Major Soil Types and Their Classification

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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.

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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

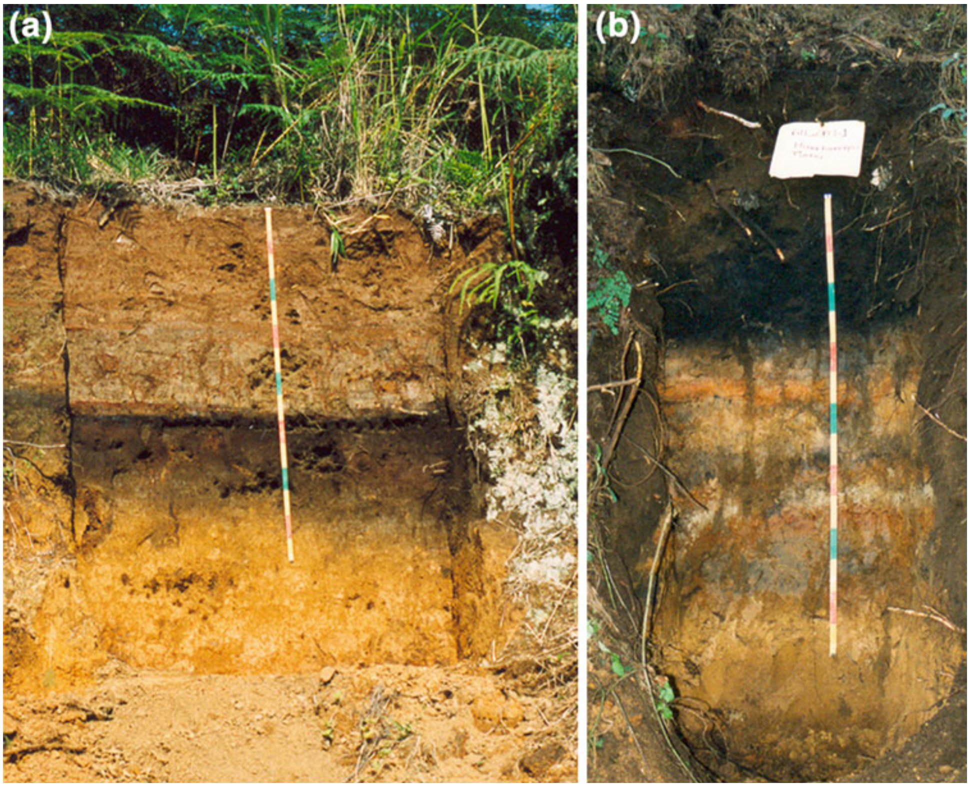

Fig. 4.1 Typical profiles of volcanic soils (Andisol/Andosol) in Puebla State: **a** a profile with a buried soil, Teziutlan district, **b** a polycyclic profile, Huauchinango district (photos by P. Krasilnikov)

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}; pH_{H_2O} = 5.5; cation-exchange capacity (CEC) = 40.6 $cmol_c$ 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

