annual temperature is isothermal with less than 5 °C variation among seasons.

5.17.5 Vegetation

The major part of this region has a tropical rain forest as the natural vegetation, but most of the forest has been eliminated and replaced by grasslands. The tropical rainforest is the most productive and diverse ecosystem on the Earth. In this region, a total of 3,400 vascular plant species distributed in 61 families were reported (Zenil-Rubio 2011). This ecosystem occupies all landscape positions independently on the soils up to 900 m asl. It has three layers where the tallest trees can reach 60 m or more. Some species characteristic of this type of vegetation in the region are the canshán (*Terminalia amazonia*), guapaque (*Dialium guianense*), ramón (*B. alicastrum*) and many others. Apart from this ecosystem there are also other vegetative communities. For example, medium evergreen forest grow on flooded hydromorphous soils. The trees have height between 15 and 25 m, and consist of four layers. The typical species include cochimbo (*Platymiscium yucatanum*), tineo (*Vataira lundellii*), tight sapote (*Diospyros digyna*) etc. Pine-oak forests occupy the positions above 850 m asl. The trees are up to 40 m in height, and the common species are pines *Pinus maximinoi* and *P. pseudostrobus*, which generally are mixed with wax myrtle (*Myrica cerifera*) and copey (*Clusia flava*). Furthermore, the lower and deep soils can support some oaks *Quercus peduncularis* and *Q. segovienensis*.

5.17.6 Soils

Although the geological material in the region is represented mainly by limestone, the shallow soils on the carbonate rock constitute just 27 % of the total area of the region. To some extent, this is due to the presence in places of other materials, such as shales. However, the impure composition of the limestone or external sources, could lead to the deep formation of soils that commonly overlie limestone rocks. These reddish clayey soils classified as Luvisols/Udalfs occupy one-third of the area of the region. They have morphology very similar to the well-known *terra rossa* of the Mediterranean regions. Both autochtonous and allochtonous materials may be considered as sources of parent material, especially if we remember that in the Central American Cordillera there are many active volcanoes. The other soil groups present in the region include humus-enriched soils (Phaeozems/Udolls), swelling and shrinking soils (Vertisols), immature soils (Regosols/Orthents) and other soil groups that occupy minor areas (Fig. 5.31).

5.17.7 Soil Use, Degradation, and Management

The soils that form in the valleys, mostly of the Vertisols group are widely used for grassland and for growing sugar cane and corn. The humus-enriched acid soils of the mountainous slopes are widely used for pastures. The pasture uses have proven unsatisfactory because of a loss of fertility, acidification, and compaction. The best management alternative for the conservation of these soils is to keep the natural vegetation.

The main soil degradation problem is soil erosion that readily follows deforestation. Karst may also cause a certain inconvenience in soil management (Fig. 5.32).

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6 Soil Degradation

6.1 Historical Evolution

Soil degradation of anthropogenic origin is not a recent phenomenon in our country. It relates to human settlements in the Valley of Mexico that date back 6,000 years (Jiménez et al. 1990) However, it peaked with the Mayan, the Teotihuacan, the Purépecha, and the Aztec cultures (4,000–1521 BP), although the intensity and duration of this degradation need additional study. According to Butzer et al. (2008), soil erosion studies related to humans in Mexico are based on two questions: (1) Did the Spanish colonization allow soil degradation? or (2) Did the Hispanic Conquest have a negative effect on the environment. Some authors suggest that pre-hispanic settlements in spite of their dense population (25.2 million people) had minimal impact on the environment (Hassing 1994). Others claim that soil erosion caused by traditional agriculture had the same impact as that provoked with the introduction of the Spanish plow (O'Hara et al. 1993) or with the steel plow in modern times (McAuliffe et al. 2001; Metcalfe et al. 2007). Human soil degradation was apparently no more severe in pre-Spanish Mexico than in modern times.

Through studies of lake sediment, it has been reported that there were erosional processes in Central Mexico (Metcalfe et al. 1991) in the semiarid Tehuacán Valley (McAuliffe et al. 1989), Michoacán (O'Hara et al. 1993), and in the area of influence of the Mayan civilization, which caused its collapse (Bennett 1926; Beach et al. 2006). The collapse has been attributed to increasing the land use to agriculture (Cook 1949). The strong soil erosion occurred with more intensity in areas where farming was practiced on slopes and in semi-arid environments. In the case of areas with a semi-arid environment, their recovery was slower apparently due to water limitation, while in semi-tropical and tropical environments, vegetation recovered once the pressure for resources decreased.

Other researchers have questioned the study of sediments as the only evidence of human-induced soil erosion. Vita-Finzi (1993) indicates that this approach does not address climate instability in the area as a factor in soil erosion, because in the central plateau the valleys display extensive alluvial fills whose ages range between 500 and 700 years old, which could cause confusion as to whether the sediments are the result of human activities or climate instability (Vita-Finzi 1979). Moreover, it is important to consider the impact of weather events (e.g., hurricanes) along with the land use practices to determine the true impact of soil erosion during the pre-hispanic and the Colonial period in Mexico (Butzer et al. 2008). It is also necessary to take into account, volcanic events, common in the Mexican highlands because they are important in shaping landscapes, vegetation evolution and lake systems within a watershed (Lozano-García and Guerrero-Ortega 1994). For example, in the Purépecha area a volcanic eruption occurred during the Post-Classic period (1393–1453 AD), where natural land degradation was more common than that caused by human activities (Farshad and Barrera-Bassols 2003).

Furthermore, detailed historical records of the Texcoco River basin, the second home after Tenochtitlan (Martinez 2001), show that the arrival of the Spaniards and introduction of the plow and other farming practices changed the environment dramatically (Ortiz-Solorio et al. 1993). According to Alva Ixtlixochitl (1578–1650) and a Colonial Indian map made in 1584 in the Coatlinchan municipality of Texcoco (Gruzinski 1987), the forest, (represented with trees and deer), reached the shore of the former Texcoco Lake (represented with fish). Thomas Gage (Thompson 1958) on his travel to New Spain (1625–1637), described the city of Texcoco as follows: *how rich and abundant a city that sustains its inhabitants, who are deprived of nothing, more than hundred thousand Indians and* 900 *Spaniards.* Meanwhile, Toribio de Benavente, better known as Motolinia (1979) related that when he reached the city of Texcoco, he found the

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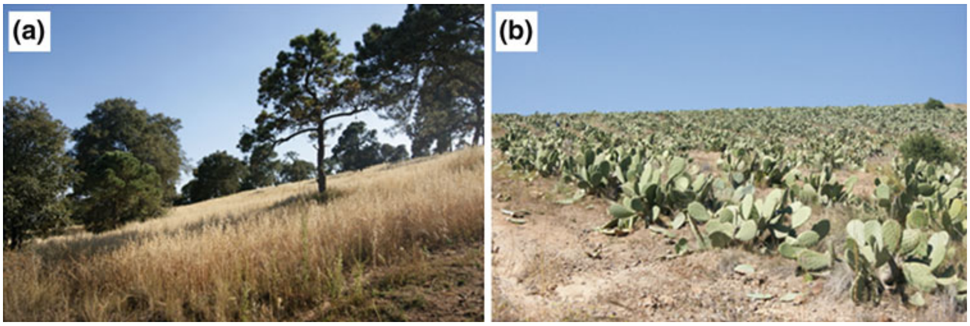


Fig. 6.1 **a** Landscape dominated with Andosols/Andisols under pine forest, **b** landscape completely eroded with cactus plantations. Both landscapes are separated only by the road. Mexico state (photo by Ma. del C. Gutiérrez-Castorena)

royal houses of Nezahualcoyotl desolated, but the great cedars still remained. The cedars from the mountains were cut systematically for the construction of the magnificent houses in Mexico City. In fact, Hernán Cortes was accused by Pánfilo de Narvaez, for cutting 6,000 cedars for the beams of his house (Martínez 2001).

The overexploitation of the forest was critical in generating a drastic change to the landscape in the eastern state of Mexico during the next 500 years, i.e., the reduction of the forest to the summit of the mountains, the introduction of olive groves, overgrazing, and farming practices that caused severe degradation mainly by water erosion (Ortiz-Solorio et al. 1993), thus leaving the hard layer of Tepetate. Moreover, the application of inappropriate soil management techniques for slopes caused a strong impact on the landscape. Figueroa (1975) reported that tepetate, although it is an indurated volcanic material, common in the mountainous area, it generates up to 16 ton/ha/year sediment. Furthermore, many of the soils covering the tepetate were Andosols or Vertisols, and recently they are now relict soils in summit area.

Andosols on steep slopes are better preserved under forest (IUSS Working Group WRB 2006), but once the cover is removed they become easily eroded, as shown in Fig. 6.1. In this area, we found a landscape dominated by Andosols and in front of it (separated only by the road), a landscape completely eroded but with cactus plantations. The fragility of these two soils in the region of Texcoco, may explain the great thickness (between 1 and 1.5 or up to 2 m in the Universidad Autónoma Chapingo; personal communication with Juan Estrada Berg-Wolf) of sediments that buried the ancient city of Texcoco and the Chapingo Hacienda.

Other historical records about the impact of farming practices and overgrazing are taken from Zacatecas, north of the Central Plateau and in the Purépecha communities in Michoacán. Elliott et al. (2010) reported that land degradation in arid areas was due to a set of intense and rapidly environmental changes related to overgrazing and deforestation after the Spaniards arrived in Mexico. However, Endfield and O'Hara (1999) reported that Spaniards introduced conservation practices for livestock production.

Furthermore, it is important to consider the social factor in land degradation studies. Farshad and Barrera-Bassols (2003) note that in some indigenous communities in the Patzcuaro lake basin, with at least 4,000 years of farming history, no land degradation was found, while in other sites with similar physical characteristics, the environment had been degraded. They explain that physical and social factors could have played a role in the occurrence or absence of land degradation. In the Mayan culture, Beach et al. (2006), using palynological techniques and geochemical records in Salpetén Lake, reported different impacts on soil throughout the history: strong erosion during the pre-Classic (250–900 years), variation in erosion intensity (light and extreme) in the Late Classic (550–830 years), and a new recovery of the forest around 1,400 AD.

This variation in soil degradation, related to a culture or a community, has been documented around Lake Patzcuaro (Street-Perrot et al. 1989) corresponding with the introduction of widespread cultivation of maize (about 1,550 BC and 350 AP) and the introduction of the plow and implementation of livestock activities in the year 1680. Meanwhile, Fisher et al. (2003) showed that initial land degradation was caused by settlement but not by agriculture, that population density inversely correlates with soil erosion, and that land degradation was associated with European Conquest but not from the introduction of European agrotechnology. Endfield and O'Hara (1999) indicate that in this lake, landscape recovery periods occurred after the conquest, as a result of the indigenous population decrease and subsequent reduction in the intensity of land use.

Soil conservation or soil management techniques used since pre-hispanic times include terraces, chinampas (floating gardens), home gardens, and slash-and-burn systems or the incorporation of materials such as soil, human manure, and ashes.

The construction of terraces in the hills was very common for the intensification of agriculture in Mesoamerica (Sanders 1956, 1976). According to Borejsza et al. (2008), some vestiges of this type of work still survive in many parts of Mexico (Fig. 6.2). Sometimes they are cultivated,

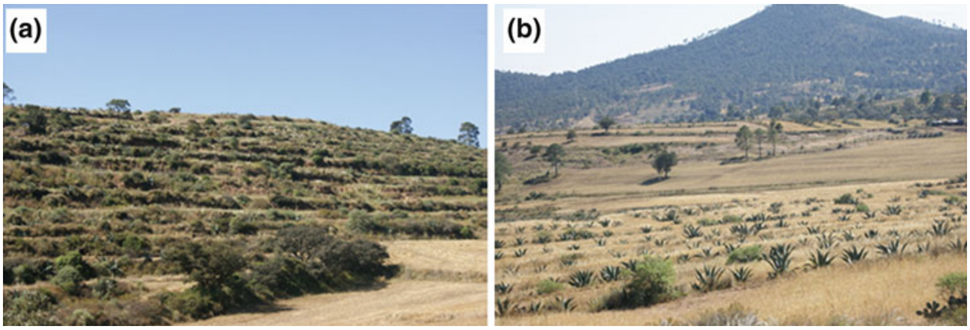


Fig. 6.2 **a** Pre-hispanic terraces built during netzahualcoyotl period (1402–1472), **b** Modern terraces with cactus as living wall barriers (photo by Ma. del C. Gutiérrez-Castorena)

but their layout and construction technique suggest considerable antiquity. More often, they lie abandoned and partially destroyed.

In the area of Texcoco, pre-hispanic terraces are common, especially in the area of Tezcutzingo (Córdova and Parsons 1997), which were built during the Netzahualcoyotl period (1402–1970) to prevent soil loss (Laird 1989) or to generate land in the area where it was very shallow. In Santa María Asunción codex, elaborated during the Contact Period in Tepetlaoxtoc, the Mexico State (year 1546), terraces were represented as continuous stones, which mean that soil conservation practices were common in the Texcoco municipality.

Chinampas and home gardens are highly productive farming systems. Chinampas, small artificial islands built manually with lake mud or soil and lake vegetation in alternate layers (Sanders 1956), were constructed by the Aztecs (Aguilar 1982); on the other hand, home gardens were made by the Mayas (Flores-Delgadillo et al. 2011). Chinampas, due to their high fertility, can produce between two and three crops per year, such as corn, chili pepper, cabbage, cauliflower, lettuce, and a wide variety of flowers (West and Armillas 1950; Rojas 1983; Frederick 2007). Home garden systems were intensively managed over a long lapse of time, supplying a diversity of fruit, trees, vegetables, herbs, and medicines (Alvarez-Buylla et al. 1989). By using these two highly productive agricultural systems, the pressure for land use change, mainly from forest to agriculture, should not have been so strong in spite of high population density; hence, it is believed that pre-hispanic agriculture had less impact on the environment transformation.

6.2 Soil Erosion

Soil erosion is divided into two types: water erosion and wind erosion. Water erosion is the removal of soil by water, while wind erosion is the movement of soil particles by wind. Soil erosion is one of the most important environmental problems in the world, because it degrades the quality of natural, agricultural and forest ecosystems, and therefore reduces land productivity (Pimentel and Kounang 1998). Water erosion is divided into four types: rainsplash, sheet, rills, and gully.

In Mexico, many studies on soil erosion have been published, nationally and internationally, mainly during the 1990s of the last century (Cotler and Martínez-Trinidad 2010). However, in the past 6 years, the number of publications has decreased, but the number of articles published in international journals of high impact has increased. Some of these articles are made by Descroix et al. (2008), to assess gully and sheet erosion on subtropical mountain slopes; by Violette Geissen in Tabasco, to evaluate superficial and subterranean soil erosion (Geissen et al. 2007) and superficial soil losses and karstification (Geissen et al. 2008); and by Vazquez-Méndez et al. (2009), who studied soil erosion and runoff in different vegetation patches in semiarid Central, Mexico.

According to Ortiz-Solorio et al. (2011), studies on soil erosion or on soil degradation have been conducted in our country since the mid-century by both the methodologies of the United States department of agriculture (USDA) and the food and agriculture organization (FAO). The first approach has been one of the most popular methodologies used in our country to assess soil erosion, and the second approach has been used recently by government agencies, such as SEMARNAP, CONAFOR, and CONABIO, at different scales (1:4,000,000, 1:1,000,000, 1:250,000).

The first soil erosion survey was conducted in late 1930s and during the decade of the 1940s to characterize types and degrees of erosion through aerial reconnaissance. In the US, these works were aimed to support a number of government programs for soil conservation and forest management (Castillo 2005). The first maps on soil erosion were carried out by Mark Baldwin (1954), at 1:5,000 000 scale (Ortiz-Solorio et al. 2011). Results showed that Mexico was perhaps the most affected by soil erosion, among Latin American countries, with a damaged area of 66 %. However, after more than half a century of this project, current data of global soil erosion (water and wind) report smaller affected surfaces (SEMARNAP-CP 2002).

Runoff calculations and the universal soil loss equation (USLE) with their modified versions (RUSLE and MUSLE) were the most common models employed in Mexico (Cotler and Martinez 2010), with 114 of 140 total erosion and degradation studies using these models.

The USLE model was used to characterize the rainfall erosivity (Cortés et al. 1992), and to validate it in temperate zones (Arias and Figueroa 1992). It has also been used in combination with a geographic information system (GIS) and to estimate and map water erosion (Flores et al. 2003) or to characterize small ruminant impacts on rangelands of semiarid highlands (Echeverria-Chairez et al. 2001). Using the RUSLE model, research in tropical mountain basins (Millaward et al. 1999) has also been conducted.

An important soil property used in these models is the textural class. The Bouyoucos method is commonly employed to determine this physical property, instead of the pipette. However, this method may overestimate the values of sand and clay percentage (Lleverino et al. 2000). Nonetheless, the Bouyoucos method is used in procedures such as EPIC (Guevara 1994); SWRRB (Fernández 1996; Torres 2000); or WEPP (Larose et al. 2004). Larose et al. (2004) indicate that in order to use this model, it is necessary to review the manner of data collection to obtain reliable estimates of soil degradation. In fact, Boardman (2006) mentions that the main problems of this type of model are the cost for their development, complexity, user-friendliness, data availability, validation, value to end user, scale changes from small areas, prediction, performance, and that even at the experimental level it is not satisfactory.

One way to overcome the lack of data in soil erosion study is the soil knowledge of farmers (González et al. 2003). This methodology has the advantage of generating maps faster and cheaper, with respect to the methodology of the land system method (Ortiz-Solorio Cuanalo 1981) and those proposed by Morgan (1979). According to Waren et al. (2003), farmers are more concerned about the loss of fertility than the loss of soil, based on decisions about land use and conservation in a much broader decision-making process. If there are no data, other models cannot be applied, such as the European Soil Erosion Model (EUROSEM), which was attempted in Mexico by Veihe et al. (2001).

Another method employed is the use of remote sensing for water erosion assessments (Vrieling 2006). In fact, in Mexico these techniques had already been tested. For example, LANDSAT satellite imagery (Trueba et al. 1984) should be done using vegetation in two seasons: the dry season and wet season (Estrada-Berg and Ortiz-Solorio 1977) to assess vegetation cover.

Studies to evaluate water erosion and wind erosion were not performed systematically until after 2002 with funding from public resources. The government agencies were SEMARNAP-UACH (2002), which elaborated a wind erosion map at a scale of 1:1,000,000 and CONAFOR (2007) who assessed soil degradation (desertification) and mitigated the effects of drought (2007–2030).

All these methodologies used different parameters, generating a significant variation in the outcomes of wind and water erosion (Cotler and Martinez-Trinidad 2010). In addition, experts do not always use remote sensing to delineate affected areas (Lagos 1983) or sufficient funding is not available to conduct such studies in a rigorous way.

6.3 Desertification Studies

Arid and semi-arid regions are very sensitive to various physical, chemical, and biological degradation processes, which together are called desertification. According to Verstraete and Schwartz (1991), desertification is often the degradation of vegetation cover through deforestation, overgrazing, wood collection, repeated fires, and inappropriate agricultural practices. Desertification accelerates the decline in land productivity and the degradation of soil resources due to wind and water erosion (Estrada-Berg et al. 1999).

Mexico has conducted several studies related to the processes of desertification (Anaya 1990), mainly in three ways: current conditions, its velocity (in 10-year increments), and risk. The methodologies used consider not only water and wind erosions but also salinity and degradation of vegetation cover (FAO-UNEP-UNESCO 1979), as well as socioeconomic factors such as migration and poverty (Estrada-Berg 1983; Boardman 2006). It is important to mention that the concepts of soil degradation, land degradation, and desertification are considered synonyms.

A relevant study on desertification in the Mexican highlands was conducted by the UACH and CONAZA (1999), which covered 225 municipalities in eight states of the Mexican Republic and an area of 53, 5095.28 ha. This study showed that social degradation and biological degradation in the study areas are very severe (81 and 77 % respectively) and physical degradation is severe (35 %). The main causes of degradation are: housing and extreme poverty, overgrazing, and wind erosion. This intense desertification that is happening in our country is due to 21.7 million ha of fragile lands unsuited to agricultural and grazing used as marginally productive agriculture, which accelerates its degradation.

According to Estrada-Berg et al. (1999), the CONAZA (National Commission of Arid Zones) along with FAO and UNEP established in 1993 “the Action Plan to Combat

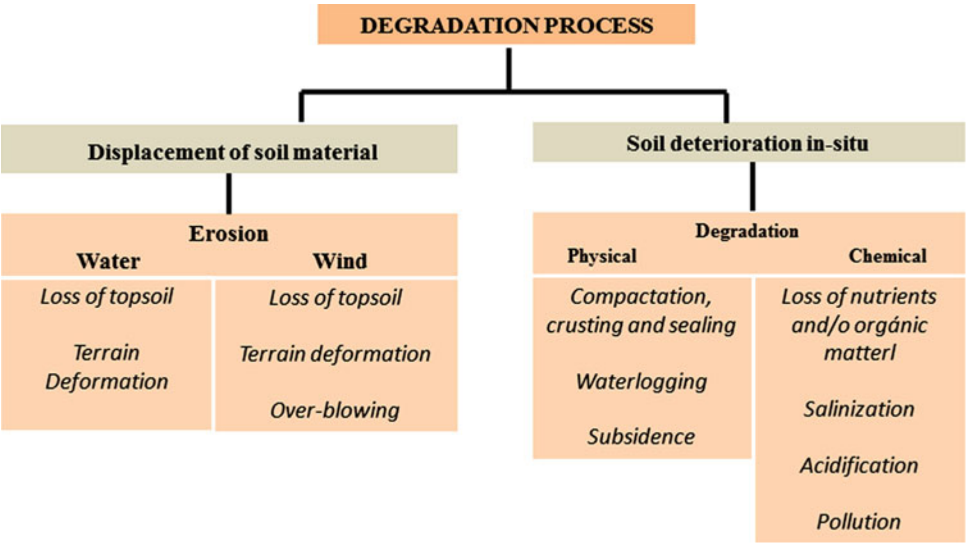


Fig. 6.3 Soil degradation processes and degradation types (SEMARNAP-CP 2002)

Desertification in Mexico", which was subsequently published by INEGI-SEMARNAP (1998). Another map of desertification was made by SEMARNAT (2006), where to the dominant degradation map was made instead of the map of arid, semiarid, and dry subhumid areas.

Studies on deterioration of the forest environment (García-Romero 2002), terrestrial biotic environment (Works and Gadley 2004) and rural biotic environment (Landa et al. 1997), including aspects of desertification, land degradation, and soil erosion have recently become important. Soil erosion and its relation to land use change (Cairns et al. 2000), land use and carbon sequestration (Etchevers et al. 2006) and tropical dry forest ecosystem (Cotler and Ortega-Larrocea 2006), have also been studied.

6.4 Studies on Human-Induced Soil Degradation

The global assessment of soil degradation (GLASOD) project was a model proposed by Oldeman et al. (1990) that began to be used globally to assess human-induced soil degradation by identifying critical points at field scales, because it is a cheap, reliable, and technically simple for erosion assessment (Boardman 2006).

The Colegio de Postgraduados has conducted several agreements for national studies on soil degradation along with SEMARNAT, at different scales: 1:4,000,000 in 1997, 1:1,000,000 in 1999 and 1:250,000 in 2001. The three surveys were developed under the coordination of C. A. Ortiz-Solorio. The first one was developed from a model and the last two included field work (SEMARNAP-CP 2002) (Fig. 6.3).

In studies at scales of 1:4,000, 000 and 1:1,000, 000, the GLASOD methodology, and the 1:250,000 survey, known as assessment of the status of human-induced soil degradation (ASSOD), proposed by Van Lynden and Oldeman (1997) were applied. Both are considered to be qualitative and subjective, but have the advantage of producing information in a short time. For example, the ASSOD map for Mexico was completed in less than 1 year.

Assessment on human-induced soil degradation in Mexico (scale 1:250,000) was prepared from the direct assessment of Mexican soils in the field, along with the methodology for soil degradation known as ASSOD (Van Lynden and Oldeman 1997), which is a modification of the so-called GLASOD (Oldeman 1988). Field work was carried out in a period of 8 months during 2002 and more than 150,000 km of roads were traveled.

Figure 6.4 shows the different types of degradation. In this picture, it can be observed that Mexico has degraded soils due to human activity in 45 % of its territory, stable land or land without apparent degradation in 10 %, and stable terrain in 26 %. The main degradation process is chemical (18 %), followed by water erosion (12 %), wind erosion (9 %), and the lowest proportion corresponds to the physical degradation (6 %).

Specific types with greater dominance for each process at the national level were: chemical degradation by decline of fertility in 17 % of the country (Fig. 6.5); water erosion with loss of surface soil in 10 % (Fig. 6.6); wind erosion with loss of surface soil in 9 % (Fig. 6.7); and physical degradation by soil compaction in 4 % (Fig. 6.8).

Of the 17 existing types of degradation in the country, not shown in the study because of scale, only two were presented: chemical degradation by acidification and

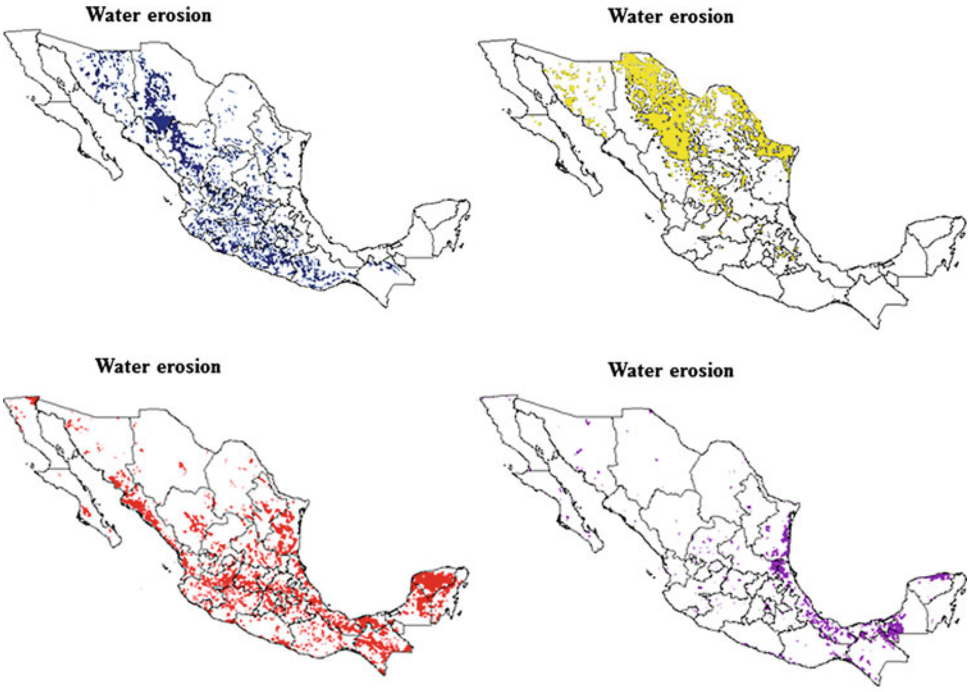


Fig. 6.4 Different types of human-induced soil degradation in Mexico (SEMARNAP-CP 2002)

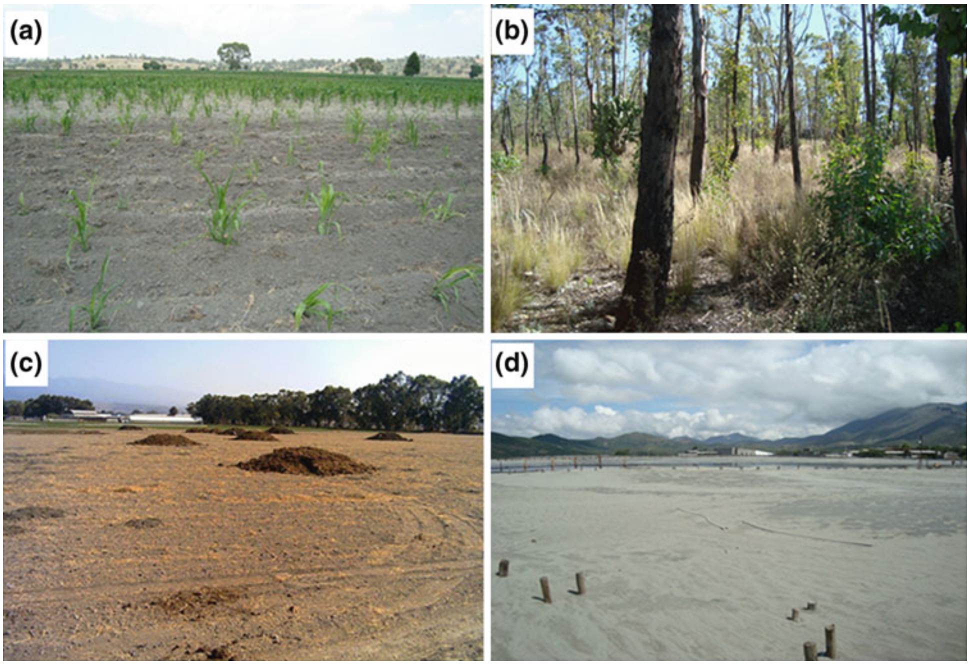


Fig. 6.5 Chemical degradation: **a** salinization, **b** acidification o distrification, **c** eutrofication, **d** pollution (photo by Patricio Sánchez-Guzmán)

physical degradation (subsidence). The main activities contributing to land degradation (Fig. 6.9) are: agricultural activities (39 %), overgrazing (38 %), deforestation (16 %), and urbanization (4 %). The factors with the lowest impact were: overexploitation of vegetation for human consumption (2 %) and industrial activities (1 %), while the levels of extreme degradation of soils are related to high-impact urban growth. Figure 6.10 reports stable terrain under natural and artificial conditions.

According to Ortiz-Solorio et al. (2011), it is important to mention that when a smaller amount of soil degradation in the different studies is reported, it could be interpreted as the result of conservation actions, when in reality it is more about precise locations and more accurate estimates of the

Fig. 6.6 Water erosion: **a** loss of topsoil, **b** terrain deformation, **c** gully erosion (photo by Patricio Sánchez-Guzmán)

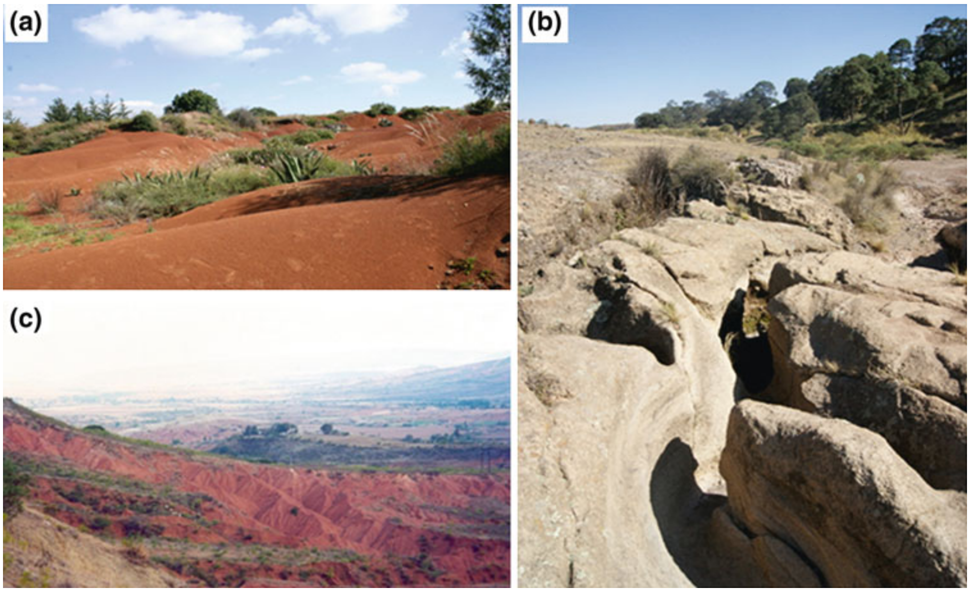


Fig. 6.7 Wind erosion: **a** and **b** overblowing, **c** terrain deformation, **d** pollution in mine tailings (photo by Patricio Sánchez-Guzmán)

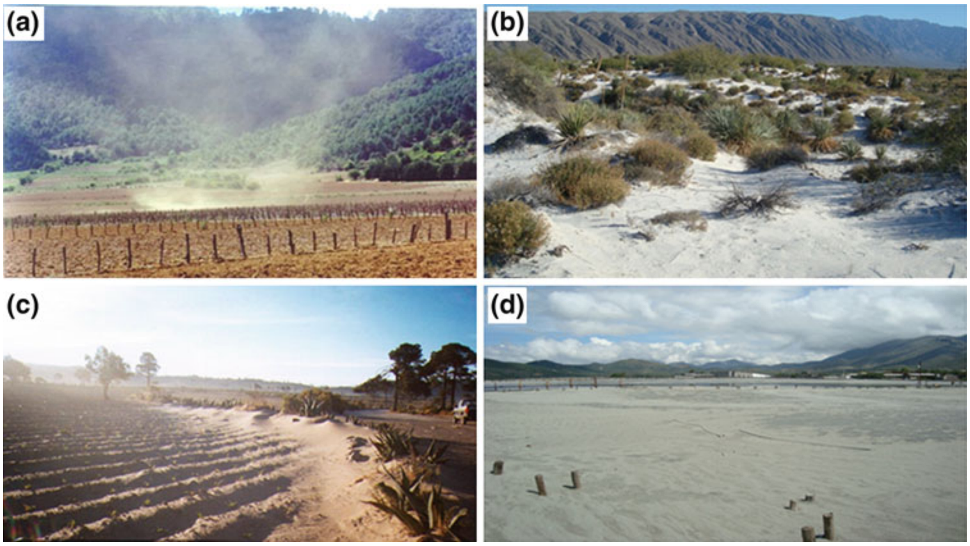
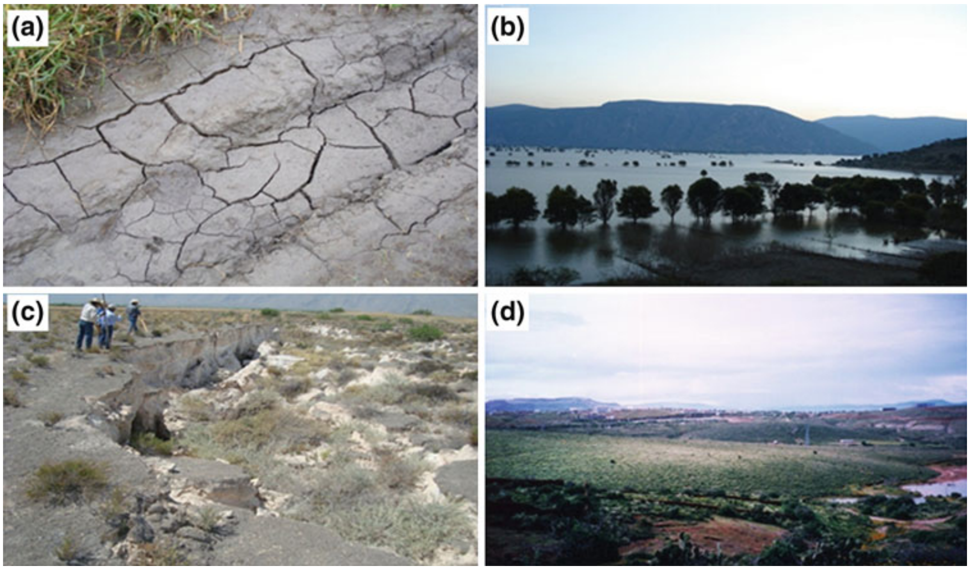


Fig. 6.8 Physical degradation: **a** Crusting and sealing, **b** waterlogging, **c** subsidence, **d** quarry for soil material extraction (photo by Patricio Sánchez-Guzmán)



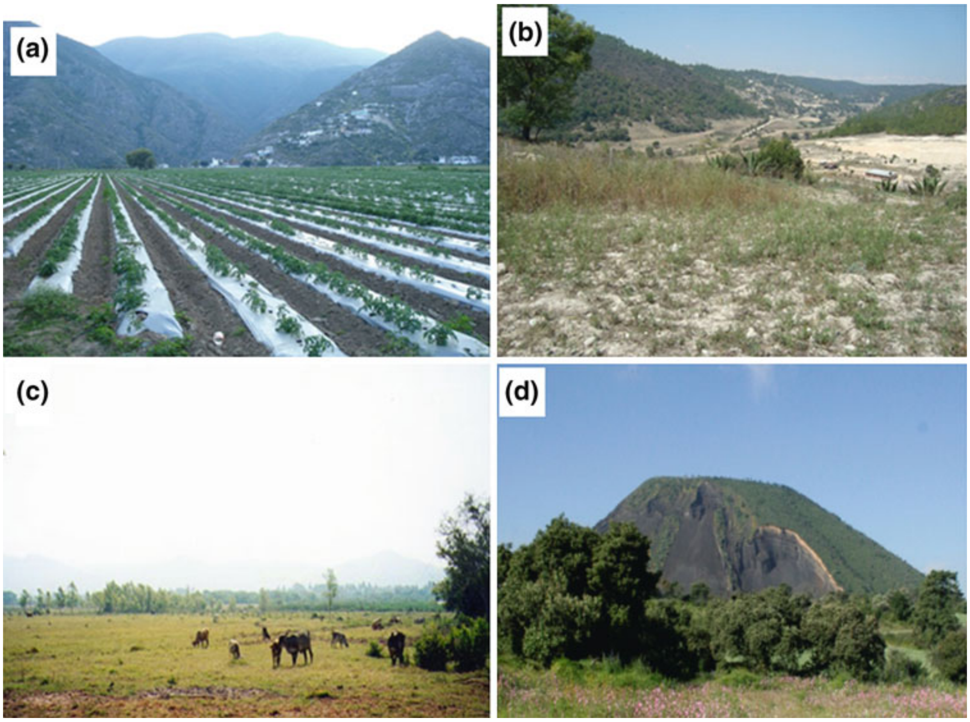


Fig. 6.9 **a** Soils with high agricultural activities, **b** deforestation, **c** overgrazing, **d** industrial activities (photo by Patricio Sánchez-Guzmán)

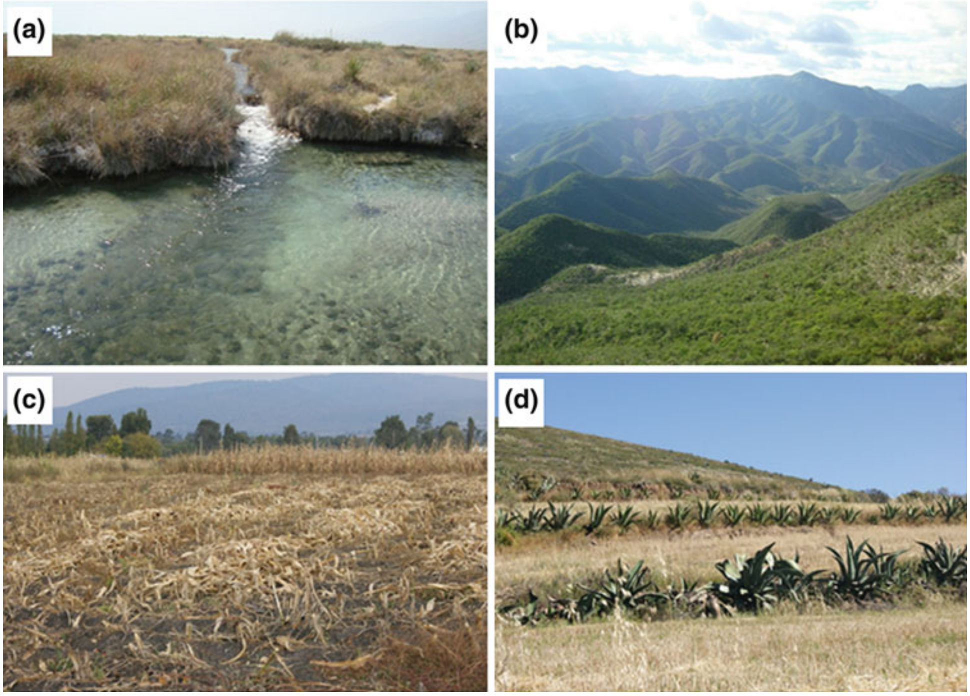


Fig. 6.10 Stable terrains **a**, **b** and **c** in natural conditions, **d** artificial conditions (*with hedge*) (photo by Patricio Sánchez-Guzmán)

observed areas in the field affected by soil degradation; in other words, data generalization decreases when work scale increases.

This study is considered as the official information on soil degradation in our country (Chapela and Alvarez 2007), which became a national reference for many soil studies at the regional level. Furthermore, it is likely that Mexico is one of the few countries in the world with information at that level of detail. Finally, since 2002 no more national studies with information and field trips have been performed, only work at the regional level has been conducted (Ortiz-Solorio et al. 2011).

One of the more detailed studies that used the ASSOD methodology was developed in the Amajac River Basin in the state of Hidalgo (1:75,000 scale) using mapping units to the Terrestrial Facets, considered as a subdivision of the Terrestrial Systems (García and Ventura 2005). This study found that stable areas and stable terrain increased, and that it is possible to identify degradation processes in specific areas.

6.5 Soil Erosion, Scales, and Physiographic Provinces

Cotler and Ortega Larrocea (2006) mentioned that it is important to understand the scale of erosion studies. For example, national maps should be the basis for environmental planning, while regional or local studies should be used for land management and soil conservation.

To obtain a general idea of what happens at the national level on land degradation, the maps elaborated by SEMARNAP-CP (2002) and physiographic provinces reported by Krasilnikov (2011) were superimposed. In addition, in each one of them the information of various subprovinces was analyzed in terms of soil, geology, and vegetation reported in the book of Soil Geography in Mexico, as mentioned above.

Water erosion is mainly found in the Sierra Madre Occidental, specifically in the subprovinces of the Sierras and Gullies (Cañadas) of the North, the Grand Plateau (Gran Meseta) and Canyons of the state of Chihuahua and Mountains (Sierras) and Plains of the state of Durango due to deforestation and steep terrain. These subprovinces are dominated by acidic volcanic rocks, pine forest or pine-oak, and the soils are Leptosols and Regosols/Lithic groups and Orthents, or Luvisols/Alfisols, Phaeozems/Udolls, Acrisols/Ultisols and Cambisols/Dystrudents in more stable areas (Herrera-Pedroza 2011). Many shallow soils are the result of erosion, so it is important to attend this problem in that area, because there are few studies on water degradation at the regional level. Some of these studies were published by Descroix et al. (2008) and Viramontes et al. (2002). Other states with this type of degradation are Oaxaca, Guerrero (González et al. 2003), Tabasco (CNA 2003; Geissen et al. 2008), where despite the efforts, there is a need for more research.

Wind erosion occurs in the Upland and Lowlands of the North, in the Sierra Madre Oriental, and the Great Plains of North America and is a process related to the arid and semiarid country, where ground deformation occurs. Valadez-Araiza (2011) reported sedimentary rocks, such as limestone, sandstone, and shale and alluvial sediments in the Great Plains of North America. The soils that occur include: Calcisols/Calcids (40.08 %), Vertisols (18.07 %), and Leptosols/Lithic groups of various Orders (14.25 %). Both the parent material, which weathers easily physically (Pape and Lagger 1994), and the flat relief and arid and semiarid condition and only patches of vegetation favor wind erosion over large areas of the north part of the country. Calcisols/Calcids generally sustain shrubs, grasses, and herbs used for extensive grazing (IUSS Working Group WRB 2006), causing further degradation.