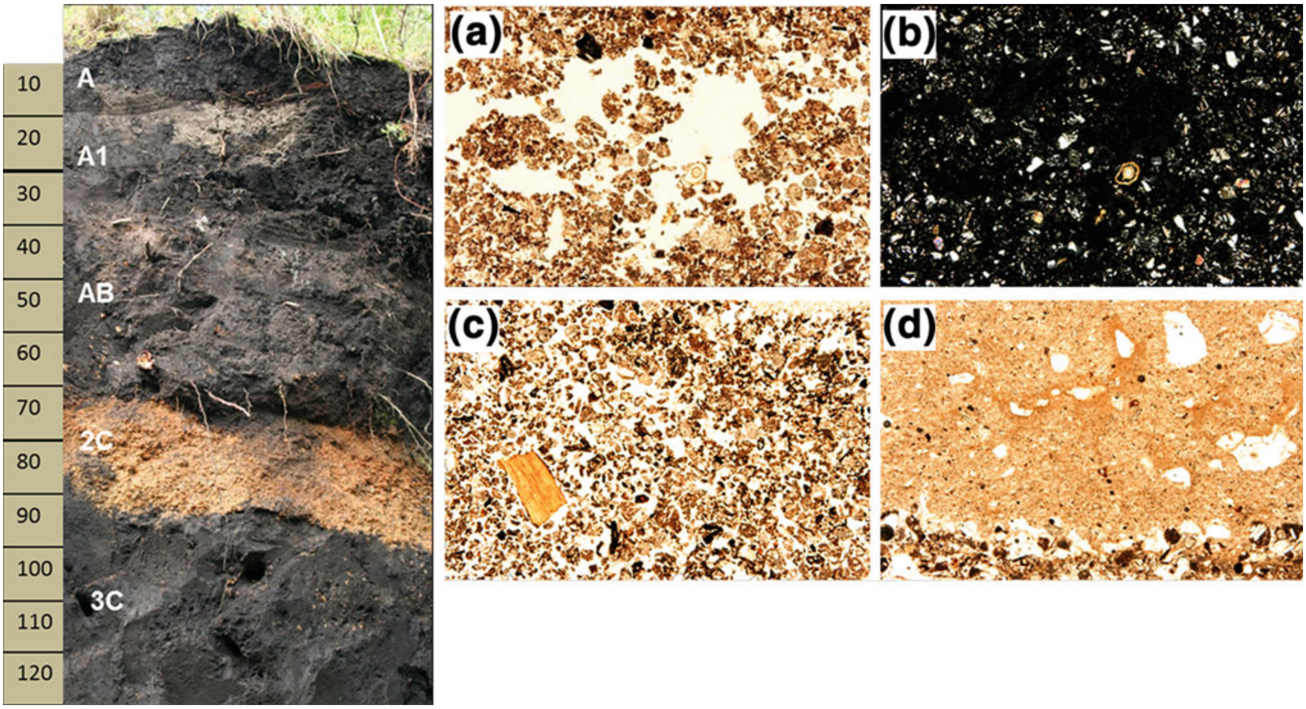

Fig. 4.2 Microstructure of an Andisol/Andosol from Popocatepl volcano, Mexico State: **a** Crumb structure, Ap horizon, **b** the same with crossed polarizers, **c** intergrain micro-aggregates structure, A/Bw horizon, **d** layers of pumice (*yellow*) and volcanic ash, 2C horizon (photos by Ma. del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

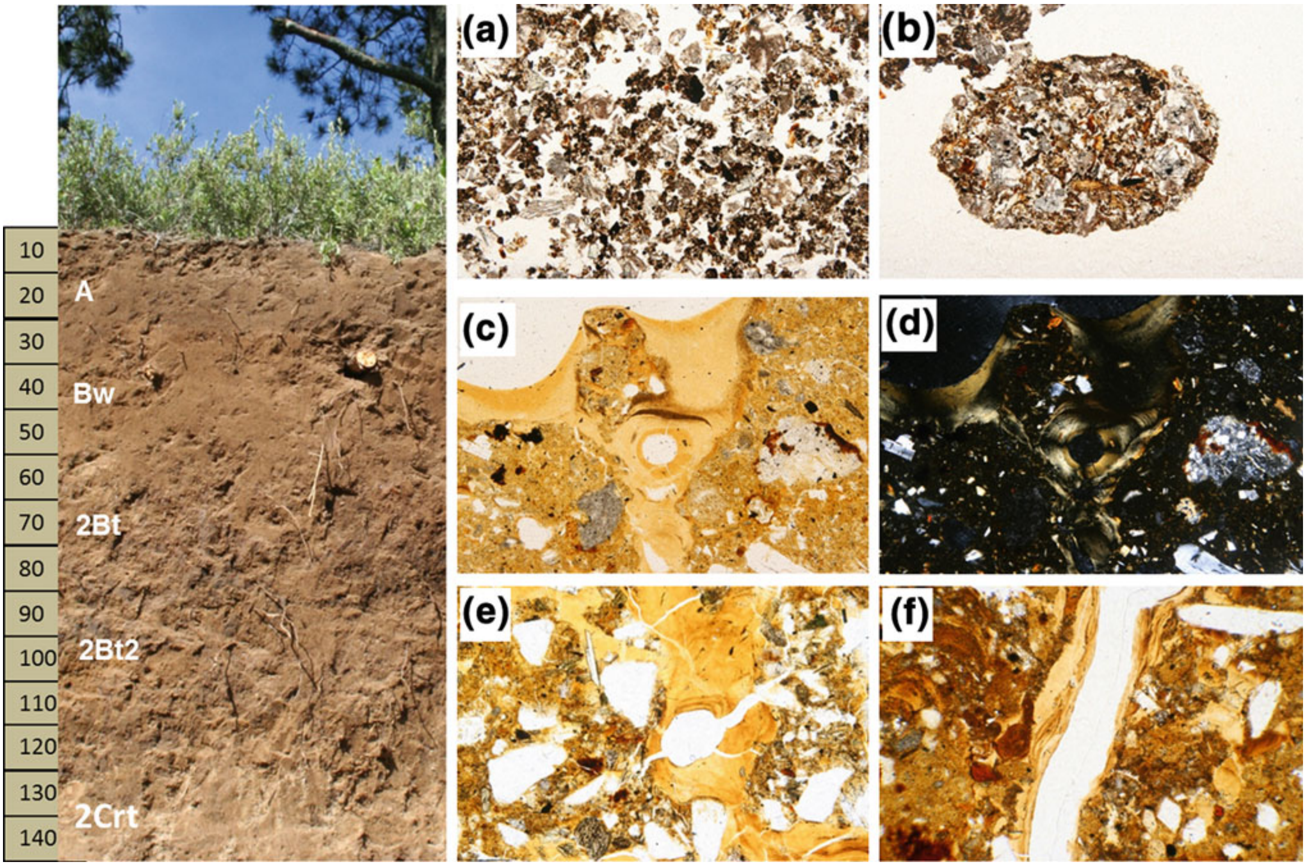

Fig. 4.3 Microstructure of an aged Andisol/Andosol from Tlaxcala State: **a** crumb structure in the A horizon, **b** mite excrements in the A horizon, **c** juxtaposed coatings of 1:1 (*whitish colors*) and 2:1 (*yellowish colors*) clay minerals in the 2Bt horizon, **d** the same as previous photo, 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 Texturally 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