Chemical degradation occurs mainly in the Pacific Coastal Plain, the Transmexican Volcanic Belt, the Gulf Coastal Plain, and in the Yucatan Peninsula. This land degradation is related to agricultural activities in volcanic areas and irrigation districts where fertility decline and sometimes salinity occur.

Finally, physical degradation is concentrated in the Gulf Coastal Plain where compaction, waterlogging, flooding, and land subsidence occur. Vertisols are the dominant soils. These soils are used generally in animal production (SEMARNAP-CP 2002), leading to compaction (Brady and Weil 1999), and are susceptible to flooding. According to WRB (IUSS Working Group WRB 2006), erosion of overgrazed Vertisols rarely is severe because gully walls soon assume a small angle of repose, which allows the grass to re-establishes easier. However, Mexico City has reported to have the most erodible soils in the country (Cotler and Martinez-Trinidad 2010). Although extrapolation of erosion rates between different scales is questioned (Renschler and Harbor 2002), two maps were superimposed by the SEMARNAP-CP (2002) and analyzed by Cotler and Martinez-Trinidad (2010), using 140 studies carried out by various academic institutions (Fig. 6.11.). The objectives were to determine which regions have conducted the studies on erosion or soil degradation more intensively, to identify areas where erosion or degradation occurs significantly, and where additional research is needed.

The analyses established that chemical degradation has been one of the most studied processes, mainly in the Trans-Mexican Volcanic Belt. However, more research is required in the Gulf Coastal Plain, the Pacific Coastal Plain, and the Yucatán. Water erosion studies are concentrated in the Central Plateau (Michoacán), but are lacking in the Sierra Madre Occidental, specifically in the states of Durango and Chihuahua, where wood extraction is provoking soil loss caused by deforestation. Wind erosion in the north of the country has practically been poorly studied in large scale.

After an exhaustive review of articles on soil degradation, it is noteworthy that these generally do not specify in what kind of soil the process is occurring. Apparently, the most degraded soils are Vertisols, Regosols, and Phaeozems (Cotler and Martínez-Trinidad, 2010). However, few studies are related to the Andosols, which are very fragile soils.

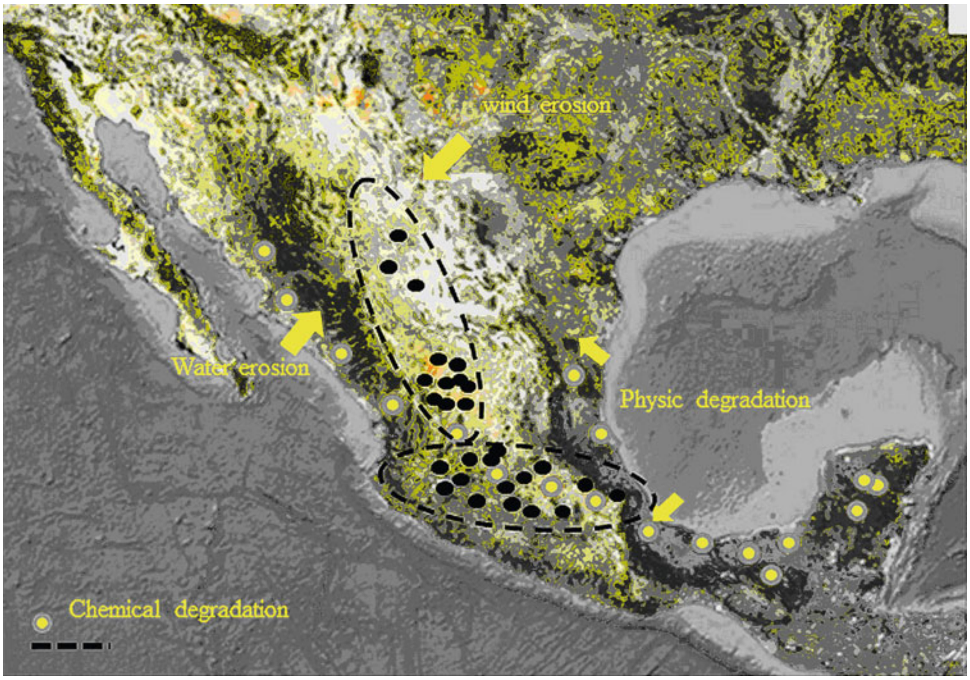


Fig. 6.11 Types of human-induced soil degradations related with some physiographic provinces in Mexican republic (from SEMARNAP-CP 2002), and distribution of extrapolated soil erosion data (from Cotler to Martinez 2010). Studies of the intensity of soil erosion are shown with black points

6.6 Conclusions

1. In the studies conducted to determine the impact that the pre-hispanic cultures had in their environment, it is necessary that they be done holistically, where studies of sedimentology, palynology, climate, geology, and historical data are provided, because one culture had periods of degradation and periods or recovery. The same occurred after the arrival of the Spaniards, although there are more records of soil degradation due to the impact of plowing on soil.
2. In Mexico, it is common having insufficient data to evaluate different models of soil erosion; therefore several alternatives are proposed. However, the USLE or RUSLE model is the most commonly used, although it has been questioned by several researchers.
3. Mexico has small-scale maps for assessing human-induced soil degradation. However, it is necessary to generate large-scale information, particularly in those areas or states where a type of degradation occurs predominantly.
4. It is recommended that degradation and soil erosion studies also integrate soil classification where the process is occurring to generate specific soil conservation practices and to transfer technology from other parts of the world.

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Soil and Humans Throughout the History

7

7.1 Soil and Humans

It is difficult to deny the fact that we live in an agricultural civilization (Hillel 1992). The fashionable toys of nowadays like airplanes, cellular phones, television, and broker's board are just the products of somewhat excessive agricultural production. Nothing would change humanity, if all of them would disappear at once. Of course, it would be a shock, but humanity would survive without automobiles, nuclear energy, and even without Internet. We are still creatures who feed ourselves from farming. After a long history as hunters and gatherers, we turned to soil cultivation and it was such a good idea that just in several thousand of years, it has led to the incredible growth of population, the development of centralized states, culture, and technical progress. Of course, all of these achievements were impossible without an excessive production of food that allowed a significant part of the population to dedicate themselves completely to trade, military service, policy, art, or science. Some people argue that agriculture "spoiled" the human race leading to overpopulation and degradation of natural resources (Manning 2005). It is a matter of point of view, but it is impossible to neglect the fact that all our life is based on soil exploitation.

The success of civilization depends on the success of agricultural production. Only globalization allows some countries to prosper without developing farming due to international differentiation of labor. Thus, any great civilization of the past had great agriculture as its basis. Mesoamerica developed a successful cluster of cultures that existed in various forms for more than 2,000 years and that contributed much to the actual Mexican and world cultural heritage. The agriculture of the region was extensively studied and discussed in the scientific literature (e.g. see Killion 1992), but most of the research had an anthropological focus. In this short chapter, we try to present several plots on the Mexican agriculture of the past from the viewpoint of a pedologist. Our question is how the soils governed the agricultural strategy of ancient Mexicans, and what the latter invented to improve the agricultural production?

7.2 Living by a Volcano

It is a well-known fact that the first agricultural civilizations appeared either in the flood plains of big rivers or in the zones of fresh pyroclastic sediments. The reasons for that are obvious. First, fresh alluvial and volcanic sediments provide many nutrients for the plants. Second, these soils are very soft and easy to manage; thus, even imperfect agricultural tools may be used for tilling these soils. The alluvial soils provide the best option, because apart from the mineral elements (K, Ca, and Mg), they contain nitrogen and phosphorus transported by water with organic detritus, and because these soils have a permanent supply of water (which can be even regulated at certain stages in the development of agricultural technology).

The main regions of agriculture development in Mexico were located in three principal zones: in the valleys and on gentle slopes of the trans-Mexican Volcanic Belt, on the flat limestone plain of the Yucatan Peninsula, and along the coast of the Gulf of Mexico. The latter zone was a typical region of agriculture based on alluvial soils (Pope et al. 2001). In the early stage of the Olmec culture development, the villages and the agricultural fields were separated in space, because the fields had to be flooded, while the villages were located in upland positions. Later, the development of agricultural technology also allowed cultivating more compact soils of the watersheds around the villages. Thus, the later Olmec settlements already had different types of agricultural fields that allowed their expansion outside of the extensive flood plains. The civilizations of the Classic period, such as the Totonac culture, also had a diversified approached to agriculture.

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Fig. 7.1 Huictli—the most common tool for soil management in pre-hispanic Mexico (an original drawing of Ma. del C. Gutiérrez-Castorena)

The Yucatan Peninsula represents a unique area that will be discussed below, because the development of an agricultural civilization on an extremely shallow soil is very uncommon, and thus there is an intensive discussion about this area.

The most extensive zone of agriculture coincided with recent deposition of volcanic ash. The major part of the volcanic soils is related to the Trans-Mexican Volcanic Belt, which served as a cradle for the majority of Mesoamerican civilizations. The areas of volcanic deposition on the coast of the Gulf of Mexico (San Andrés volcano) and in Central American Cordillera also served as important centers of agriculture for some groups of Olmecs and Mayas, respectively. It does not mean that the only cultivated soils were Andosols/Andisols, but these soil groups had the best physical properties for agricultural production. Since in pre-Hispanic agriculture the main tool for managing soils was *huictli* (Fig. 7.1), a sharp stick that could not loosen hard soils, the physical workability was the primary criterion for land selection.

The agrotechnology of the pre-Hispanic cultures was surprisingly a combination of primitive techniques and ineffective tools with some really incredible notions. Swidden farming was widespread. For example, in the Michoacán State the periodic burning of the natural vegetation and land cultivation resulted in several cycles of accelerated erosion (Heine 1987; O'Hara et al. 1993). The cited study used the lacustrine sediments for the records of erosion intensity. Similar results might be obtained for the soils formed at the toeslopes: many profiles are composed of multiple layers of sediments transported by superficial water fluxes (Alberto Gómez-Tagle-Rojas, unpublished results). The accumulative character of these layers could be easily identified by their loose morphology, difference in color, and the presence of charcoal particles in the lower limit of each layer. There is almost no doubt that each cycle of agricultural activity resulted in intensive water erosion. Did erosion bother the farmers? It seems that at least in the trans-Mexican Volcanic Belt it was not the major problem for the agriculturalists. Since the depth of pyroclastic sediments was great almost everywhere, the loss of some part of the earth from the topsoil was not catastrophic. One should remember that the volcanic ash with easily weatherable substrate is potentially fertile at any depth, like eolian loess-like sediments. Even more, the deeper layers formed in ancient sediments (paleosols) with crystallized clay minerals could have better agronomic properties: they are also soft and easy to manage, but lack such unfavorable properties of Andisols as strong phosphate retention. The situation resembles the positive effect of erosion in some places in Africa, where erosional processes might wash excessively weathered substrates from the surface, and thus expose potentially more productive soil-forming materials (Fyfe et al. 1983).

Although there was certain indifference of local agriculturalists to the issues of erosion in most places, terracing was a usual practice in Pre-Hispanic Mexico, from Sierra Madre Oriental to the southern border (Donkin 1979). Terracing was reported to be a common technique in many parts of the world (Sandor 2006) aimed at the formation of plain fields. The main reasons for terracing worldwide were soil conservation purposes, i.e., preventing water erosion on steep slopes. Also plain terraces were more convenient for plowing using domestic animals. In many places, terraces also served for better capture of water, including even flooded terraces for rice growing, like in China.

The Mesoamerican people did not have domestic animals for cultivation, but still constructed terraces for soil protection from intensive erosion and for capturing water. The dates of the beginning of the construction of terraces vary from 1,000 to 600 BC according to different authors (Herold 1965; MacNeish 1958). The terraces were reported to be used mainly for water collection and storage. Outside of the trans-Mexican Volcanic Belt, the most famous localities with well-preserved terraces are found in Oaxaca: in Monte Albán, a famous memorial of Zapotec culture (Laird 1989), near Tehuacán (Palerm and Wolf 1957), in Ozolotepec (del Paso y Troncoso and Vargas-Rea 1944), and in Montenegro-Tilantonga, the zone of the Mixteca Alta (Spores 1969). There are also some examples of terraces in the areas with no volcanic influence, where intensive erosion really destroyed soils down to the solid rock, like the mountains of Tamaulipas (MacNeish 1958) and in the vicinity of Veracruz (Rojas-Rabiela 1985). Although the volcanic soils had better resistivity to erosion and higher water-holding capacity, still there was a consistent deficit of soil moisture due to a long dry season. Most authors consider that the whole region suffers from draught since the end of the first millennium, which among other consequences, provoked the fall of the Maya culture (Haug et al. 2003; Hodell et al. 2007). The majority of the terraces within the Trans-Mexican Volcanic Belt are believed to have been constructed between the eleventh and fifteenth centuries, though many of the terraces have never been

Fig. 7.2 A typical view of *chinampas*, Xochimilco. Reproduced with a permission of JRC

dated, and their age was considered to be the same as the settlements (Donkin 1979). We believe that the construction of the terraces intensified with the progressing aridization of climate. The most important places with terraces were reported within the volcanic areas in San Miguel Tlaixpan, in Tlaminca and in Cerro de Tezcutzingo, in Texcoco, the center of the Acolhua culture (Laird 1989; Oropeza-Mota1999), in Hidalgo, Tlaxcala and Puebla (West 1970; Donkin 1979), in the Valley of México (Rojas-Rabiela 1985), and in Chilchota, Michoacán state (del Paso y Troncoso and Vargas-Rea 1944).

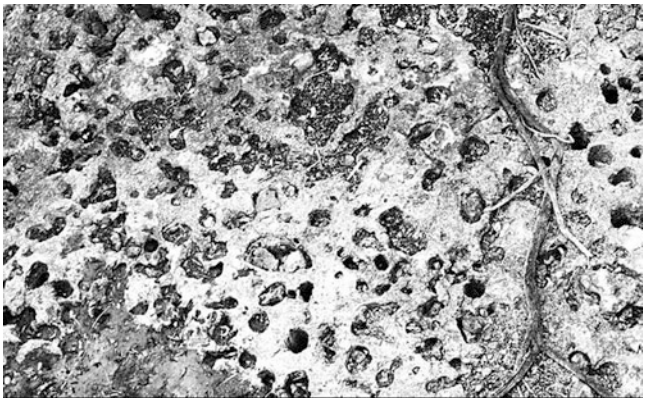
The use of slash-and-burn techniques (also known as swidden farming) shows that there was no scarcity in land for the native population. Actual degradation of soils in such important nodes of ancient civilization as Teotihuacan should be ascribed both to the climatic fluctuation and to the effect of intensive agricultural exploitation (Rivera-Uria et al. 2007; Solleiro-Rebolledo et al. 2006). It is important to note that the agrarian techniques imported from Europe appeared to be much more destructive for the soils and the environment (Whitmore and Turner 1992; Montogmery 2007). For example, plowing, especially for corn cultivation, had a catastrophic effect on the development of soil erosion. See Chap. 6 of this book for impressive details.

Was the Pre-Hispanic agriculture in Mexico effective? We think that the answer is positive: the volcanic belt of Mexico supported the well-being of several major cultures with millions of inhabitants. When the Spaniards came to Mexico, the population of Tenochtitlan was several times greater than of Madrid, and the Valley of Mexico had about one million inhabitants (West 1970). The fact that such a great number of people could live with few small domestic animals and almost no source of proteins of animal origin, and still develop an advanced complex culture shows that the effectiveness of agricultural production was very high.

7.3 The Floating Gardens of Tenochtitlan

The most advanced technique for agricultural production was developed in the Valley of Mexico. There soils were constructed of lacustrine mud at the bank of the lakes; these soils remain to be the most productive in Mexico even now. The tribes of hunters and fishermen came to the borders of a big system of lakes in the center of the valley around 200 BC (García-Calderón et al. 2007). The water system included two lakes with fresh water, Xochimilco and Chalco, and three lakes with brackish water, Texcoco, Xaltocan, and Zumpango. When the Spaniards came, the total area of the water body was 1,500 km^2. Settlements occupied mainly the southern coast that corresponded to the Xochimilco Lake. From the very beginning, the native population practiced the construction of *tlatel*—high rectangular platforms for housing, and *chinampa*—agricultural fields constructed of the mud excavated from the bottom of the lake (García-Calderón et al. 2007). The blossom of *chinampas* agriculture is referred to the Classical period of Pre-Hispanic culture in Mesoamerica, to the beginning of eleventh century AD (Rojas-Rabiela

Fig. 7.3 Cavities in the limestone bedrock, the diameter ranges from 10 to 70 cm. A fragment of the original picture provided by S. Sedov



1983). These areas were used by small ethnic groups such as the Chichimeca, Acolhua, Tepaneca, and Otomi, some groups influenced by Toltec culture, and later dominated by the Aztecs. The chinampas agriculture became the main source of food for the growing capital of the Aztec Empire—Tenochtitlan, a city with a population of more than 200,000 inhabitants.

The system of *chinampas* is a traditional agrarian technique, which includes a series of agronomic, fishery, and forestry activities (Gómez-Pompa 1978; Ezcurra 1990; Rosas et al. 1984). Crop production, at least of 30 species, including corn, vegetables, and other edible crops, provided high diversity of the agroecosystem and balanced nutrition for the inhabitants (West and Armillas 1950; Rojas-Rabiela 1990). The *chinampas* zone of Xochimilco was characterized by a combination of growing vegetables and flowers that favored biological diversity and economic sustainability of the region. Moreover, most cultivated fields were combined with fruit trees and some forest trees, such as *Salix bonplandiana* and *Schinus mole,* which stabilize the soil. Other activities developed in the system were fisheries and collection of various organisms: birds, water invertebrates, rabbits, frogs etc., which formed a significant part of the diet for the inhabitants (Rojas-Rabiela 1983).

An important component of the agroecosystems is the net of channels (Fig. 7.2), which have been used as a drainage system, as well as for irrigation and maintaining soil humidity. Excessive use of the water from the channels resulted in lowering of the water level and the almost disappearance of the lake. The properties of the anthropogenic soils of *chinampas* are discussed in a number of papers, which deal with particular issues, such as *chinampas* cultural heritage (Rojas-Rebiela 1983), organic matter composition (García et al. 2007; Reyes-Ortigoza and García-Calderón 2004; González-Salgado et al. 2010), contamination (Vallejo and Aguilera 1994; Ramos-Bello et al. 2011), or microbiology (Rosas 1984). The morphology and properties of *chinampas* soils were also discussed in a recent paper by (Ramos-Bello et al. 2011).

The soils of *chinampas* are unique products of a combination of lacustrine sedimentation with a strong influence of pyroclastic materials, artificial soil construction, and long-term intensive agricultural management. These soils are layered, and characterized by relatively uniform dark gray color, irregular distribution of organic carbon and clay with depth, generally high percentage of carbon, including organic materials in some layers. Some soils show an increase in organic matter with depth, and other profiles have maximum organic matter content in the surficial layers and in the subsoil. Generally, the dynamics of sedimentation resulted in the decrease in organic matter in the upper layers of lacustrine sediments because of recent increases in erosion rate, and consequently an increase in the proportion of mineral particles in the sediments. Most probably, the high organic matter content in surficial layers of some of these soils is due to excavation and accumulation of organic-rich subsoil material in the course of digging the channels. The *chinampas* soils are characterized by alkaline reaction and high exchangeable sodium content. The alkalinity of soils depends more on exchangeable Na than on free sodium bicarbonate. The dominant salts are Na and Mg sulfates and chlorides. Soluble salt content varies in a wide range and depends on the proximity to uplifted areas that serve as sources of freshly released ions. During a dry season, we observed strong concentration of salts in the surficial layers of the majority of soils. Soil remediation in *chinampas* is a big challenge because a combined treatment of water, soil, and vegetation is needed.

Actually, the soils of *chinampas* are strongly affected by the urbanization of the Valley of Mexico. The entire ancient zone of cultivation is now within Mexico City. More and more people prefer constructing new housing on the raised surfaces rather than to continue cultivating corn, vegetables, and flowers. The quality of food strongly decreased due to urban contamination (Rosas 1984; Vallejo and Aguilera 1994; Ramos-Bello et al. 2001). The quality of water is getting worse every year. The *chinampas* zone of Xochimilco, which has been included to the list of world cultural heritages of UNESCO in 1987, is now at the edge of losing this status.

7.4 The Maya Miracle

Perhaps, the Maya culture is the most popular Mesoamerican civilization among the general public. An impressive level of architecture and social organization leaves open a question that is important for an agriculturalist or soil scientist: how this culture could rise on an almost flat limestone platform with practically no fine earth on it? This question is tightly related with such topics as the growth and fall of the entire Mayan civilization. The drop in the developments of this culture and the abandonment of the cities are usually related to the decrease in agricultural production, either because of climatic change or due to soil degradation (Haug et al. 2003; Hodell et al. 2007; Fedick et al. 2008).

Maya agricultural techniques are not well understood yet for all the environments where they were applied (Bautista et al. 2011). The elements of the Mayan technology are taught in agricultural schools in Mexico. The pre-Columbian Mayas developed different agricultural techniques for three different habitat types: mountain, swamp, and coastal environments. Large areas of existing terraces in southern Campeche and Quintana Roo indicate that the Mayas successfully developed agriculture in the highlands. On the flood plains and valleys, the Mayas fought the floods by raising fields and building irrigation and drainage channels, as in Belize, Quintana Roo, and the East River depression area along the Rio Candelaria. Multi-microhabitat agriculture established by the ancient Mayas in forest areas is still a viable solution for the current agricultural development (Quezada 2002). The Mayas developed a very detailed soil-landscape classification that is still used by the farmers (Bautista and Zinc 2010).

The geological structure seems to be very unfavorable for agricultural production on the limestone platform. However, actual practices of the farmers evidently demonstrate how the ancient Mayas managed to use small karst cavities in the limestone (Fig. 7.3), where the fine earth accumulates, for producing a great variety of crops (Fedick et al. 2008; Flores-Delgadillo et al. 2011). The natural biofertilizer for these "pots" of various sizes is periphyton that forms in these cavities in rainy season (Palacios et al. 2003). The physical and chemical properties of the fine earth in the small karstic containers were shown to be good (Flores-Delgadillo et al. 2011). However, the technique required selection of a suitable plant for each cavity, a kind of an ancient "point" or "precision agriculture" (Fedick et al. 2008). Evidently, the agrarian system was very fragile, and any external influence could easily unbalance it.

7.5 Conclusions

Sustainable agriculture is a common concern nowadays (Jackson 2002; Montogmery 2007), and the soils are one of the key issues for providing stability. Many civilizations in the human history disappeared just because they could not manage their soils well, and the processes of soil erosion, salinization, or any other degradation phenomena shortened the agricultural production (Krupenikov 1992). In this sense, the agricultural history of Mexico is edifying. It gives the examples of both very wise and sophisticated agricultural techniques and the feebleness of many solutions facing environmental change and the growth of population. Whitmore and Turner (1992) give a good overview of the state of agriculture in Mexico when the Spaniards came. It was a somewhat perfect system, but a system that had no capacity for adaptation for changing climate and to the population growth. Finally, the balance between food production and population growth was maintained by mass human scarification. Thus, we can hardly consider the pre-Colombian Mexico as a kind of agrarian paradise.

However, we still have to learn more about the traditional practices of the Mesoamerican civilizations. Some of the solutions were extremely effective, and much more research and comprehension are needed to understand the value of these traditional techniques.

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Paleosols of Mexico: Origin, Paleoecological Significance, Role in the Actual Soil Mantle

8

8.1 Brief Introduction to Paleopedology

Although formed on the land surface under the influence of dynamic climatic and biotic factors, soils are rather stable natural bodies. Once developed under certain sets of environmental conditions, they could persist when these conditions change: staying on the surface in a changing environment or buried by younger sediments in the geological contexts. Soils formed in the ancient landscapes different from the present ones are called paleosols. During the last decades, these objects have attracted interest as one of the "geological records" of past environmental changes promoting a rapid interest in paleopedology—a branch of soil science dealing with paleosols (Catt 1990). The concept of "soil memory" was introduced which characterizes the set of pedogenic characteristics capable of recording and storing information from past ecosystems (Targulian and Goryachkin 2004).

This information is especially rich in the series of buried paleosols contained in the continental sedimentary sequences of various origins and timescales (alluvial, loess, volcanic, etc., from Precambrian till Quaternary (Retallack 2001). Such contexts provide stratigraphic and chronological control and correlation with other paleoecological records.

Paleosols that persist on the land surface (nonburied paleosols or relict soils) have specific implications for studies of soil geography, ecology, and management. In fact, these soil bodies form part of the modern soil mantle and provide ecological services for the current (agro)ecosystems but are neither formed nor re-produced by these ecosystems, conforming locally extinct soils (although similar profiles can develop at present under other bioclimatic conditions). Consequently, they are heritage of past climatic and biotic conditions now extinct, thus presenting a nonrestorable component of the present landscape.

Mexico has an abundance and diversity of paleosols, both surface and buried, that really can be considered to be a "paleopedological paradise". Two groups of factors promote generation of this abundance:

1. The major part of the territory of Mexico is occupied by mountainous landscapes with a high intensity of tectonic, volcanic, and geomorphic processes. These processes create a complex mosaic of geological materials and landforms of different age (i.e., alluvial and lake terraces, eroded slopes, and volcanic deposits of various eruptions). Meanwhile, younger landsurfaces are occupied by the recently developed soils, and the older ones could reveal the relict soil bodies. The same processes produce sedimentary strata (alluvial, colluvial, pyroclastic, etc.) which frequently cover the pre-existing landsurfaces and soils, producing a series of buried paleosols.
2. Mexico had a complex and tortuous environmental history with contrasting climatic and biotic shifts. Even the late Quaternary (last glacial cycle) was characterized by dramatic changes of temperature, humidity, and vegetation which occurred over the intervals of thousands—tens of thousands years, as evidenced by the available geological records (Metcalfe et al. 2000; Caballero et al. 2010). These changes left behind the relict soil bodies, developed under bioclimatic conditions different from the present day ones.

Although frequent and informative, the paleosols of Mexico only recently drew attention of researches and the existing knowledge is still rather fragmentary. Quite surprising is the little attention they received after the pioneer research of Bryan (1948); only in few works were paleosols used as stratigraphic markers or studied from a sedimentological perspective (Arellano 1953; Heine and Schönhals 1973; Cervantes-Borja et al. 1997). Before the systematic work made by the Group of Paleosols of the Institute of Geology (UNAM) there is only one paper that interprets

P. Krasilnikov et al., *The Soils of Mexico*, World Soils Book Series,
DOI: 10.1007/978-94-007-5660-1_8,

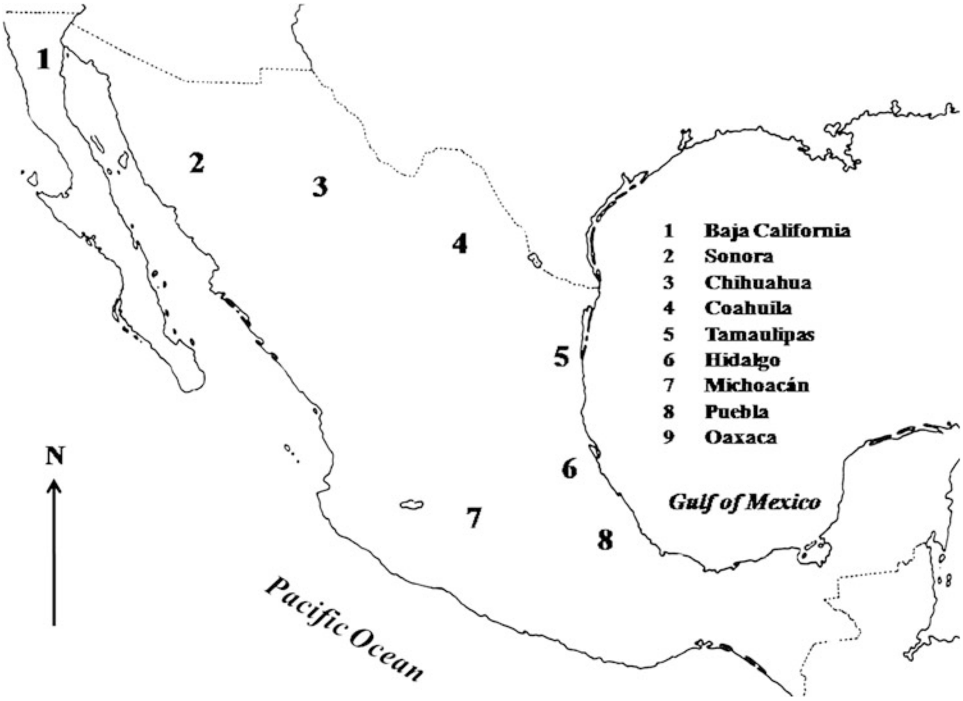


Fig. 8.1 Localities in Mexico with potential Pre-Quaternary paleosols

paleosols properties for paleoenvironmental reconstruction (Assi et al. 1997).

Here, we present some already studied cases as well as some perspectives of the regional paleopedological research.

8.2 Buried Paleosols of Mexico: Chronology, Geological Contexts, and Paleoecological Significance

8.2.1 Pre-Quaternary Paleosols: Tracks of Extinct Ecosystems

Difficulties in recognizing Pre-Quaternary paleosols are well summarized by Retallack (2001). Valentine and Dalrymple (1976) postulated that the main identification problems in the sedimentary record are: the classification of the material (soil, weathered zone, or sediment) and the changes due to diagenetic processes that modify the original properties making soils similar to sedimentary deposits. The study of Pre-Quaternary paleosols contributes to the understanding of extinct ecosystems, and it is an important tool along with the sedimentary record, to decode the evolution of the landscapes in time.

We have made a general search for the information about Pre-Quaternary paleosols in the sedimentary record of Mexico. Results are scarce, and most of the references or descriptions do not identify them specifically as soils. Thus, we try to relate the terrestrial flora and fauna record with several layers that could be interpreted as paleosols. What we find is very interesting and gives us an idea about the presence of paleosols in the terrestrial landscapes of different ages.

Perhaps the oldest continental rocks in Mexico belong to the Late Paleozoic (Permian), where some findings are related to taphoflora descriptions in several localities in northwest (Sonora), northeast (Tamaulipas), and South Puebla (e.g. Silva-Pineda and Villalobos-Carmona 1987; Weber 1997) (Fig. 8.1). The Matzitzi Formation (Permian), South Puebla, consists of conglomerates, sandstones, siltstones, and slates with fluvial facies, with some strata with abundant flora fossil (Centeno-García et al. 2009).

In the Mesozoic localities the potential for paleosols is more abundant. In the Late Trissic–Early Jurassic, there are evidences of paleofloras in the Santa Clara Formation in Sonora (Weber 1997) and Huizachal Formation in Tamaulipas and Hidalgo (Silva-Pineda 1963). The related environments for these formations are alluvial plains and wetlands.

Continental Jurassic Formations include facies of red siltstone associated with alluvial plains and abundant floras as in the Basomari Formation in Sonora (González-León et al. 2011), the Huayacocotla Formation in Hidalgo, which are interpreted as formed in warm and humid environments (Weber 2008). In the Early Jurassic Huizachal red beds, in el Cerro de los Bonetes, Michoacán (Fig. 8.1), there are fossil vertebrates buried and incorporated in volcanic materials (Fastovski et al. 2005). More recently, a paleopedological study recognized the presence of calcretes intercalated with the red beds (Tovar et al. 2012). These authors did testify the pedogenetic origin of these calcretes.

Cretaceous rocks of Sonora are included in several formations described as red or greenish mudstones developed in alluvial environments, such as the Besbee Group. In fact, García y Barragán and Jacques-Ayala (2011) described the Morita Formation as red mudstone related to alluvial plain environments affected by sub-aerial processes. They also recognized the presence of "pedogenic nodules" in the Mural Formation that also includes dinosaur bones, charcoal, and fossilized wood. The Late Cretaceous Cabullona Group in Sonora is another example of continental facies, where we can find paleosols. It has abundant fossil bones (dinosaur's vertebras) and plant and woods fossils. Calcareous nodules have also been identified. The El Tuli formation has abundant fossils of palms (Cevallos-Ferriz and Ricalde-Moreno 1995).

Besides Sonora, there are several other localities associated with dinosaur bones from north to south: Baja California (Molnar 1974); Chihuahua (Montellano-Ballesteros 2003); Coahuila (e.g. Rodríguez- de la Rosa and Cevallos Ferriz 1998); Puebla (Applegate and Cabral-Perdomo 1994); and dinousar's footprints in Oaxaca, Michoacán, Puebla and Coahuila (Ferrusquía-Villafranca et al. 1995) (Fig. 8.1).

Although in the Paleogen of Mexico, marine environments were more restricted and the terrestrial systems extended, sedimentary sequences are only studied paleontologically and sedimentologically. Perhaps, the only one paper that studies paleosols in a Mexican sequence has been done in the La Popa Basin in NE Mexico. These paleosols are found in the uppermost part of a sedimentary sequence of Paleogen red beds and have been characterized as evaporitic paleosols (Buck et al. 2010) where there are also reports of the presence of Eocene–Oligocene leguminosae (Calvillo-Canadell and Cevallos-Ferriz 2005).

Other papers related to fauna and flora discoveries in the Paleogen layers document the potential localities to find paleosols. For example, Miocene plants have been studied in Baja California Sur, Veracruz Oaxaca, Chiapas, and Tlaxcala (summarized in Castañeda-Posadas et al. 2009). Palynological research has been extensively conducted in the sediments of southern Mexico, reporting the presence of angyosperms (Martínez-Hernández and Ramírez-Arriaga 1996). In Oaxaca, Ferrusquía-Villafranca (2003) points to the presence of mammals in Miocene sediments in several localities.

As we can see Mexican Pre-Quaternary paleosols offer good perspectives of potential areas for paleopedological research that can be complementary to the knowledge produced by sedimentological, paleontological, and geological records.

8.2.2 Volcanic Paleosol Series: Archives of Quaternary Environmental History at Different Time Scales

A major part of paleosol research deals with relatively recent Quaternary paleosols that are more frequent, better preserved, and still bear a more rich and complete "soil memory". Being the last and shortest period of geological history, the Quaternary is characterized by cyclic climatic fluctuations of high magnitude (glacial–interglacial cycles). These cycles caused dramatic effects in biotic systems, surface geological processes, and soil development, leaving behind various paleoecological records among them—paleosols. Recently, the interest to "reading" these records and reconstructing Quaternary environmental history grew, being motivated by the concerns about future climate change.

In Mexico, fossil soils of the volcanic geosystems present the most attractive object for paleopedological research and have been intensively studied over the last decade. The country has numerous volcanoes with recent activity. Many of them are concentrated within the Trans-Mexican

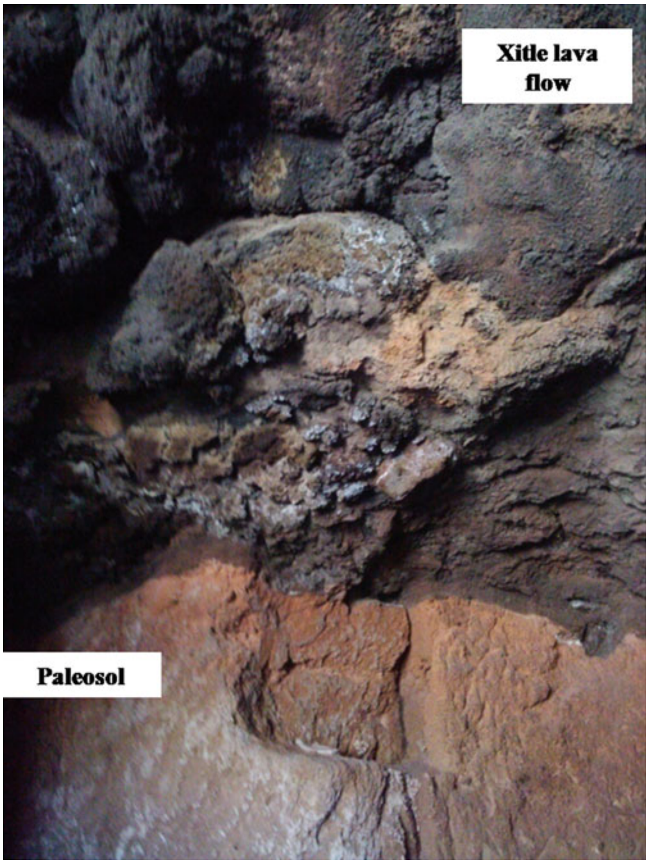


Fig. 8.2 A reddish paleosol buried by Xitle lava flow, around 2,000 years ago

Volcanic Belt. Their eruption produced lavas and pyroclastic sediments deposited on the surface, burying preexisting landscapes, landforms, and soils. Of course, soil materials are transformed by such burial to a variable extent that hampers their investigation. Some earlier researchers of Mexican volcanic soils refrained from studying buried profiles thinking them to be too modified (Mielich 1991). Under lava, soil is strongly heated causing loss of organic matter and even alteration of mineral components especially iron oxides: upper horizons loose dark humus pigmentation and become reddish (Fig. 8.2). However, under tephrous sediments (ashfall, pyroclastic flows, etc.), the transformation is much less and consists in the burning of vegetation, some compaction due to heaving and mixing of the uppermost thin layer with the fresh volcanic components. Below this layer the preservation is really good, even organic components (usually rather unstable) are not lost.

Repeated deposition of tephra by the regular eruptions of larger stratovolcanoes produces a series of buried paleosols—the most valuable "archive" for paleopedological and paleoenvironmental studies. In these series well-developed soil levels are separated by pyroclastic sediments, each of them covering older soils and serving as a parent material for the next soil generation (Fig. 8.3). Such series look similar to the famous Quaternary loess-paleosol sequences of China, Central Asia, the Great Plains of the US—now extensively studied as a "proxy" for glacial–interglacial–interstadial cycles.

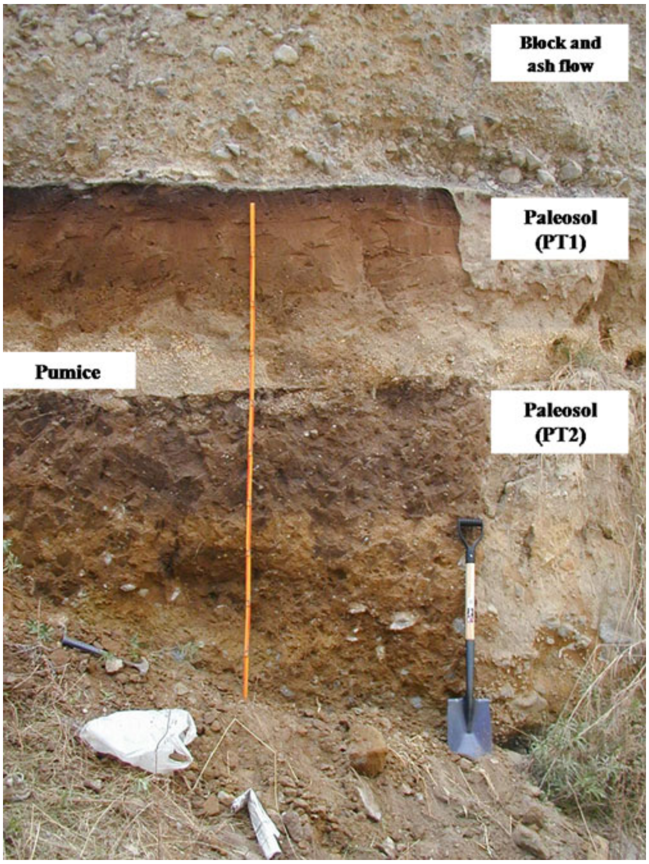


Fig. 8.3 Well-developed paleosols separated by volcanic pyroclastic materials in el Nevado de Toluca volcano, Central Mexico

The thickness of sedimentary strata is variable, sometimes they are so thin that they do not separate well the individual paleosols (then welded soils or pedocomplexes are formed), sometimes they are much thicker than the soil units. For us, however, it is very important to evaluate also the relative duration of time intervals for the sedimentary and paleopedological units. It is known, that volcanic sedimentation occurs usually in the form of violent, but short-term catastrophic event, whereas pedogenetic processes are slow and require extensive periods of stability. We conclude that a major part of the timescale of the tephra-paleosol sequences is occupied by soil formation interrupted by only short intervals of geomorphic and depositional activity (this is quite different from loess–paleosol sequences where eolian deposition of loess occurs slowly and the duration of sedimentation phases is comparable or longer than that of pedogenesis stages). Thus, these volcanic paleopedological records could be considered as semi-continuous, although they are made up of an individual buried paleosols, separated from each other spatially. The grade of soil development provides an additional "chronometer" to estimate the duration of soil formation in each unit.

The instrumental datings rather than relative time estimations are needed to produce a reliable chronological scale for a paleopedological record. The tephrous sequences provide rich possibilities for various independent geochronological methods: radiocarbon dating of charcoal from burned vegetation, paleosol humus and pedogenic carbonates, luminescence and isotope (K/Ar, Ar/Ar) dating of volcanic minerals, as well as paleomagnetic measurements are possible. Major stratovolcanoes of Mexico have well-developed chronostratigraphic schemes of their Quaternary eruptions, which can be used for paleopedological research.

Below we present three case studies of the buried volcanic paleosols (Fig. 8.4), demonstrating their potential for understanding soil and landscape evolution for different time intervals—from hundreds to hundreds of thousands years.

8.2.2.1 Tlaxcala Paleosol Sequence

The oldest paleosol series was studied in the northern part of the Tlaxcala State (Fig. 8.4). Nine individual paleosols are separated by strongly compacted and indurated ash layers, locally named tepetate. The K/Ar date from the lowest tepetate already yielded 900,000 years BP (Sedov et al. 2009); the paleomagnetic studies revealed reverse polarity (A.M. Soler, personal communication) that means

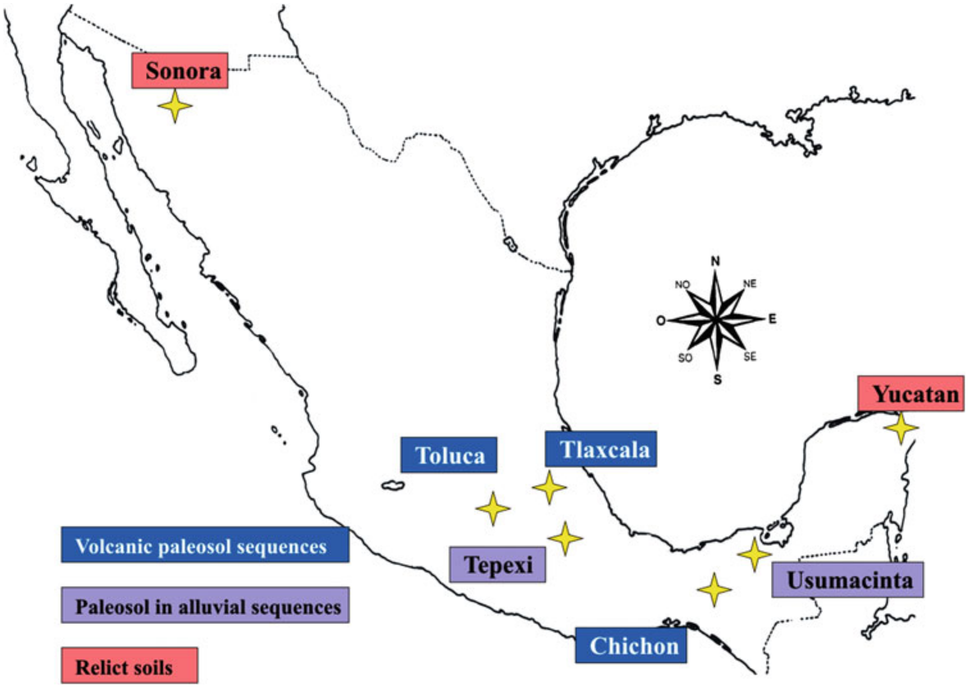


Fig. 8.4 Localities with Quaternary paleosols studied in Mexico: volcanic- paleosol sequences, alluvial-paleosol sequences and relict soils and pedosediments

that the material is older than the Brunhes–Matuyama boundary set at 780,000 years BP, which is in good agreement with the K/Ar date. The uppermost three paleosols were dated with radiocarbon, their ages ranging between 15,000 and 40,000 years BP. We have concluded that the uppermost paleosols were formed during the Late Pleistocene–Last Glacial period, whereas the middle and lower paleosols correspond to the Middle Pleistocene. Until now, there are no other geological objects in Mexico which could provide paleoecological record for this latter interval!