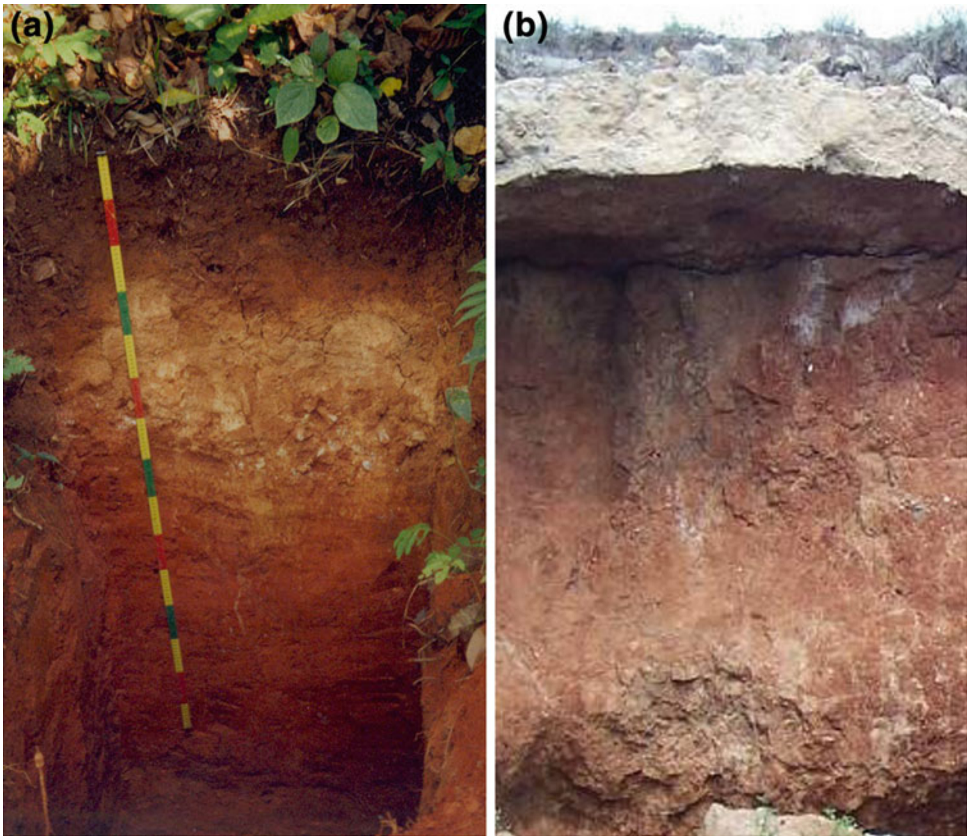

Fig. 4.4 Texturally differentiated soils: **a** Udult/Alisol with whitish colluvial material in the topsoil, Sierra Sur de Oaxaca (photo by P. Krasilnikov), **b** a polygenetic texturally differentiated soil in Garrochitas, San Luís Potosí (photo by C.O. Cruz-Gaistardo)