All buried soils have some common features: they demonstrate strong morphological evidences of clay illuviation, observed both in the field and under microscope in thin sections. This allowed the identification of Argic Bt horizons in all units. However, other pedogenetic characteristics of these paleosols differ greatly. The color differences are especially noteworthy and allowed us to discriminate three paleopedological units: upper Gray, middle Brown, and lower Red, each including three individual paleosols (Sedov et al. 2009).

The Gray Unit paleosols (Fig. 8.5a) have pale reduced color patterns and abundant Fe–Mn neoformations—mottles and hard concretions (Fig. 8.5b). The values of pedogenic (dithionite-extractable) iron and values of magnetic susceptibility are low (Ortega-Guerrero et al. 2004). These characteristics point to the surface redoximorphic and eluvial (stagnic) processes, thus the paleosols of this unit were classified as Stagnic Luvisols. Their weathering status, however, is low: the matrix contains abundant fresh primary volcanic minerals, even so unstable as volcanic glass. The illuvial clay coatings frequently have dark pigmentation, indicating that colloidal humus migrated and precipitated together with clay minerals (Fig. 8.5c).

The Brown unit Luvisols (Fig. 8.6a) have most pronounced and well-preserved clay illuvial features—coatings and infillings in the fissures and channels. In thin sections, they demonstrate high interference colors and undulating extinction patterns (Fig. 8.6b, c) indicating continuous precipitation of clay particles. The weathering grade is moderate. These soils were defined as Haplic Luvisols.

The Red unit paleosols (Fig. 8.7a) are apparently different from all other units. Their rubification together with relatively high dithionite extractable iron content (about 1.5 %) and magnetic susceptibility values (Rivas et al. 2006) point to the accumulation of pedogenic iron oxides. The clay content is also the highest in the sequence—about 50 %. Coarse volcanic minerals demonstrate features of advanced weathering in the Bt and even in BC horizons: volcanic glass is substituted by clay, and pyroxenes are etched (Fig. 8.7b). Both processes—accumulation of secondary products and destruction of primary components—are evidence of a high weathering status. Clay coatings are abundant but some of them are deformed by pedoturbation. These soils are classified as Chromic Luvisols. In one exposure, we found a thick bleached eluvial E horizon above the uppermost Bt with characteristic tonguing of the lower boundary, supposing that some of the paleosols of this unit could be Albeluvisols.

Unexpectedly, the search for a modern soil in Tlaxcala presented a more difficult task than hunting for the

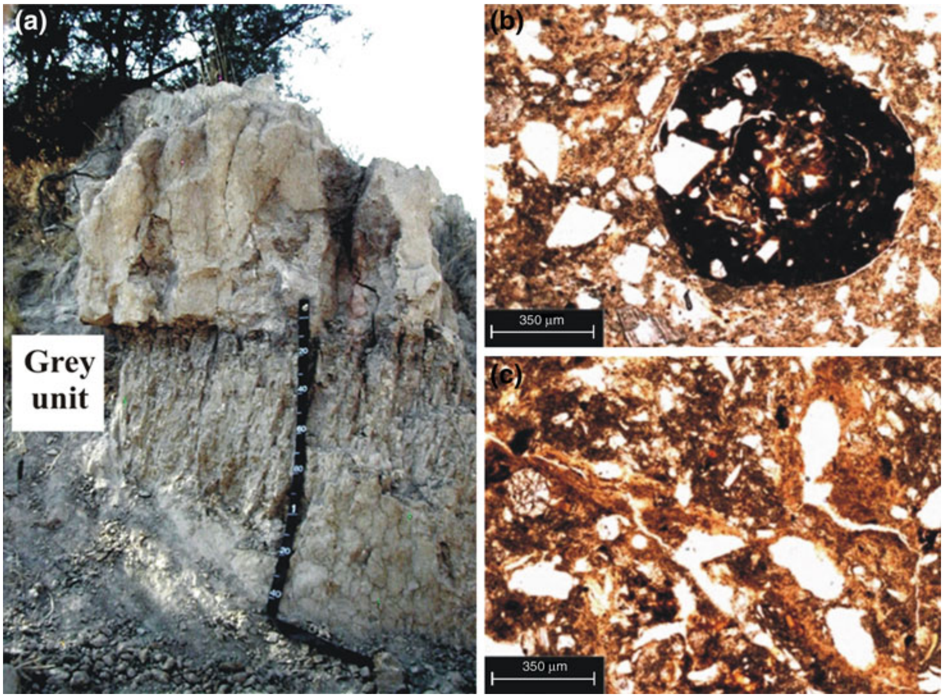


Fig. 8.5 Profile of the Gray unit paleosol in Barranca del Mamút exposure. **a** Gray unit buried by a volcanic sediment. **b** Micromorphology showing Fe–Mn and, **c** thin clay coatings with humus punctuations

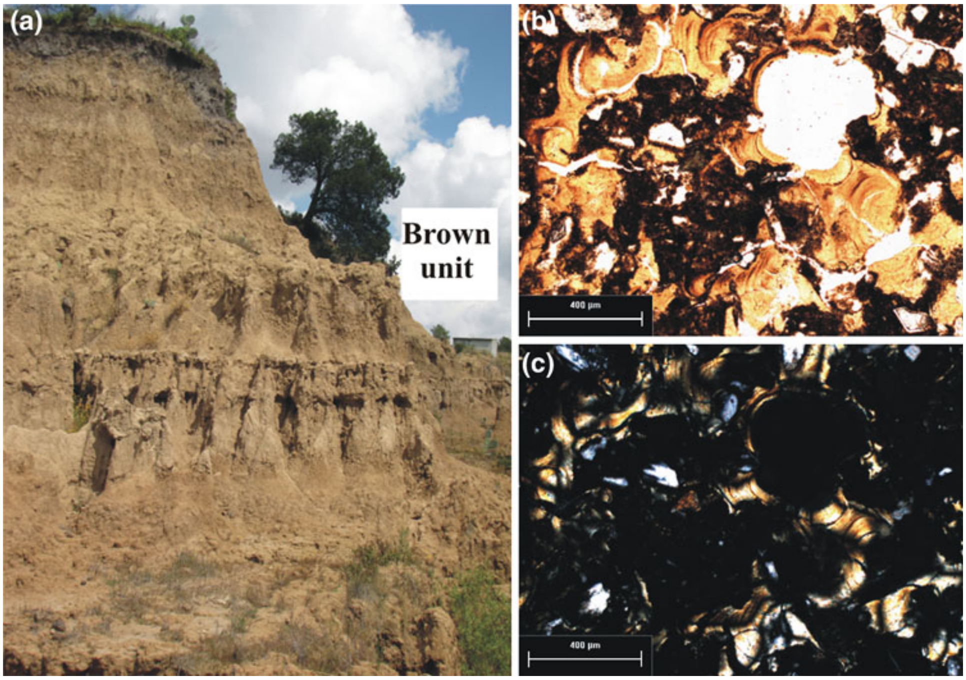


Fig. 8.6 Profile of the Brown unit in Tlalpan exposure. **a** General overview of the Brown unit. **b** Micromorphology showing abundant laminated clay coatings. **c** Same with crossed polarizers; note the high interference colors and undulated extinction pattern of the coatings

exposures of the buried paleosols. Nearly, everywhere perturbation by agriculture and human occupation, that started more than 3,000 years BP, is evident. Many profiles are eroded to the BC (tepetate) horizon or strongly mixed and enriched with artifacts (ceramics, charcoal, etc.) constituting an archeological sediment. We had to reconstruct the Holocene soil development, collecting, and linking the evidences of natural pedogenetic processes from different profiles. The resulting model includes moderate weathering together with precipitation of illuvial carbonates in the lower part of the profile. Sometimes these Holocene calcitic pedofeatures penetrate into Pleistocene Btg horizons of a Gray unit producing a conspicuous combination of neoformed carbonates, clay illuvial and redoximorphic pedofeatures. In this case, the very young radiocarbon age of carbonates (1,300 years BP)

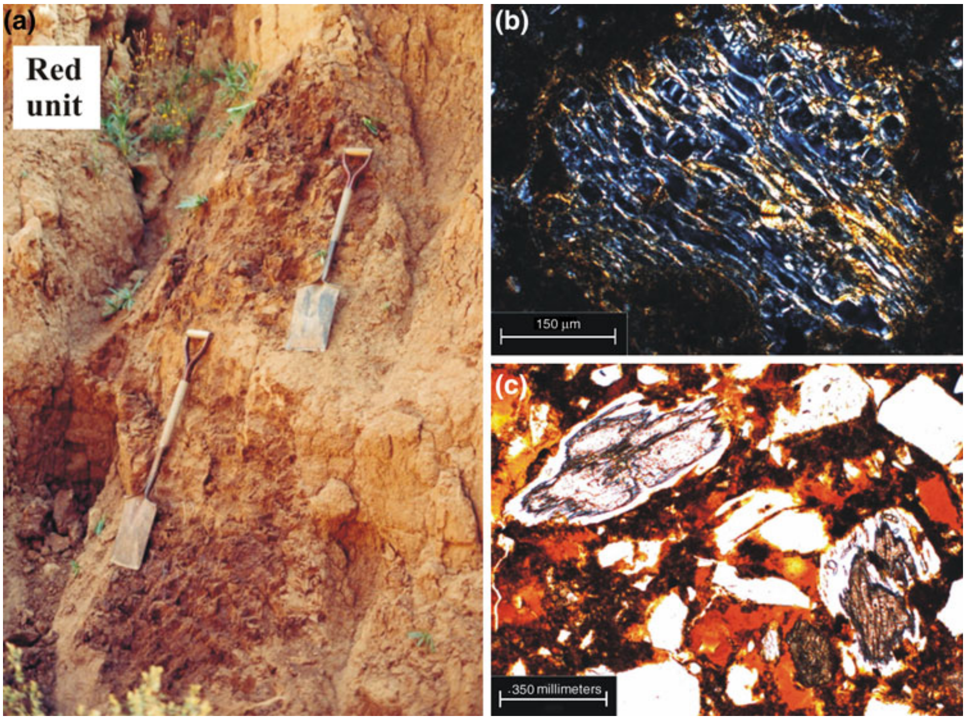


Fig. 8.7 Profile of the Red unit. **a** General overview in the Tlalpan exposure. **b** Micromorphology showing volcanic glass, substituted by clay; and an etched pyroxene

confirmed their recent origin (Sedov et al. 2009). Finally, "reconstructed" Holocene profile is supposed to correspond to a Calcic Cambisol.

The data from the Tlaxcala sequence are quite motivating to make some paleoecological inferences. First, comparing all studied paleosols with the Holocene soil we see that the latter have features typical for drier climates, whereas the former have only signs of humid pedogenesis. This evidence documents a recent arid trend in the region.

Furthermore, within the Pleistocene Luvisol sequence, the differences have a paleoclimatic significance. The most weathered Chromic Luvisols correspond to the warmest climatic stage with abundant moisture, which was sufficient to produce an Albic horizon—not found in the modern soils of Central Mexican Volcanic Highlands. Their modern analogs are Luvisols and Acrisols developed in the humid sectors of the Trans-mexican Volcanic Belt (States of Puebla, Michoacán, Morelos) at the altitudes below 2,000 m asl, mean precipitation above 1,000 mm and mean annual temperature above +18 °C. Their high weathering status also indicates a greater duration of uninterrupted pedogenesis. Weathering is known to be the slowest soil forming process. What was the reason for a milder climate in Tlaxcala during the early Middle Pleistocene? It could be a regional response to the global climate trend: the interval known as Middle Pleistocene Climate Transition (MPCT) was in general warmer, the extensive severe glacial phases were not yet fully established and that could provide the necessary climatic and temporal requirements for the Red Unit development. However, there is an alternative explanation: regional tectonic uplift. The Tlaxcala sequence is located within a tectonic block, which has been elevated throughout the Quaternary. Correlation of volcanic layers at the base of the sequence estimates a vertical displacement of about 500 m. Probably, the Red Unit paleosols were formed under a warmer climate of the lower altitudes and then uplifted to their current position. Further research is needed to evaluate the relative importance of both mechanisms.

On the contrary, the pedogenesis of the Gray Unit, Stagnic Luvisols, documents a cooler environment. The combination of strong surface redoximorphic features with low weathering status suggests that the excess of water (necessary for redoximorphic processes) resulted from low evapotranspiration due to low temperatures, rather than to high precipitation. Clay coatings with humus are rare in the tropical and subtropical Luvisols but are frequent in temperate Luvisols (e.g., Russian Gray Forest Soils)—again pointing to a cooler climate. This explanation agrees with their development during the Last Glaciation—one of the coldest periods of the Quaternary. According to the existing paleoecological records from the lacustrine and glacial sediments of the Central Mexican Highlands, the temperature during the Last Glacial Maximum was some 6–7.5° lower than at present (Lachniet and Vázquez-Selem 2005).

We conclude that the succession of Red, Brown, and finally Gray unit paleosols records a regional cooling trend of climatic change throughout the last approximately one million years.

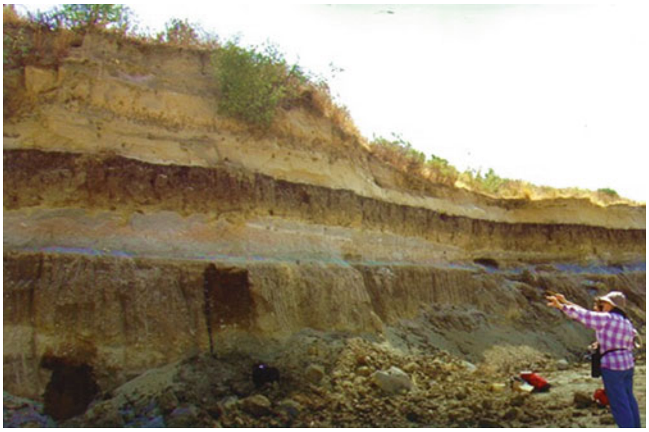


Fig. 8.8 Upper "Mollic" paleosols of Toluca sequence in Zacango exposure (reproduced with the permission of the Institute of Geology of the UNAM)

8.2.2.2 Nevado de Toluca Paleosol Sequence

A more detailed paleopedological archive for the Last Glaciation was found and studied on the northern flank of the Nevado de Toluca—4th highest volcano of Mexico, some 50 km west from Mexico City (Fig. 8.4). It consists of seven well-developed paleosols separated by thick deposits of pyroclastic flows—the products of the violent Late Pleistocene eruptions of Toluca. The upper four paleosols (PT1–PT4) have well-developed thick dark Ah horizons (Fig. 8.8) with still more than 3 % humus (despite post-burial losses). We identified these horizons as Mollic (Sedov et al. 2001). The lower three profiles (PT5–PT7) demonstrate a contrastingly different set of features: the color is reddish brown; humus content is very low, whereas proportion of clay is the highest. Abundant illuvial clay coatings are clearly seen on the aggregate surfaces and in the channels. All these features clearly point to an Argic Bt horizon.

The chronological scale for the uppermost part of the profile has been based on the radiocarbon dates from the Ah organic materials—which agreed well with the Toluca tephrochronological scheme (Macías et al. 1997). According to these dates, the sequence of Mollic horizons was formed between 10,000 and 50,000 years BP. The underlying Argic horizons contain no organic materials, but they should be older than the lower limit for the radiocarbon method. The volcanic sediments below these soils are not dated yet and the attempt to estimate their age with the luminescence method failed. Until now, only the "pedological clock" could give us a hint to the timing of their pedogenesis. From a number of soil chronosequences it is known that the well-developed Bt horizons require more than 10,000 years for their development (Birkeland 1992; Targulian and Krasilnikov 2007). Thus, we suppose that formation of the whole sequence PT5–PT7 needed some dozens of thousands of years. This allows us to set the lower limit of the whole Toluca sequence close to 100,000 years before present. This means that it covers the last glacial–interglacial cycle until Marine Isotope Stage 5 (MIS5).

Already the field observations provoked a question: Does the contrasting morphological differences between the upper "Mollic" and the lower "Argic" paleosols record the difference in the bioclimatic conditions of paleopedogenesis? Comparing buried profiles with the well-known sequence of the modern "zonal soils" could lead to the following initial hypothesis: horizons with strong clay illuviation point to humid forest ecosystems, whereas dark horizons could indicate drier—semihumid to semiarid grasslands, where such horizons are typically formed in Chernozems or Phaeozems. Similar paleoecological inferences are often done from buried Ah and Bt horizons of loess–paleosol series worldwide (Bronger and Heinkele 1989). The temptation of such straightforward interpretation of Mollic horizons is even higher, because it would be congruent with some Quaternary paleoclimate reconstructions which suppose more arid conditions during the last Glaciation compared to the Holocene (Heine 1984; Caballero et al. 1999). There are precedents for interpreting volcanic dark humus paleosols as indicator of drier grassland paleolandscape of Late Pleistocene in South America (Fölster et al. 1977).

Careful comparisons of buried paleosols with the modern analogs, taking into account not only bioclimatic, but also geological factors of soil formation, leads to a different conclusion concerning the upper "Mollic" paleosols. A number of studies of climosequences on young pyroclastic materials have shown that the highest accumulation of dark humus and development of thick Ah horizon takes place under forest vegetation and humid climates, udic soil moisture regime (Nizeyimana 1997), in contrast to a classic "zonal" sequence. The explanation of this phenomenon lies in the specific organo–mineral interactions of volcanic soils: the major part of the humus is bound to amorphous Si–Al compounds—allophanes, which are actively produced by the weathering of unstable volcanogenic silicates, especially glass under humid climates (Nanzyo et al. 1993). The resulting soils are classified as Mollic or Melanic Andosols. In Mexico, they are common within the Trans-mexican Volcanic Belt and other regions with recent depositions of tephrous materials under coniferous forests, cloud forests and tropical rainforest with abundant precipitation (Mielich 1991, see also this book). Thus, humus-rich dark-colored buried volcanic paleosols, Andosols are evidence of past humid forest ecosystems. This interpretation is further supported by high values of oxalate-extractable Al and Si (coming from allophanes) and micromorphological features of redoximorphic processes and silicate weathering, all indicative of humid pedogenesis.

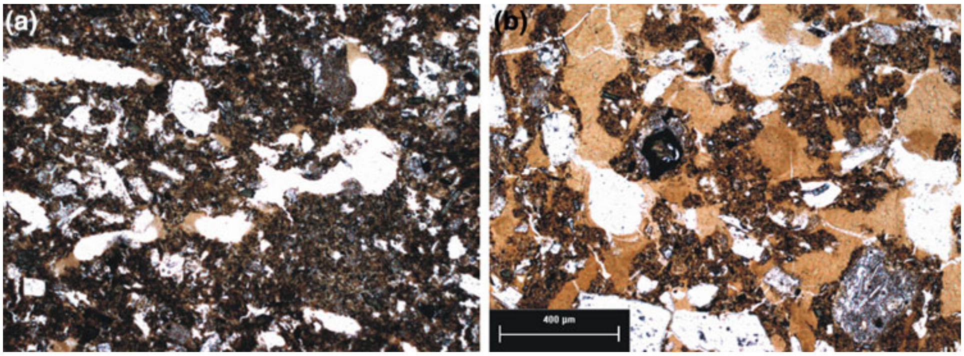


Fig. 8.9 Micromorphological features of the evolution of Andosols toward Luvisols in the paleosols of Toluca sequence. **a** Thin clay coatings in the Mollic Andosol PT3. **b** Relict granular structure in the Luvisol PT7

The assertion that such different paleosols, such as Andosols PT2–PT4 and Luvisols PT5–PT7, indicate fairly similar paleoenvironments seems contradictory at first. However, it makes sense if different durations of pedogenesis are assumed. It has been shown in a number of studies that Andosols are formed on recent volcanic sediments, whereas evolution toward soils with clay illuviation takes place on older land surfaces (Martini 1976; Delvaux et al. 1989). The driving force of this evolution is a slow transformation of neoformed minerals in volcanic soils from amorphous compounds (formed during the early stages of pedogenesis) into crystalline minerals as weathering and soil formation advance (summarized by Shoji et al. 1993). The fact that Luvisols of PT5–PT7 have more crystalline clay and less amorphous compounds (highest clay content, sharp peaks of kaolinite, and halloysite in the X-ray diffractograms and low quantities of Feo, Alo and Sio) fits well with our interpretation.

Furthermore, we found additional convincing evidence that Andosols and Luvisols form an evolutionary sequence. In the thin sections from Andosols PT2, PT3, and PT4 tiny clay coatings are visible (Fig. 8.9a). X-ray diffraction revealed the presence of halloysite in the fine material. This evidence that clay crystallization and even incipient clay illuviation already started in these profiles marks the onset of their evolution toward Luvisols. On the other hand, the micromorphological observation in the Bt horizon of the Luvisol PT7 revealed areas with fine granular aggregates—already surrounded by illuvial clay (Fig. 8.9b). We interpret this structure, not typical for Argic horizons as a relict, inherited from the earlier Andosol stage when this material formed part of the Andic Ah horizon. These observations complete the evolutionary scheme demonstrating intermediate feature sets between two end members, Andosols and Luvisols.

Thus, the paleosol record does not demonstrate major climatic changes but rather changes in the intervals of pedogenesis—they become shorter toward the upper younger part of the sequence. These intervals correspond to the periods of geomorphic stability between the episodes of volcanic sedimentation, and are thus controlled by the timing of the eruptions. We conclude that the differences among paleosols of the Toluca sequence point to the increase of the frequency of eruptions throughout Late Quaternary. This could have implications for modeling of its future activity and forecasting geological risks.

We see that volcanic paleosols of Toluca, Tlaxcala and other locations formed during the Late Pleistocene (including the Last Glacial Maximum) are indicative of humid forest pedogenesis. We conclude that during this period of major stress for the forest ecosystems on the global scale, the territory of Mexico provided conditions for a *refugium* of arboreal vegetation where a lot of tree species could survive during the "hard times" of glaciation. This could help explain the impressive high present day biodiversity of some trees (*Pinus*, *Abies*, *Quercus* among them) in Mexico.

8.2.2.3 El Chichón Paleosol Sequence

A spectacular case of very young tephra-paleosol sequence with a very short time scale was discovered in the vicinities of El Chichón volcano in Chiapas, southern Mexico (Solleiro-Rebolledo et al. 2007). This volcano is famous for its disastrous eruption in 1982 that destroyed several villages killing thousands of people. This eruption left behind thick pyroclastic deposits. On the surface until now only an incipient Vitric Leptosol was formed. However, below these deposits a set of two buried paleosols was found. The upper one was developed on the tephra from the eruption dating back to 550 years BP; this tephra buries the lower paleosol formed on the pyroclastic materials 1,250 years old. Both paleosols labeled PCh1 and PCh2 are well-developed Andosols with dark humus horizons demonstrating Andic properties (pH NaF above 9) and transitional weathered B horizons. Although quite similar in their appearance, these paleosols demonstrate certain differences in some morphological and analytical properties (Fig. 8.10). The upper buried humus horizon is darker, has better developed structure, porosity and higher humus content. We interpret this difference as evidence of strong

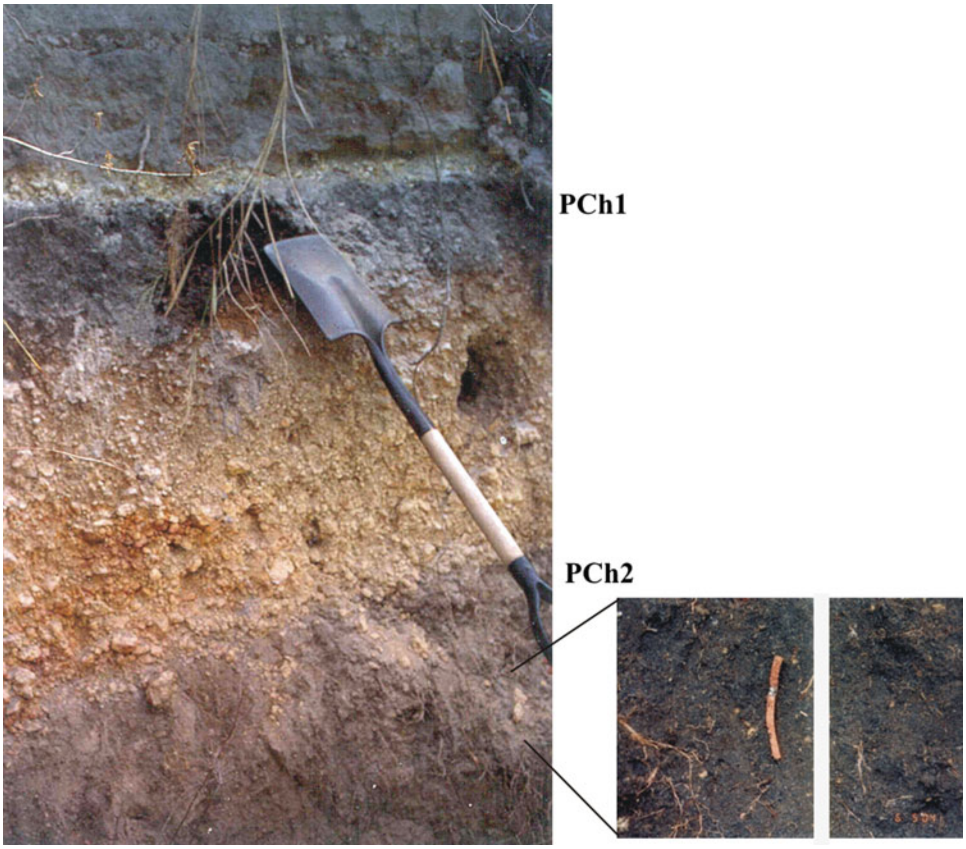


Fig. 8.10 Buried Andosols near El Chichón volcano. **a** PCh1 and PCh2 buried by the 1982 and 1408 eruptions. **b** Ceramic found in PCh2

past human impact which transformed the lower paleosol. The site belongs to the area of very dense Classic and Postclassic occupation by Maya, the major pre-Hispanic civilization in Southern Mexico. The PCh2 paleosol corresponds chronologically to this occupation period and contains direct evidences of local human activities i.e., ceramic fragments and microartifacts (charcoal, allochtonous clay materials, etc.). Loss of humus, compaction, and deterioration of structure are typical signs of degradation due to cultivation. More details about paleopedological indicators of ancient human impact will be given below when discussing the Holocene alluvial profiles.

The example of the El Chichón sequence confirms again that Andosol formation on the loose pyroclastic sediments is quite fast (Miehlich 1991). Frequent burial tephra-paleosol sequences can have rather high chronological resolution and provide soil memory for rather short intervals—at millennial–centennial scale.

8.2.3 Alluvial Paleosols: Interaction of Climate, Biota and Humans in a Dynamic Geosystem

It is well-known that river systems are attractors for organisms. Thus, the alluvial sedimentary sequences have a great potential for paleontological and archeological studies. Paleosols are frequently present in these sequences, sometimes showing close relationships to the plant and animal fossils and human artifacts. In this context, paleopedological research in such sequences has advantages for use in both paleontology and archeology, because they provide information about periods of landscape stability, when organisms overspread the landscape (including man), and periods of instability, when the river dynamic changes, causing an impact in biota. Both pedogenesis and alluvial sedimentation are climatically controlled and can be interpreted as climate signals (different from volcanic series where this signal is restricted to paleosols). Soil and sediment memory provide a proxy of environmental change complementary (although independent) to the paleobiological data. If we combine both records, the environmental history in relation to the areas for fauna–flora distribution and human settlement can be interpreted.

In Mexico, paleosols in alluvial sequences are poorly studied. In fact, fluvial systems have not been received sufficient attention as a good tool for paleoenvironmental reconstruction. Works are scarce and cover specific localities, as Chihuahua (Nordt 2003), Tlaxcala (Borejsza and Frederick 2010) and Teotihuacan (Solleiro-Rebolledo et al. 2011a). In recent time, we have started a project to study with more detail the alluvial-paleosol sequences in the

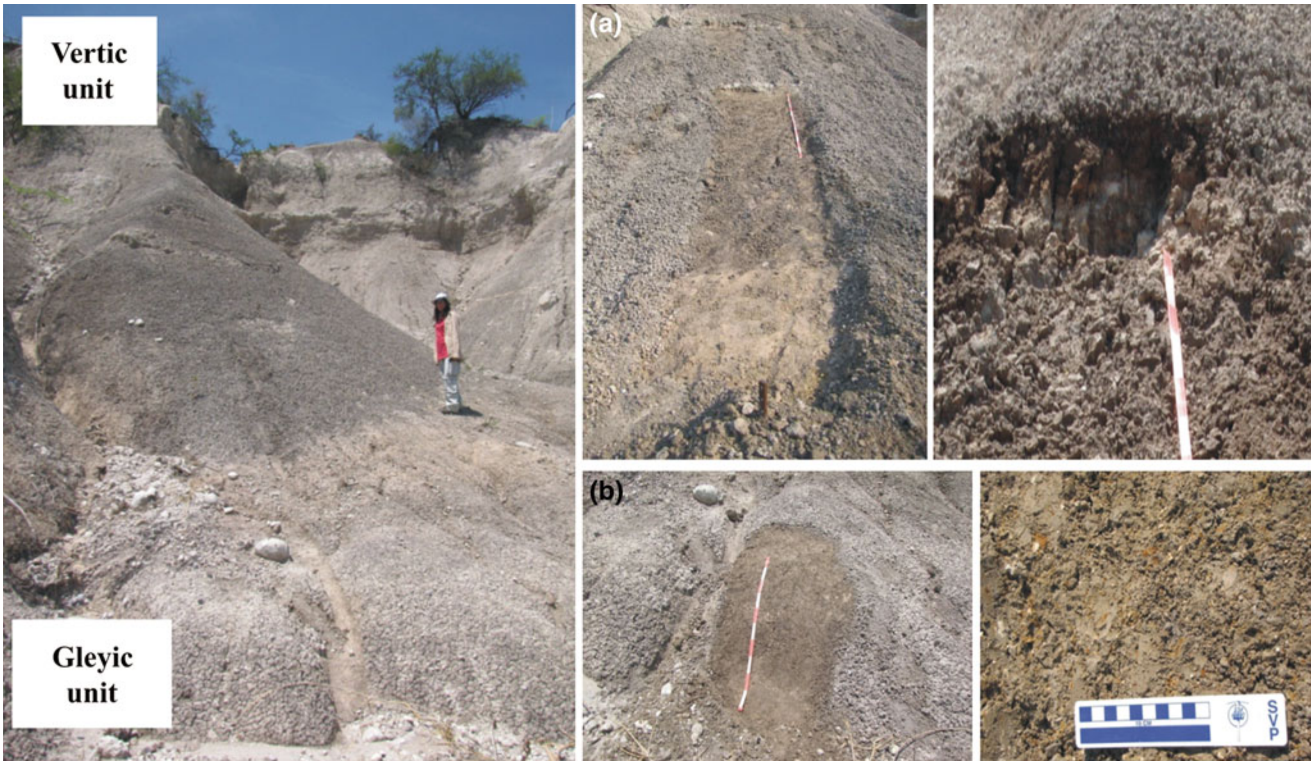


Fig. 8.11 Gleyic and vertic units in the bottom of Tepexi paleosol sequence. **a** Paleosol of vertic unit with angular blocky structure. **b** Paleosol of Gleyic unit showing the redox features (reddish yellowish mottles in a dark-gray matrix)

country. Here, we have selected two study cases, with the aim to show their use in the paleontological and archeological research, Tepexi, Puebla and Usumacinta, Tabasco, respectively (Fig. 8.4).

8.2.3.1 Paleosols in Tepexi

The study area is located in south Puebla (Fig. 8.4) on the terraces of the Axamilpa River. As mentioned, the objective of this study is to reconstruct the past environmental conditions where mammalians lived. The area is famous for its great fossil record as *Mammuthus columbi*, *Cuvieronius* sp., *Equus* sp., *Bison* sp., *Paleolama* sp., proboscidean *Mammuthus* sp. and *Glyptodon* sp. (Torres-Martínez and Agenbroad 1991; Castro-Azuara 1997; Montellano-Ballesteros 2002).

The Axamilpa section has a total length of around 22 m. It was divided into 4 units, according to its main morphological features, from the base to the top: gleyic, vertic, calcic and humic units. All of them are constituted by several paleosols with different degrees of development with intervening alluvial sediments. The gleyic unit (20–22 m) corresponds to the end of the marine isotope stage 3 (MIS3) and beginning of MIS2, according to the AMS dating of charcoal fragments included in one paleosol (28,900 ± 220 years BP). One of the most prominent features in this unit is the presence of reddish yellow mottles in a dark gray matrix (Fig. 8.11a). In this unit Glyptodon bones have been found.

Vertic unit (12–20 m) includes 10 clayey paleosols with the presence of dark A horizons with angular blocky structure (Fig. 8.11b) and stress cutans as the dominant features. This unit has been formed during the MIS2, according to the age obtained from the organic matter of one of the paleosols (26,140 ± 170 years BP). The paleontological findings in this unit include the proboscidean *Mammuthus* sp. (Tovar personal communication).

The calcic unit (6–12 m) includes two soils with spectacular laminated and indurated caliches (Fig. 8.12a), The soil matrix also has a high amount of carbonates (around 30 %). No material for dating has been found, and no chronology frame has been established. Caliche layers are not suitable for dating, because of possible contamination from Cretaceous limestones that are common in the area. *Cuvieronius tropicus* and *Equus* sp. have been associated to this unit.

The humic unit (3–6 m) has three paleosols. The most distinct feature is the presence of well-structured Ah horizons (Fig. 8.12b), with the dominance of granular structure. The age of the organic matter of the youngest paleosol in this unit is 13,450 ± 60 years BP. Thus it formed at the end of MIS2.

Fig. 8.12 Calcic and humic units in the middle and top of Tepexi paleosol sequence. **a** Humic unit with a subangular-granular structure. **b** Calcic unit showing thick laminated caliches and carbonates accumulation along the pores and fractures

The humic unit is separated from the modern soil by 2 m of alluvial sediments composed by rounded limestone gravels.

One of the most interesting results of this research is the stable isotopic composition of soil organic matter evaluated in the paleosols of all units. Values are similar and range from −24.6 to −21.9 ‰. The lowest value corresponds to the gleyic unit, which indicates the dominance of C3 plants. The highest (−21.9) has been evaluated in a paleosol of the vertic unit, indicating a mixture between C3 and C4 plants. On the contrary, modern soil has a higher value (−15) in agreement to the presence of CAM type vegetation.

The set of features found in the Tepexi paleosol sequence (morphology, isotopic signature, and paleontological findings) allows to establish the following conclusions:

1. Paleosols seem different, however, their morphology does not provide a reliable record because they are poorly developed and synsedimentary. According to Tovar and Sedov (2011), paleosols show low values of humus and magnetic susceptibility and microlamination visible in thin sections, as evidences of such character. We could conclude that they were formed in a dynamic landscape with alternating dry and humid phases and additional moisture due to high groundwater level and flooding.
2. In this situation, the paleosol characteristics which provide a direct paleobotanical signal are of major interest. Contrary to morphological features the stable carbon isotope values are similar and indicative of C3 plant domination—typical for humid environments. Phytoliths showed that grasses were always present in paleovegetation—providing food for grassers.
3. The ancient paleolandscapes were different from present ones. Much higher isotopic values in modern soils indicate climate and vegetation change toward xerophitic shrub land. Earlier slow alluvial sedimentation is now substituted by erosion and incision. It could be related to the extinction of ancient fauna.

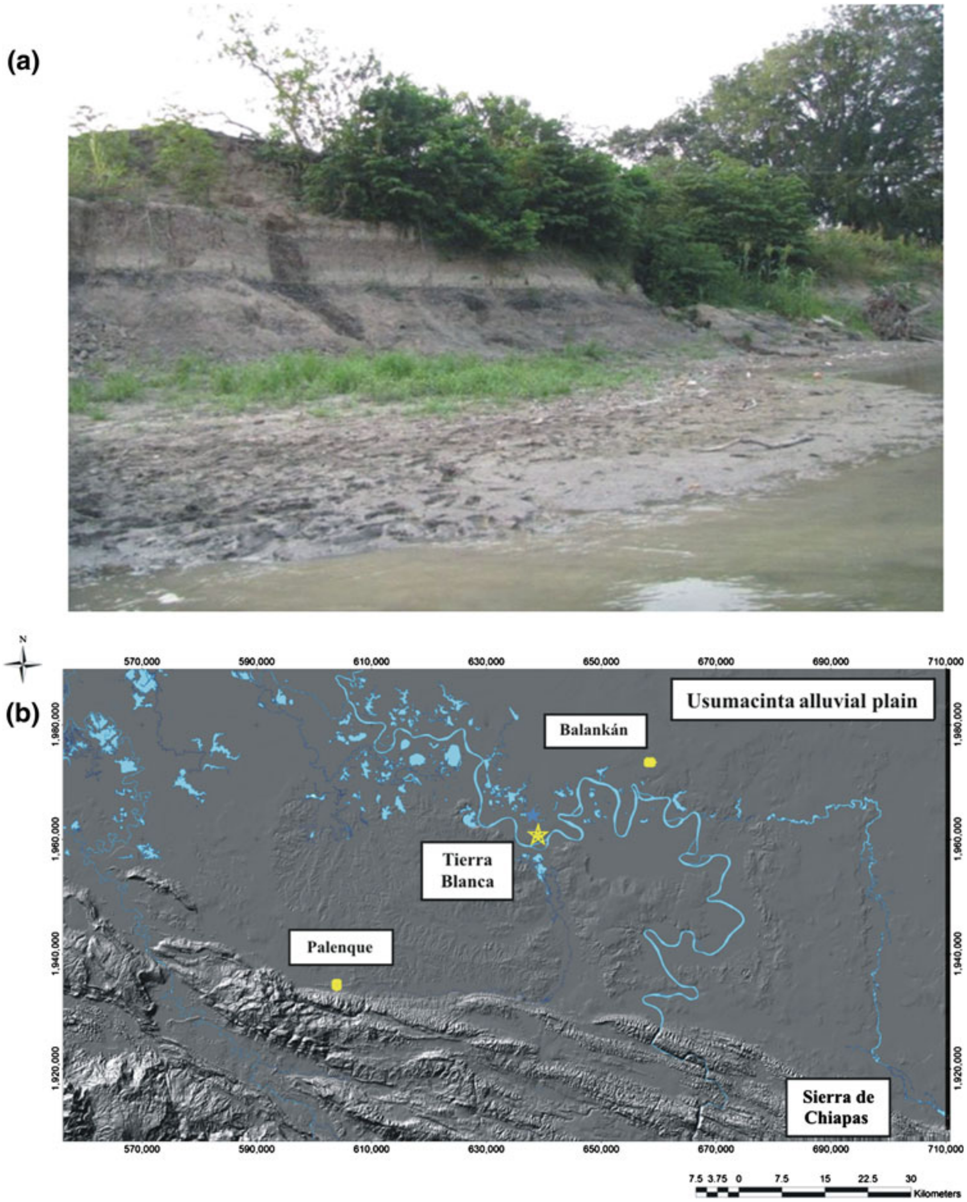


Fig. 8.13 Usumacinta River. Southern limit is Sierra de Chiapas constituted by limestone where river follows the ridge configuration through fractures and faults. In the north, the alluvial plain where the study paleosol sequence is found (the map prepared by B. Solís)

8.2.3.2 Paleosols in the Usumacinta River

The Usumacinta river is located in the southeastern part of Mexico. It runs from the south, starting in Guatemala, to the northeast toward the Gulf of Mexico. The river crosses through a mountain range belonging to Sierra de Chiapas that consists mainly of Tertiary folded limestones. This area is characterized by karstic processes where dissolution and infiltration prevail over the runoff. The river follows to the north by the alluvial plain of Tabasco State. Here the river has a different configuration, with meanders, oxbow lakes, wetlands, lagoons, and swamps (Fig. 8.13). World famous ancient Mayan urban centers Palenque, Tonina, Petén, and Yaxchilán are located in the Usumacinta basin.

We have conducted a paleosol study on the lowest river terrace in order to understand the Holocene paleoenvironmental conditions and the relationship between humans and the environment. This is especially important because the area was densely populated during the last 4,000 years.

Several soil sections have been studied, but here we report the results of one of them, where a lot of artifacts have been found.