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

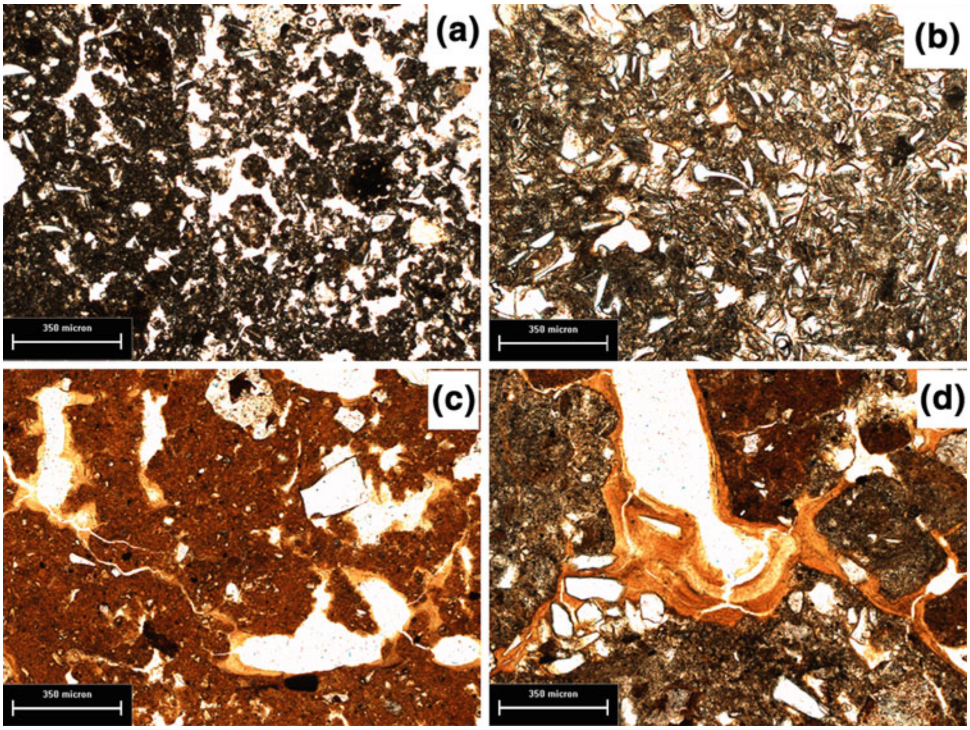

Fig. 4.5 Microscopic photos of thin sections derived from the horizons of Durustalf/Luvisol in Garrochitas, San Luís Potosí: **a** Ap horizon (0–17 cm), **b** Bw horizon (17–29 cm), **c** 2Bt1 horizon (29–48 cm), **d** 2Bt2 horizon (48–75 cm) (photos by S. Sedov)

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;

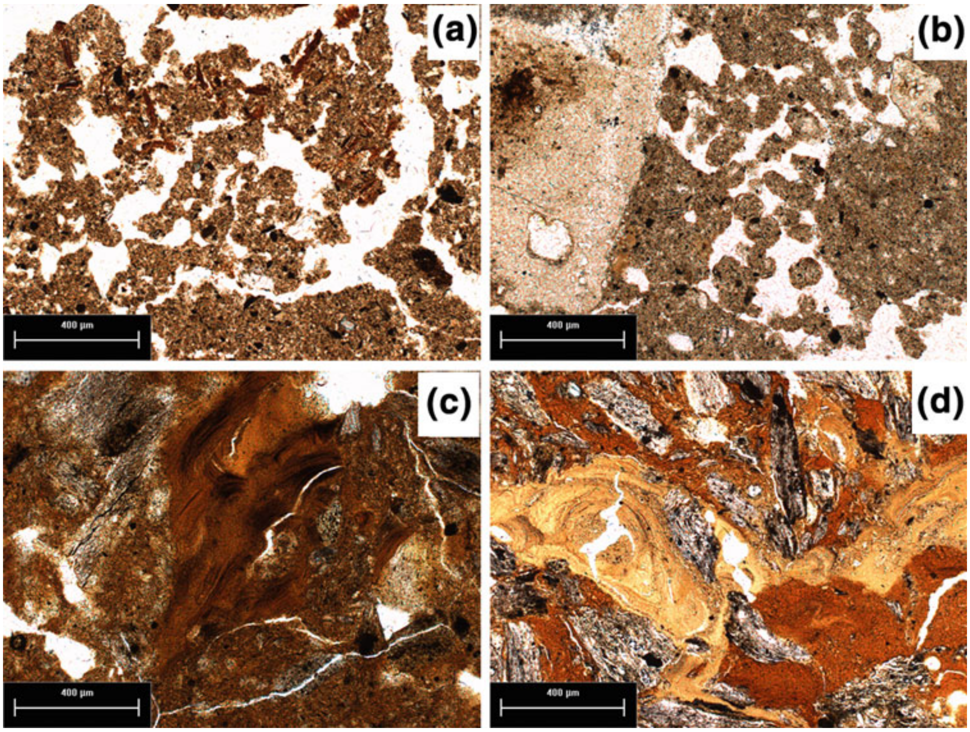

Fig. 4.6 Microscopic photos of the horizons of the Typic Hapludalf/Cutanic Luvisol, Puerto de San Agustín, Querétaro state: **a** biogenic structure in the A horizon, **b** mineral weathering and excrements of mites in the AE horizon, **c** humus-enriched clay coatings and compact structure in the B12 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 $\text{cmol}_c\ \text{kg}^{-1}$, 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 $\text{cmol}_c\ \text{kg}^{-1}$ will be 50 $\text{cmol}_c\ (\text{kg of clay})^{-1}$. 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