The profile section Tierra Blanca is located in the Usumacinta alluvial plain where nine soil stratigraphic units were recognized (Figs. 8.14, 8.15). The lowermost part of this profile contains a set of four paleosols formed in a

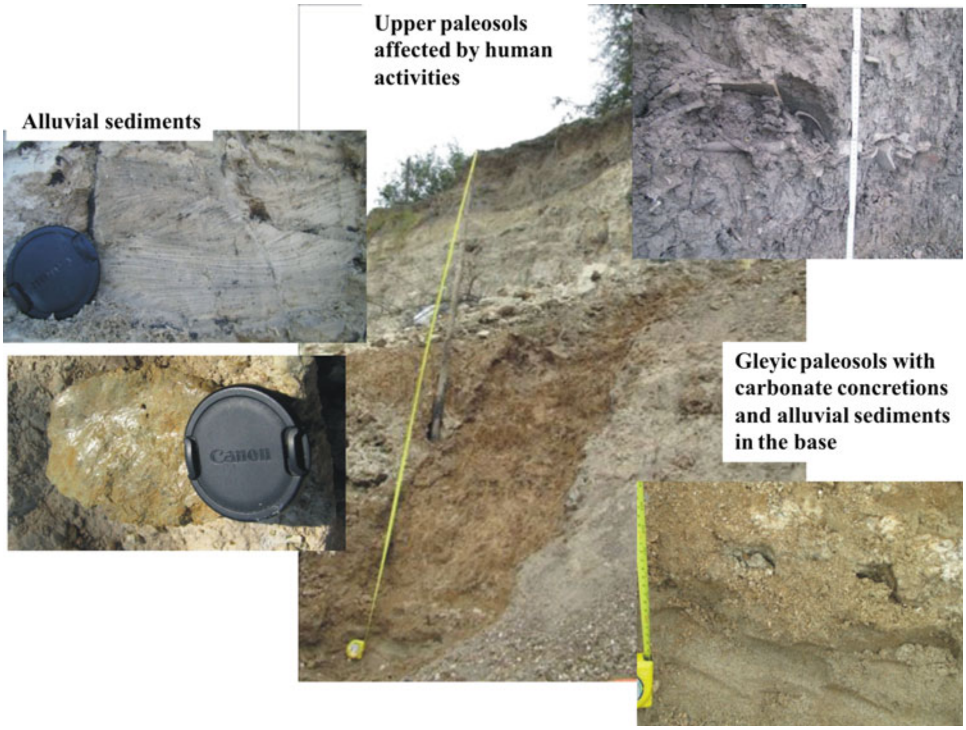


Fig. 8.14 Tierra Blanca paleosol sequences, showing the gleyic paleosols with carbonate concretions in the base and the upper most part with dark paleosols where a lot of artifacts have been found. Both kinds of paleosols are separated by a silty sediment with cross stratification

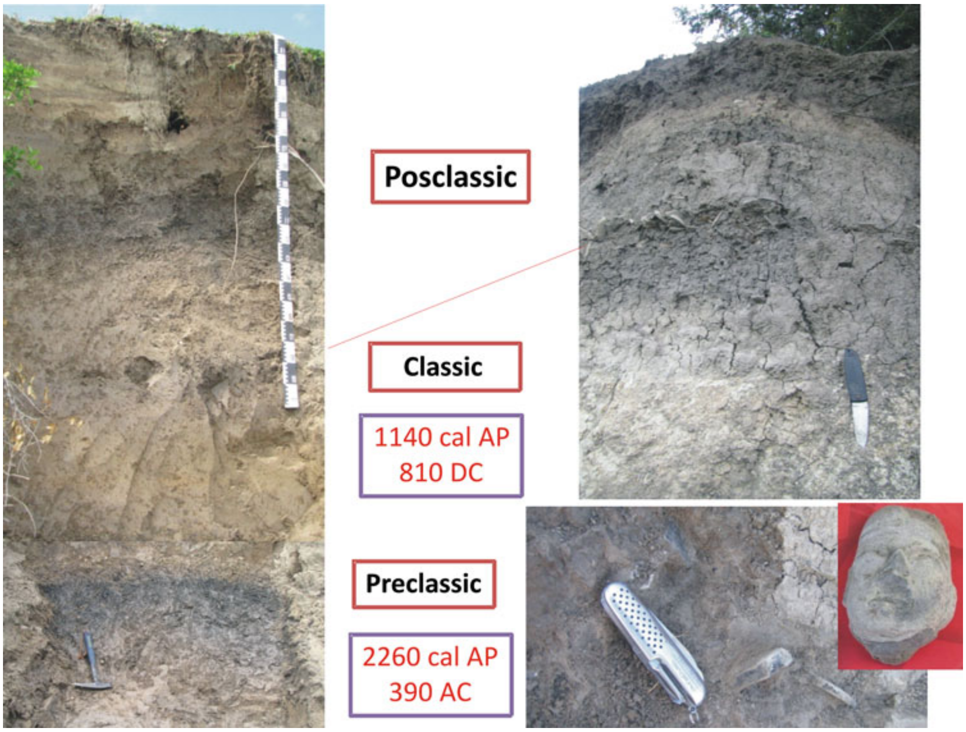


Fig. 8.15 Top paleosols in Tierra Blanca show strong human disturbance with abundant artifacts that clearly differentiate the cultural periods

pre-occupation period related to the alluvial plain environment that was flooded frequently. We defined four phases of soil development (paleosols 6, 7, 8, and 9) all with strong gleyic features (mottles, Fe–Mn spots, and concretions). In the lowermost paleosol we found hard carbonate concretions, 5–10 cm diameter that seems in discord with the redox features (Fig. 8.14). These carbonate concretions were dated, giving an age of 3240–3110 years BC.

Separated by 1.50 m silty sediments (Fig. 8.14), the uppermost part has three paleosols with abundant artifacts.

Although the younger paleosols are less developed than the gleyic ones, they are well-differentiated morphologically. We distinguished five paleosol levels (Fig. 8.15). Four of them have dark A horizons, with granular and angular blocky structures. The oldest (paleosol 5) is the better developed and shows vertic features (angular blocky structure, stress cutans, and cracking) evidence of seasons of wetting and drying. Here preclassic ceramic has been found (not Maya but Olmec). The AMS dating of charcoal pieces gave an age of 390–210 years BC. The third paleosol has ceramic of the Maya classic period (250–900 AD). The age of charcoal included in the 3A horizon is 810–980 AD. In the youngest paleosol, we have also found abundant ceramic and burials belonging to the Postclassic (900–1500 AD).

Figure 8.16 shows qualitative differences in the morphology of the studied paleosols, interpreting them in terms of the intensity of different pedogenetic processes. In the oldest paleosol, we recognize the dominance of gleyization related to an environment with high humidity and water saturation. These paleosols are very similar to those observed today in the alluvial plain in Balankan (Fig. 8.13) on an older terrace. In contrast, we have also the presence of carbonate concretions, which are related to a dryer climate. We suppose they were formed at the final stage of gleyic paleosols formation that occurs around 5,000 years ago (according to the radiocarbon age of carbonate concretions).

Silty sediment document an activation of alluvial geomorphic processes, related with changes in the fluvial system probably because of climate changes in the region. These changes can be correlated to other records from Southern Mexico and Central America. For instance, Mueller et al. (2009) document a progressive drying trend that began about 4,000 years ago in northern Guatemala.

What indicates the upper paleosols? The presence of the vertic paleosol (paleosol 5) indicates a seasonal climate during the Formative period (600 BC–250 AD). Younger paleosols show that this seasonal contrast has diminished.

It is important that during preclassic and classic periods there were long stages of geomorphic stability allowing soil development. These conditions favored human occupation of the lowest terrace, where the ancient inhabitants found fertile lands and easy access to water resources. Productive and sustainable agrosystems on alluvial soils of Usumacinta are now supposed to be vital for subsistence of the upland urban centers of Classic Maya period (Solleiro-Rebolledo et al. 2011c).

Tepexi and Usumacinta alluvial paleosol-sequences have shown the high value of paleopedological studies in the alluvial systems that can be integrated to other

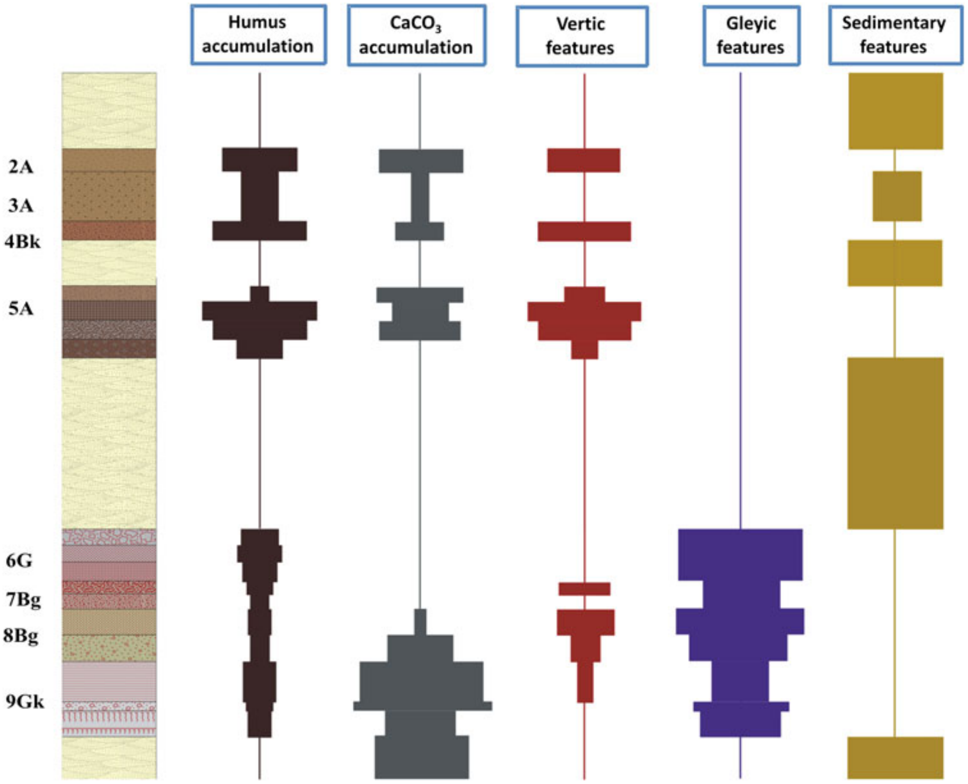


Fig. 8.16 Qualitative rate of morphological features in Tierra Blanca section, where clearly differentiates between gleyic paleosols, sediments, and cultural paleosols are found

paleoenvironmental proxies and give better indicators of climate change in relation to biotic and cultural evolution.

8.3 Relict Soils in the Modern Soilscapes: Memory and Present Functioning

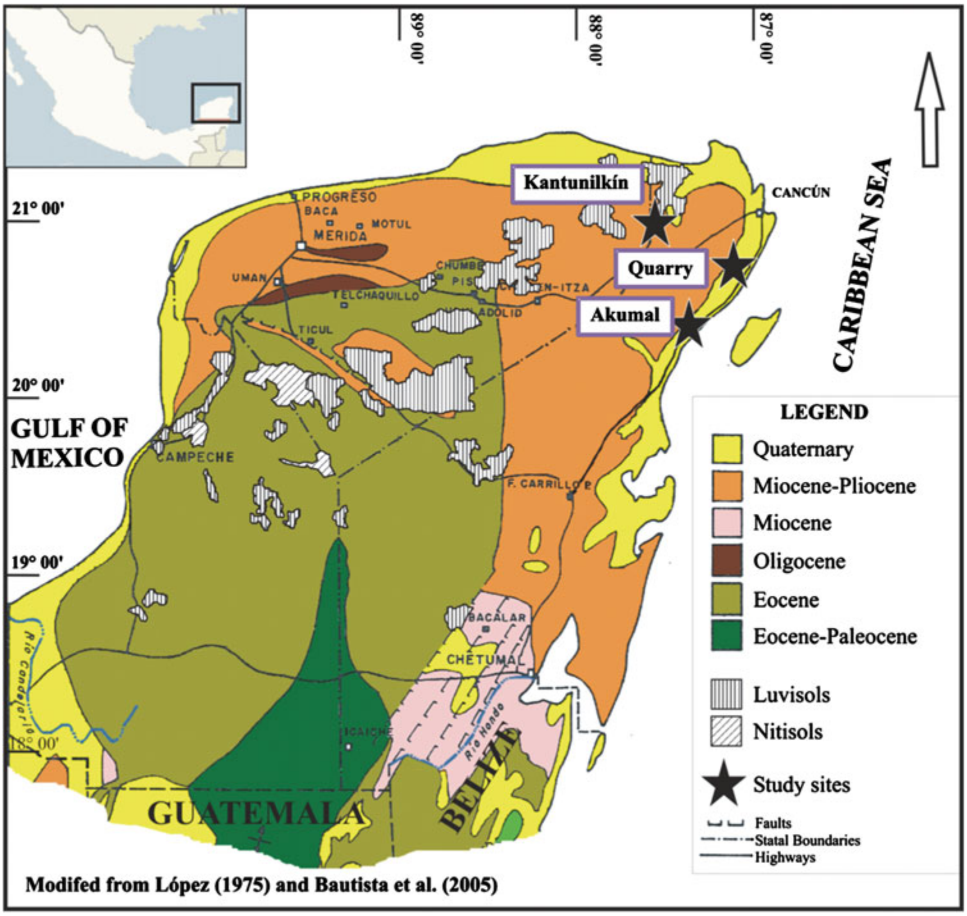
8.3.1 Red Clayey Soils in the Karstic Landscape of Yucatan: Long-Term Tropical Pedogenesis on Limestones and Allochtonous Materials

Thick, red and clayey soils, known as Terra Rossa or Red Mediterranean Soils (e.g. Yaalon 1997; Durn 2003), developed on limestones are usually different from soils formed on other parent rocks. For many years there have been attempts to understand their genesis, considering them as product of autochthonous processes (e.g. Tučan 1912; Bronger et al. 1983); or by the contribution of allochtonous material (Yaalon 1997; Muhs and Budhan 2009). Extensive research was done explaining the transformation of the parent material (whichever origin) into the soil matrix by limestone dissolution (Boero and Schwertmann 1989; Durn 2003) or by replacement of the limestone by authigenic clay at a narrow reaction front (Merino et al. 2006; Merino and Banerjee 2008).

Karstic landscapes of the Yucatán include a mosaic of soils as thin Rendzinas, thick red soils (e.g. Aguilera 1959; Quiñones 1975; Bautista et al. 2005; Cabadas-Báez et al. 2010a), pedosediments in karstic sinkholes (Cabadas-Báez et al. 2010b), and hydrogenic Calcisols in the wetlands (Sedov et al. 2008; Solleiro-Rebolledo et al. 2011b). Despite their small depth, Rendzinas contain high percentages of clay and show a strong weathering with a soil matrix completely leached (Sedov et al. 2008).

We have formulated several questions regarding the soil diversity of the Yucatán and its link to the landscape evolution. Is there any relation between thick red, clayey soils and thin Rendzinas? Are the kind of limestone and age controlling their formation? Are red soils the sign of longer stable landscapes versus Rendzinas representing short periods? Finally, do Rendzinas, red soils and pedosediments represent quite different environmental conditions during their formation?

We present here the results from studies in Península de Yucatán trying to answer such questions.



Modifed from López (1975) and Bautista et al. (2005)

Fig. 8.17 Geology of Peninsula de Yucatán, showing location of study objects: red soils in Kantunilkin over Tertiary limestones; pedosediments in karstic “pockets” in Quaternary limestones (in a quarry); and Rendzinas in Akumal

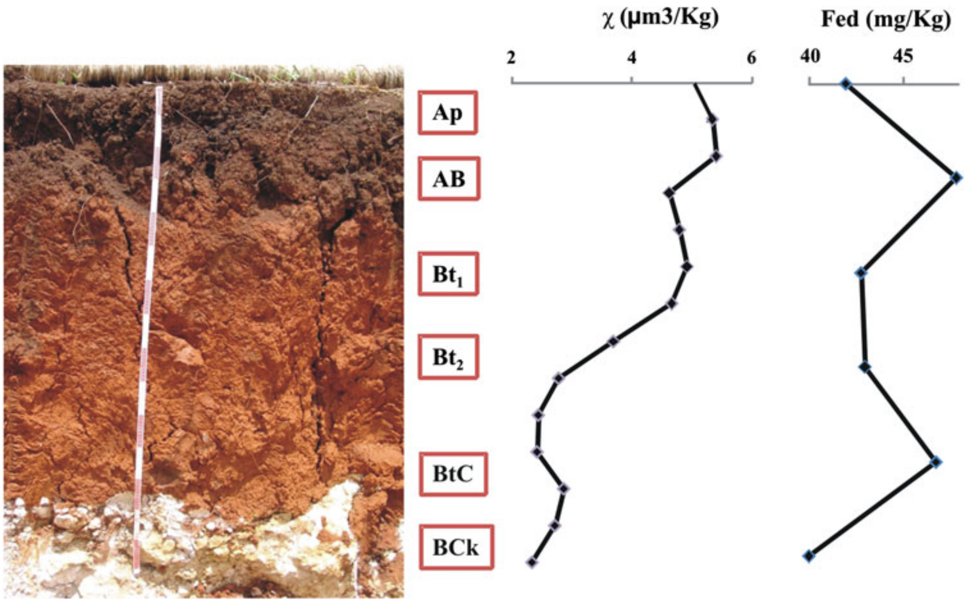


Fig. 8.18 Red soil profile in Kantunilkin, Yucatán showing the magnetic susceptibility values (χ) and Fe extracted by dithionite-citrate-bicarbonate solution (Fed)

Peninsula de Yucatán (Fig. 8.4) is a relatively smooth platform composed of limestone of low elevation (altitude ranges between 25 and 35 m) broken by numerous rounded karstic depressions (Lugo et al. 1992). The oldest calcareous rocks are Tertiary and are distributed in the center of the peninsula (Fig. 8.17). Quaternary marine and coastal sediments are restricted to the external stripe, outlining the actual peninsula configuration.

We have conducted extensive research to understand the spatial soil variability and distribution as well as the processes controlling such variability. Field work includes sites in the eastern part of the Peninsula de Yucatán; at the shoreline near the famous beaches of Cancún, where soils and pedosediments are developed over the Quaternary sediments; at localities in the central part of Yucatán, where red soils are present on Tertiary limestones (Fig. 8.17); and at sites in the natural forest where Rendzinas dominate, also over Tertiary limestone.

8.3.1.1 Composition of the Carbonate Free Residue

Samples from limestones from two sites were dissolved with acetic acid in order to obtain the silicate residue. While 800 g of limestone of the karstic pockets were treated, getting only a very low proportion of insoluble residue (0.116 %) by weight of the original material (Cabadas-Báez et al. 2010b), where the clay fraction is clearly dominant (>99 %). In Kantunilkin, after dissolving 1 kg of rock, 3.3 % by weight of the original material was collected. This residue has also 90 % clay. Landa (2007) got low quantities of residue (0.2–0.08 %) for limestone of Yucatán.

Kantunilkin residue has illite as the dominant phase, in contrast to the dominance of kaolinite in the red soil. Small proportions of vermiculite are also detected (Cabadas-Báez et al. 2010a). The mineralogical composition of the fine fraction from the residue of the limestones in karstic pockets, contains kaolinite, but not vermiculite. Instead, sepiolite was clearly identified (Cabadas-Báez et al. 2010b).

8.3.1.2 Red Soils

We have studied several profiles of red soils in the Yucatan. Here, we report the results of one of them, considered the most representative and the better characterized of the study sites (Cabadas-Báez et al. 2010a).

The Kantunilkin soil (Fig. 8.18) has a well-developed profile with Ap/AB/Bt1/Bt2/BtC/BCk/horizons. Contact with the limestone is at the depth of 135 cm. All horizons are clayey and very hard with a prismatic structure that easily breaks into subangular blocks. The Bt1 horizon has clay cutans and slickensides. In the Bt2 clay, cutans are thicker and contains abundant Fe–Mn concretions.

The soil matrix in all horizons is dominated by clayey material, pigmented with red iron oxides. Very few sand grains of quartz and volcanogenic minerals are immersed in clay.

This was unexpected despite the “weathered” appearance of the groundmass, even unstable sand-size silicates like plagioclases and pyroxenes look fresh. The clay fraction reaches percentages between 88 and 99.5 %. Although the soil profile appears homogeneous, silt fraction shows interesting discontinuities. The surface horizons (Ap-A) have 3.8–4.6 % of silt; the Bt1 horizon, 0.4 % and, the deeper part 2.8–12 %. Evidence of discontinuities is also provided by the magnetic susceptibility (χ) pattern (Fig. 8.18) where we observe strong changes in the

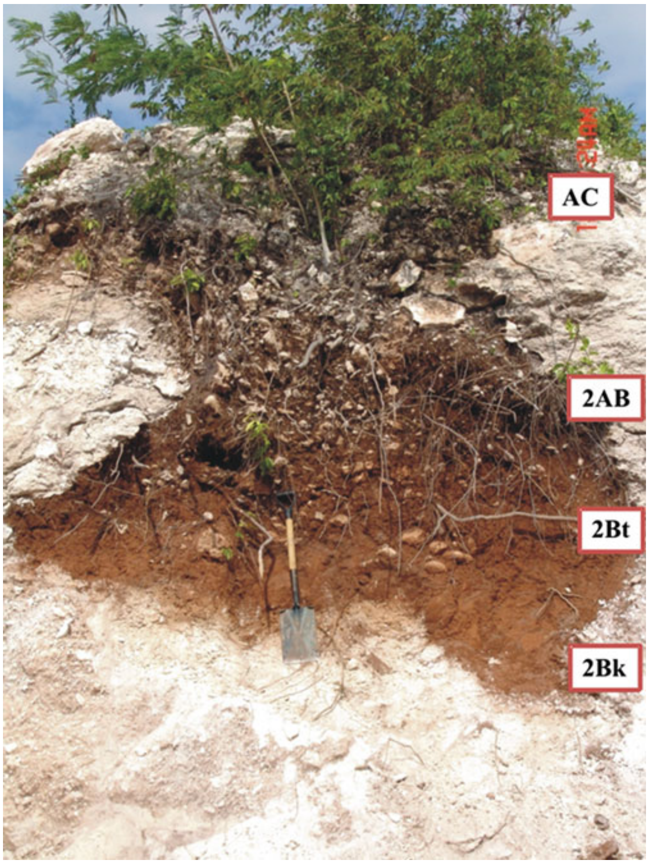


Fig. 8.19 Pedosediment in a karstic "pocket" in the shoreline of Península de Yucatán

configuration. The biggest difference is found in the Bt1 and Bt2 horizons with a considerable drop in χ which coincides with a higher proportion of Fed (Fe extracted by dithionite-citrate-bicarbonate solution) (Fig. 8.18). In general Fed content is high, ranging between 4 and 4.7 % (Cabadas-Báez et al. 2010a).

8.3.1.3 Rendzinas and Pedosediments on Quaternary Sediments

Rendzinas in Yucatán were studied at natural conditions at the Reseva Eológica El Edén (Sedov et al. 2008) and Akumal (Cabadas-Báez et al. 2010b), as well as in a homegarden in El Naranjal (Flores-Delgadillo et al. 2011). They are very shallow (10–30 cm thick) but showing a high variability in depth, reaching in some places more than 1 m, and in others the rock is on the surface (Flores-Delgadillo et al. 2011). Characteristics of these soils are: dark gray color, well-developed granular structure with strong bioturbation, neutral pH, high organic carbon content (25 %), a very elevated proportion of clay (80–93 %), and variable Fed content (0.7–5 %) (Sedov et al. 2008; Cabadas-Báez et al. 2010b; Flores-Delgadillo et al. 2011). The micromorphological observations reveal that Rendzinas have a reddish-brown groundmass because of staining with iron oxides, completely free of carbonates and very rich in fine clay material. There are abundant fragments of plant tissues in different degrees of decomposition and coprolites. Mottles of dark gray–brown organic pigment and tiny black specks are abundant within groundmass. Clay mineralogy is dominated by vermiculite (Sedov et al. 2008).

Pedosediments were studied in quarries along the shoreline of Quintana Roo, where we found sinkholes, labeled as "karstic pockets" (Cabadas-Báez et al. 2010b), showing different sizes and morphologies. One of the biggest has a complex profile with AC, 2AB, 2Bt, and 2Bk horizons (Fig. 8.19). The AC horizon (0–40 cm) is dark brown, sandy silt with more than 50 % gravel of different size (limestone fragments). The 2AB horizon (40–120 cm) is silty, darker than the AC horizon and has fine subangular blocky structure. The 2Bt horizon (120–155) is more reddish (10YR 5/3), has a coarse subangular blocky structure with a tendency to be prismatic with 70 % of clay. Organic horizons have 7–13 % organic carbon and a weak reaction with HCl. The deepest 2Bk horizon (155–205) is reddish brown (7.5YR 4/2) with lighter mottles (10YR 7/3), because of the presence of neoformed calcite crystals; as a result, the reaction with HCl is strong. It also has some ferruginous concretions (Cabadas-Báez et al. 2010a, b). In thin sections, rounded soil fragments were detected (Cabadas-Báez 2011).

The mineralogy of the sand fraction shows two kinds of components according to their origin: (1) Igneous (volcanic/plutonic): plagioclases, quartz, alkaline feldspars, amphiboles, pyroxenes, zircon, rutile, and volcanic glass, the later in large range proportions (around 15 %). The grains of quartz and plagioclase have etched surfaces. (2) Metamorphic: zoisite and clinozoisite, pistachite, and garner. The dominant clay mineral is vermiculite—hydroxy-interlayered vermiculite (HIV) with minor quantities of kaolinite.

8.3.1.4 Red Soils Versus Rendzinas and Pedosediments: Different Stages of Soil Development?

When we observe the quite contrasting properties of red soils, Rendzinas and pedosediments in the karstic sinkholes, we may conclude that they belong to different stages of soil development. At first glance, Rendzinas are the less developed soils so they represent the initial phase of formation (Fig. 8.20), while fillings of karstic pockets needs more time, and red soils are the product of even longer periods of pedogenesis. When we observe the areas where red soils are located in Yucatán, the later consideration seems to be valid, because they are formed over Tertiary limestones, and thus they are associated with older phases of karstification. However, Rendzinas are not restricted to the Quaternary rocks. In fact, they occupy 70 % of the surface of the Peninsula (Bautista et al. 2005) and are

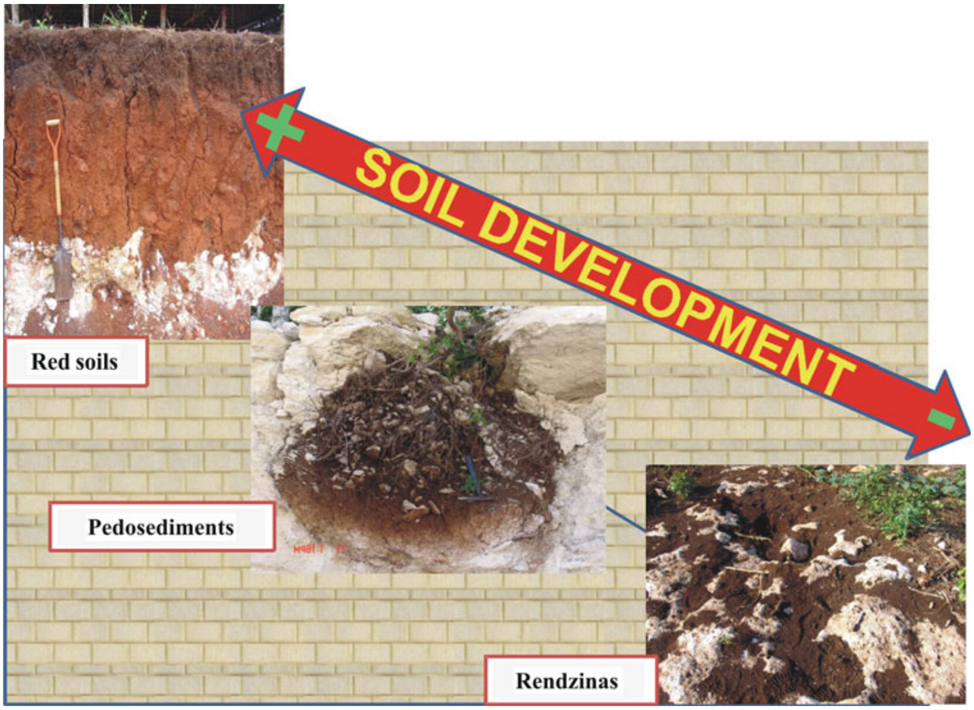


Fig. 8.20 Hypothetic soil development model for soils formed on limestones in Yucatán

developed on limestones of different ages. When we analyze the Rendzinas' properties, it is clear that they are not immature Leptosols. They are free of primary carbonates and weatherable minerals and are dominated by clay and iron oxides with few resistant quartz grains (Sedov et al. 2008; Cabadas-Báez et al. 2010b). As a consequence, they cannot be considered as incipient soils. The fillings found in the karstic pockets have properties also related to well-developed soils, mixed with fragments of redeposited soil materials, which are similar to red soils (Cabadas-Báez et al. 2010b).

It is suggested that these three kinds of materials: red soils, pedosediments, and Rendzinas are genetically related, and they are the result of the interaction between pedogenesis and geomorphic processes (Sedov et al. 2007, 2008; Cabadas-Báez et al. 2010b).

Erosion of the pre-existing soils and short-distance transport and deposition of pedosediments in the karstic depressions is responsible for the development of the fillings in karstic pockets (Sedov et al. 2007, 2008; Cabadas-Báez et al. 2010b). This process coincides with the studies made in the Mediterranean region where Terra Rossa is formed (e.g. Durn 2003; Yaalon 1997; Priori et al. 2008). Durn (2003) reports in those areas erosion and deposition processes are responsible for both the soil patchy distribution and the thick accumulation of colluvial and alluvial Terra Rossa.

However, this process does not explain why the morphology of the fillings in some pockets (especially the larger ones) differs so greatly from Rendzinas. In fact, small pockets contain Rendzina-like material. We suggest that once pockets are filled by eroded soils (Rendzinas and red soils), pedogenetic transformation starts inside the pocket. Small pockets are in contact with the vegetation. Thus organic matter recycling is possible, while in the biggest, post-depositional (diagenetic) loss of humus and reddening can occur in a similar way described in some ancient paleosols (Retallack 1991). Another explanation is related to the effect of forest fires (Heraud 1996), which are supposed to accompany pedosediment development as mentioned above. Sedov et al. (2008) observed loss of dark organic pigment and reddening in Rendzinas affected by recent burning.

The model of redeposited soils as parent material from pedosediments can be also applied to the red soil genesis, where discontinuities have been observed among their horizons. Their material is partly derived from previously formed soils, not only Rendzinas but Chromic Cambisols identified in the area (Bautista et al. 2005). We suppose that earlier red soils with chromic B horizons and locally with some redoximorphic and luvic properties were more frequent in the soil mantle. Later they were degraded, eroded and transported to the karstic depressions, contributing to (and even controlling) the macro- and micromorphological characteristics of resulting pedosediments. Within this model, Rendzinas are considered to be the remainder of the pre-existing more developed soils left after their erosion, rather than the products of incipient pedogenesis on the limestone. A similar scheme of local soil and geomorphic dynamics was proposed for karstic landscapes in the Eastern Mediterranean (Atalay 1997; Durn 2003).

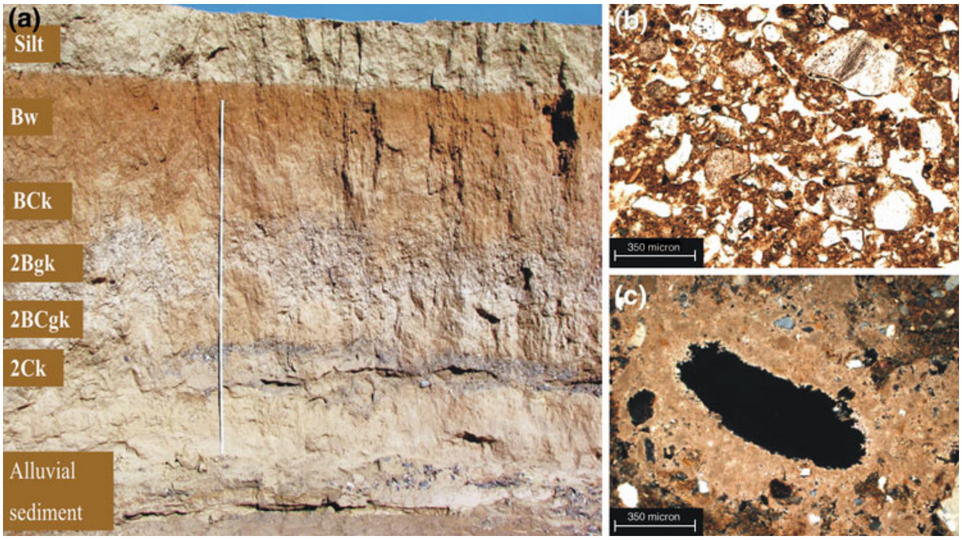


Fig. 8.21 San Rafael paleosol (Chromic Cambisol) in Sonora State

Later they were degraded, eroded, and transported to the karstic depressions, contributing to (and even controlling) macro- and micromorphological characteristics of resulting pedosediments (Cabadas et al. 2010a, b).

The proposed model incorporating pedogenetic and erosion/deposition processes supposes alternation of sharply different stages of landscape development corresponding to the classic sequence of geomorphic stable and active phases (Rohdenburg 1970). After formation of Late Pleistocene calcarenites–eolianites and corresponding landforms a prolonged stability period should occur, providing pre-conditions for weathering and pedogenesis accompanied by carbonate dissolution and generation of karstic depressions. We relate this phase to a humid interval in the Early Middle Holocene, documented by various regional records (Leyden et al. 1994; Haug et al. 2003). The phase of geomorphic activity could be related to the human-induced landscape change—forest clearance and cultivation, started by the ancient Maya at least 3,000 years BP.

8.3.2 Pleistocene Rhodic Cambisols in Sonora: Relict of Humid Late Glacial in the Modern Arid Ecosystems

The territory of Northern Mexico (still poorly studied) has broad perspectives for paleopedological research. Recently, we discovered a specific paleosol unit in the north of the Sonora State (Fig. 8.4) corresponding to late Pleistocene—Early Holocene, called the San Rafael paleosol (Fig. 8.21a). In the La Playa location this paleosol is buried under recent alluvial deposits in which only incipient Fluvisols are formed. The paleosol profile includes Bw and BCk horizons, the former has an intensive red color that motivated us to classify it as Chromic Cambisol. The micromorphological studies have shown that the fine material of the Bw horizon is dominated by clay and iron oxides (Fig. 8.21b) that agrees with the maxima of dithionite-extractable iron and magnetic susceptibility (Cruz 2011). However, in the thin sections of BCk horizon we observed abundant neoformed calcite (Fig. 8.21c). Carbonate contents are the highest, reaching 14 %, whereas in the Bw it is 6 % (Cruz 2011). Radiocarbon dating of these secondary carbonates gave an age of 14,900 years BP, providing instrumental chronological

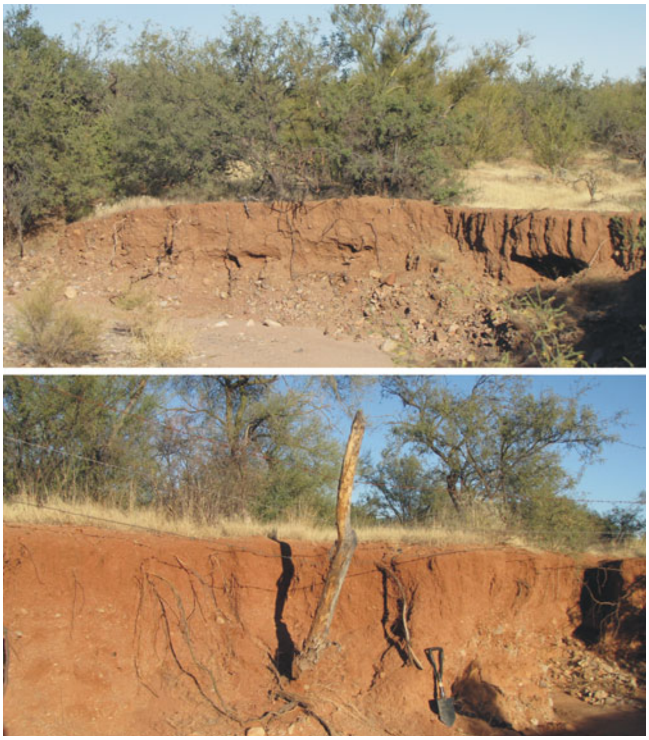


Fig. 8.22 Red soils found in the modern surface in Sonora, correlative to San Rafael paleosol

control. We have concluded that the pedogenetic processes which formed this paleosol include weathering, eluvial–illuvial redistribution of carbonates, clay formation, and rubification of the Bw horizon. We believe that this type of palepedogenesis corresponds to more humid conditions of the Late Pleistocene in Northern Mexico and South-Western USA—documented by a number of paleoecological records (Van Devender 1990; Nordt 2003).

During the posterior field observations in the north of Sonora we found very similar red soils on the present day landsurface (Fig. 8.22). They occupy mostly stable older landsurfaces i.e., high river terraces and foothills with gentle slopes, protected from erosion and surrounded by poorly developed Leptosols. We believe that these red soils are Late Pleistocene relicts, correlative to the San Rafael paleosol. Thus, red soils of northern Sonora should be considered as a valuable, nonrestorable soil resource that needs special protection measures.

8.3.3 Tepetate (Volcanic Fragipans): Relict Pleistocene Pedosediments Controlling Current Processes of Accelerated Erosion and Landscape Degradation

Tepetates are subsurface indurated horizons, which fit into the definition of Duripans or Fragipans in the international soil classification WRB (IUSS Working Group WRB 2006). The word comes from the nahuatl language that means "stone bed" and was given by the Aztec farmers who encountered them under the soil mantle with strong limitations for cultivation (Gibson 2000). These horizons are spread over the piedmont of the Trans-Mexican Volcanic Belt (Gama-Castro et al. 2004) and often appear on the surface due to erosion (Fig. 8.23a) (Gama-Castro et al. 2004, 2007). A number of previous studies about these specific layers have been done mostly to identify causes of the induration and the ecological and land use significance (Zebrowski 1992; Oleschko et al. 1992; Flores-Román et al. 1996). In these papers, tepetates were considered as pedogenic phenomena, but never related to the past soil forming processes and environmental conditions.

Recently, tepetates have been studied as the product of Late Pleistocene environments which are not present any longer. Thus they are relicts of older landscapes (Solleiro-Rebolledo et al. 2003; Díaz-Ortega et al. 2010), being integrated to modern day conditions and controlling geomorphic processes.

But what kind of environment can produce tepetates and why do we postulate that they are signs of past environmental conditions? Tepetates are pedosediments that involve different kind of materials such as fresh volcanic sediments, rock fragments, and reworked soils, formed previously under stable conditions. These materials are mobilized through erosion in the form of lahars (extensive volcanic mudflows) and incorporated into a hyperconcentrated flow. When the material is deposited, rapid drying produces structural collapse and hydroconsolidation (Solleiro-Rebolledo et al. 2003).

As a consequence, the environments that can produce such materials have to be quite contrasting: first, intense rains and storms, followed by severe droughts. According to the age of several tepetate layers in central Mexico, their formation occurred at the end of Pleistocene during the Younger Dryas. This is well-known to be a period of high climate and landscape instability (Heine 1994). This landscape instability, also related to volcanism, results in erosion and sedimentation processes that limit soil formation. We also have to keep in mind that during this period, the conditions in the high mountains of Mexico, such as Popocatepetls, Iztaccíhuatl, and many monogenetic volcanoes located more than 3,500 m asl in Sierra Chichinautzin,

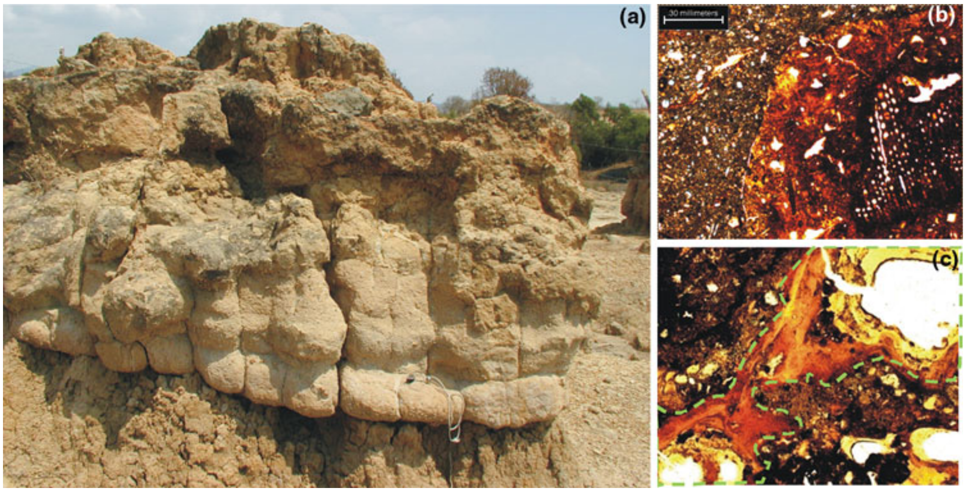


Fig. 8.23 Tepetates of the Glacis de Buenavista. **a** Profile of the indurated layers; micromorphology of tepetates. **b** Charcoal and rounded, redeposited soil fragments. **c** Clay cutans

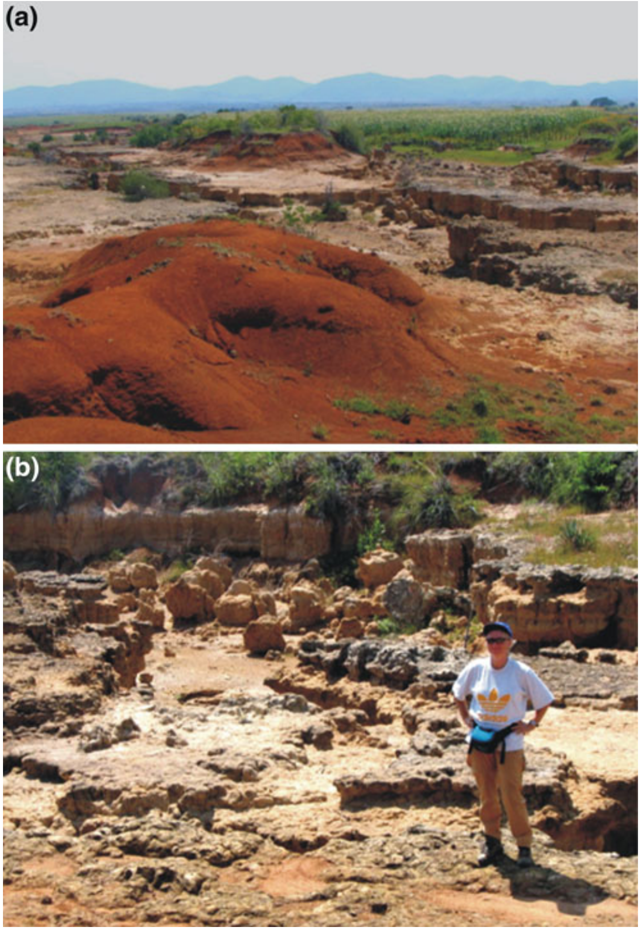


Fig. 8.24 Red Luvisol kind soils over tepetates. **a** "Islands" of Luvisols in the surface after strong erosion. **b** Tepetates in the surface, in the areas where red soils are eroded

could frequently have snow cover that after melting could be responsible of lahars. Thus, it is possible to associate the presence of tepetates in the landscape with the Late Glacial climates.

Besides the particular combination of soil fragments and volcanic materials, tepetates also contain clay cutans, charcoal (Fig. 8.23b), phytoliths (Fig. 8.23c), Fe oxides as mottles, and hard concretions; thus, they have been affected by later pedogenic processes. As a consequence, pores left after primary consolidation are filled by clay reducing the hydraulic conductivity and promoting the lateral soil drainage.

Tepetates are overlain by thick Luvisol profiles, formed in humid ecosystems during the subsequent phase of landscape stability in the Holocene (Solleiro-Rebolledo et al. 2003; Díaz-Ortega et al. 2011). Such Luvisol-tepetate profiles (Fig. 8.24) are stable in the natural ecosystems, were dense forest vegetation prevents soil losses with runoff. Under cultivation the accelerated erosion could quickly destroy the upper part of the profile, exposing tepetates to the surface and causing advanced land degradation. In this case, root penetration is hampered and surface runoff strongly encouraged due to high density and low porosity of tepetate. The very limited water availability and low cation exchange capacity causes a decrease in the agroecosystem productivity. Vast areas covered by tepetates are set aside as badlands. In consequence, tepetates, relicts of Late Pleistocene landscapes, control the present erosion and land use.

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