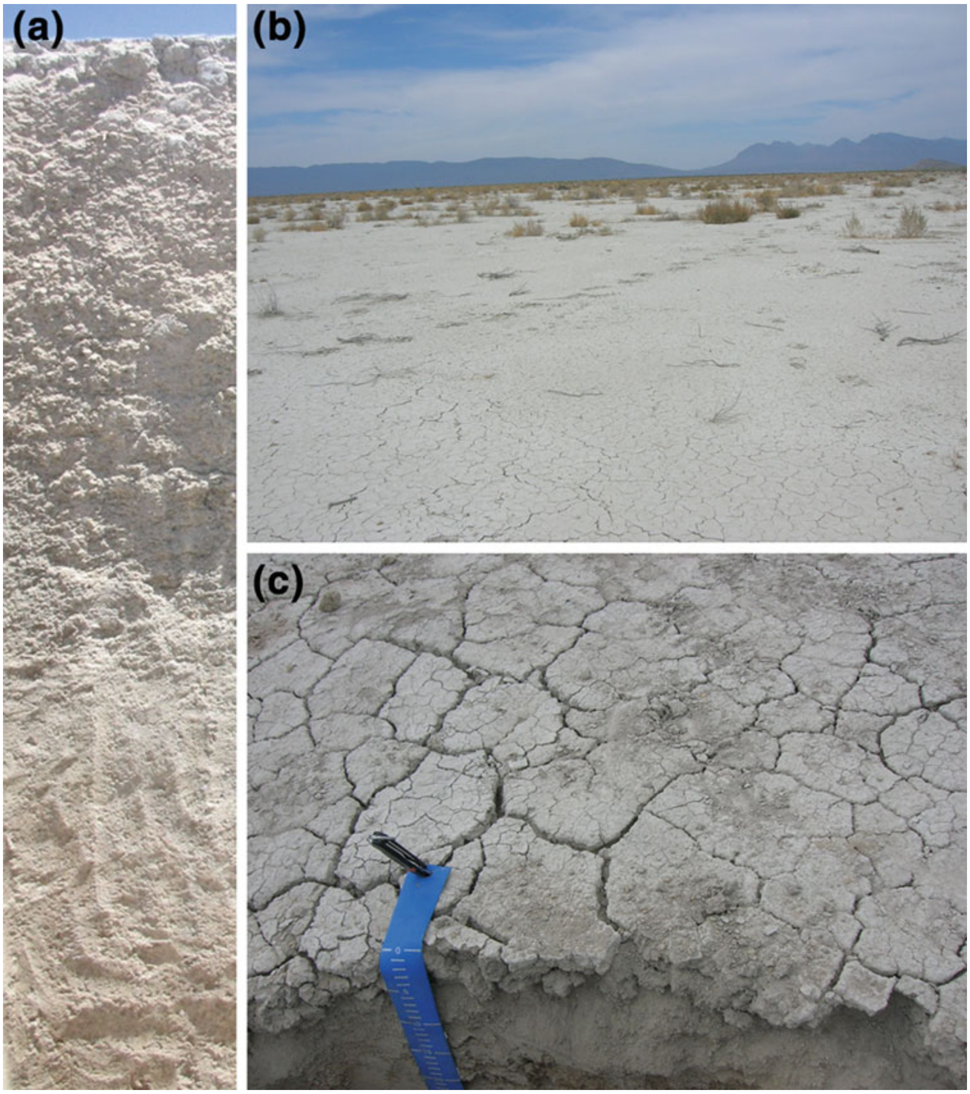

Fig. 4.10 Haplosalid/Solonchak in the Laguna de Mayran, Coahuila State: **a** soil profile, **b** landscape with sparse vegetation, **c** soil surface (photo by C.O. Cruz-Gaistardo)

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

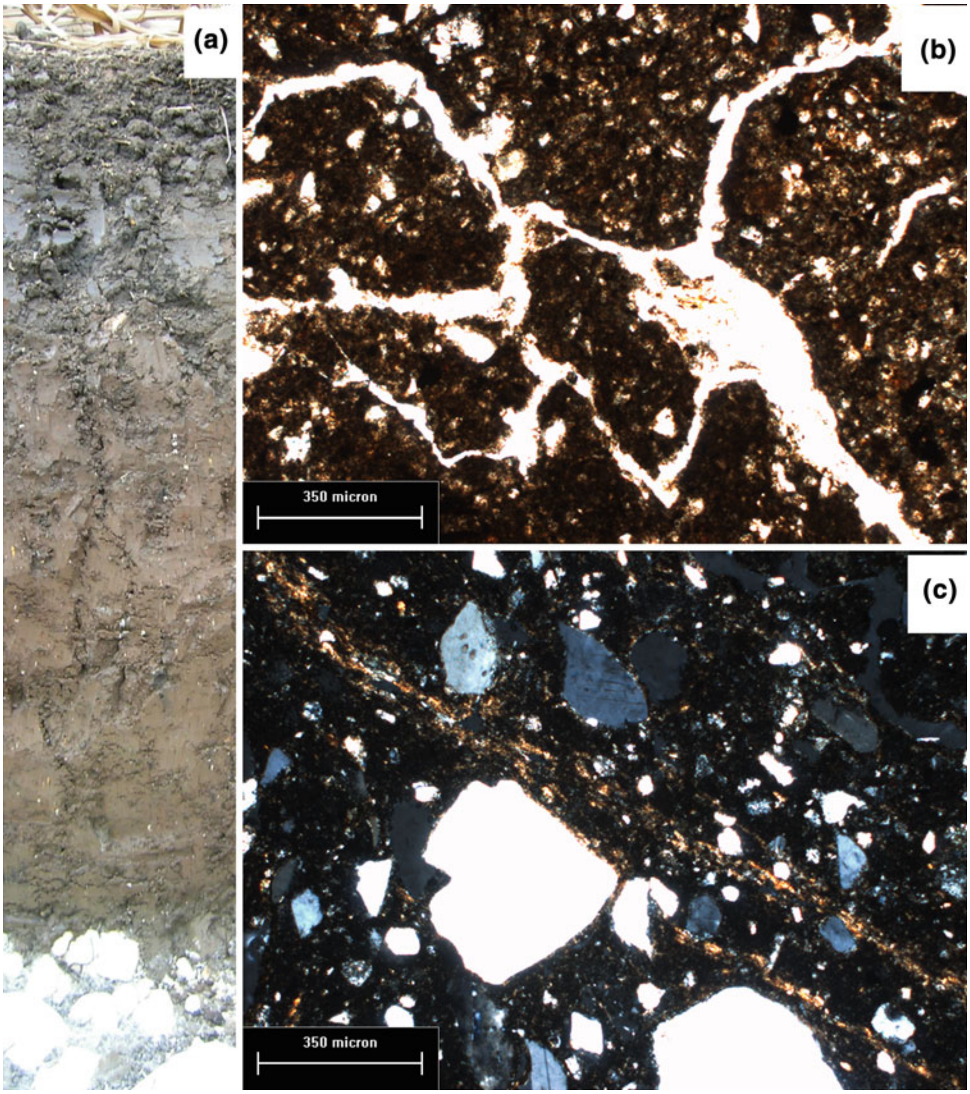

Fig. 4.11 Typic Calciustert/Calcic Vertisol at the Río Gallinas site, Veracruz State: **a** soil profile, **b** typical angular structure in the topsoil, **c** stress cutans in the AB horizon, with crossed polarizers (photos made by S. Sedov)

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

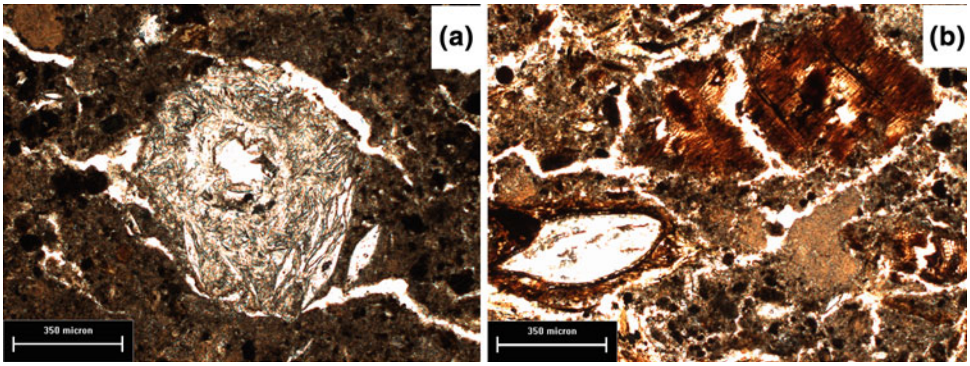

Fig. 4.13 Microphotos of Aridic Ustorthent/Gypsisol at the Rio Verde site, San Luís Potosí State (see text). **a** secondary gypsum in the pores of the C1y horizon, **b** underdecomposed organic matter in the A1k horizon (photos made by S. Sedov)

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

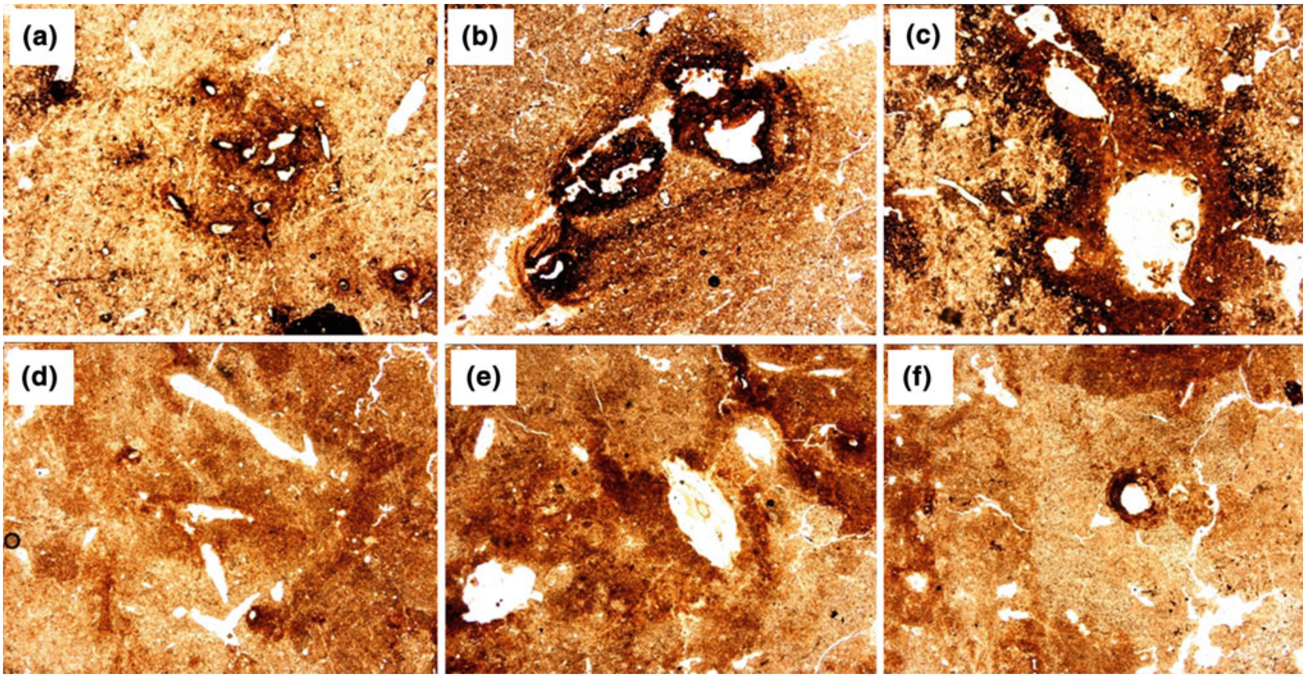

Fig. 4.14 Microphotos of a Aquent/Gleysol from Conduacan, Villahermosa, Tabasco. Low reduction degree: **a** manganese hypocoating, **b** and **c** manganese quazi-coatings. Moderate reduction degree: **d** and **e** iron depletion, and **f** hypocoating of Fe. Frame length 2.9 mm (photos made by Ma.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

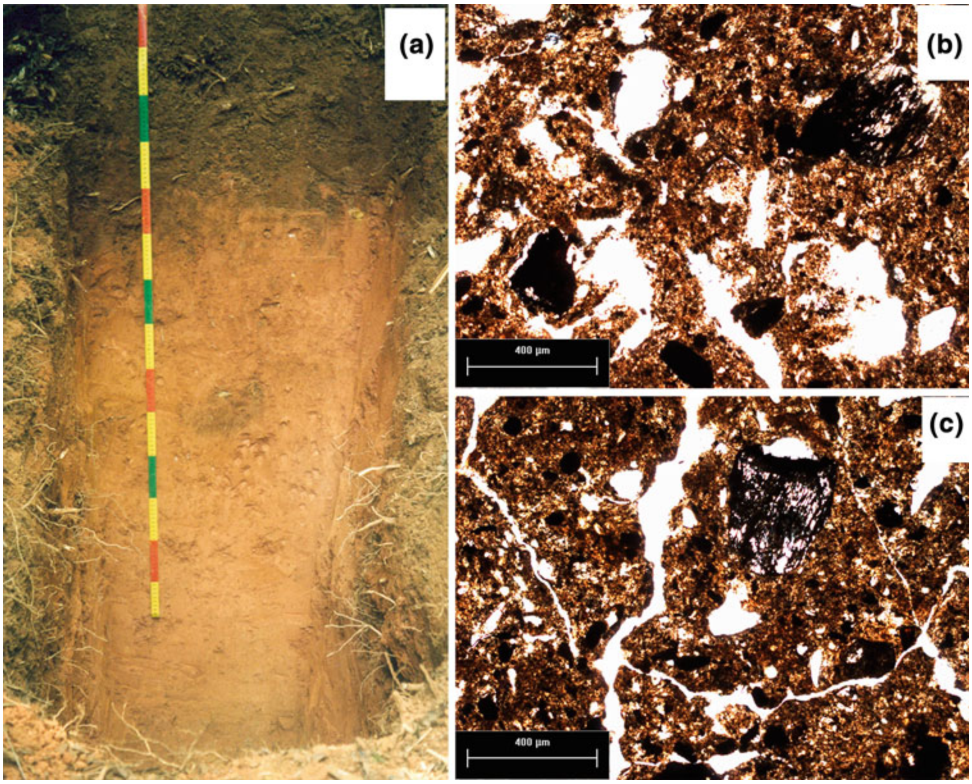

Fig. 4.15 Hapludox/Ferralsol at the El Nueve site, Oaxaca State (see text). **a** soil profile, **b** microphoto of porous Bo horizon, **c** angular blocky structure of the Bw horizon (photos made by S. Sedov)

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

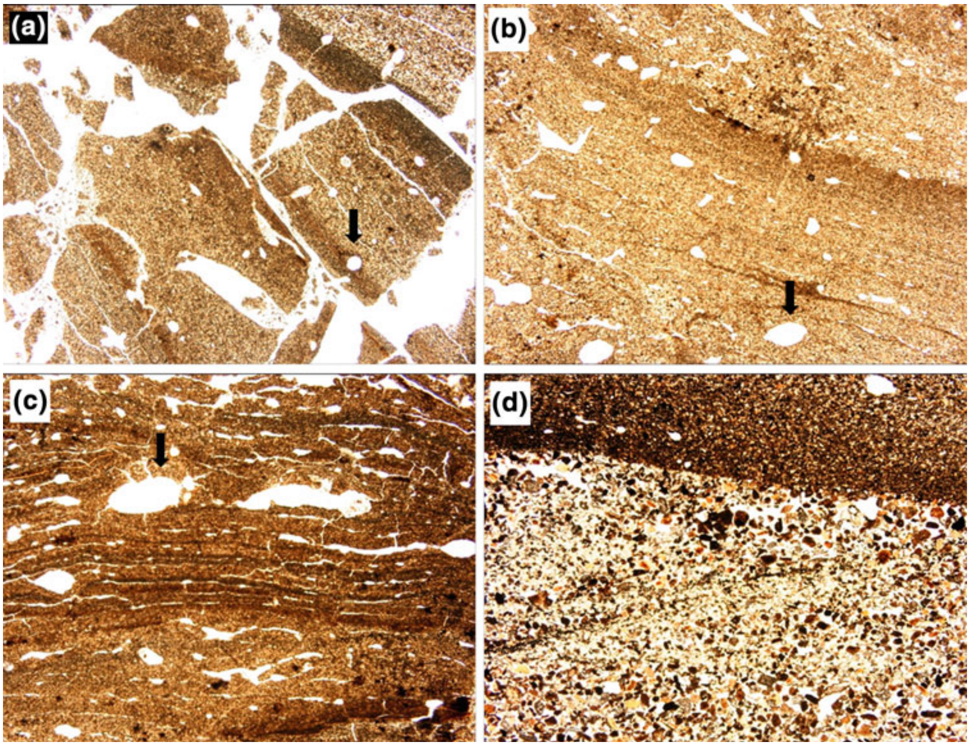

Fig. 4.16 Typic Ustifluvents/Fluvisols in the alluvial sediments in Texcoco ex-lake, Mexico State.: **a** angular blocky structure with a banded distribution pattern, Ap horizon; **b**, **c**, and **d** banded distribution pattern of sand grains of different sizes and mineral composition, and vesicules 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

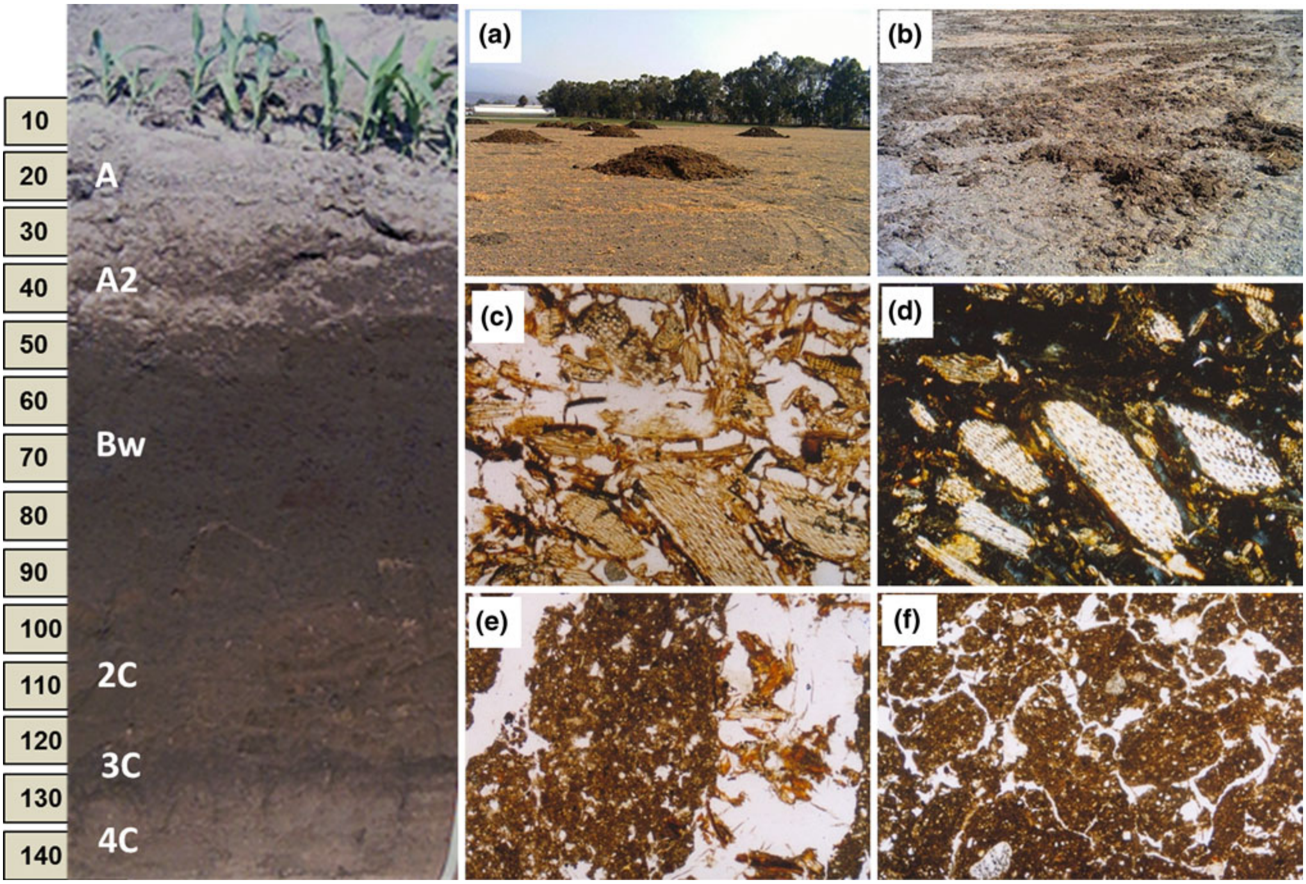

Fig. 4.17 Hortic Anthrosol (Eutric), and some microphotos of its topsoil horizon (Ap, 0–29 cm): **a** mounts of manure, **b** spreaded manure, **c** fragments of manure, **d** the same as b, but with crossed polarizers, **e** moderate grade of manure decomposition in the pore space, **f** granular and 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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