Micromorphology of a Soil Catena in Yucatán: Pedogenesis and Geomorphological Processes in a Tropical Karst Landscape

Sergey Sedov, Elizabeth Solleiro-Rebolledo, Scott L. Fedick, Teresa Pi-Puig, Ernestina Vallejo-Gómez, and María de Lourdes Flores-Delgadillo

Abstract Development of the soil mantle in karst geosystems of the tropics is still poorly understood. We studied a typical soil toposequence formed over limestone in the northeastern Yucatán Peninsula of Mexico, to assess the pedogenetic and geomorphological processes which control soil formation and distribution, as well as to understand their relation to landscape development and their influence in ancient Maya agriculture. The soil cover is dominated by thin Leptic Phaeozems and Rendzic Leptosols in the uplands, and Leptic Calcisols in the wetlands. Upland soils have weathered groundmass containing abundant vermiculitic clay and iron oxides. The combination of thinness and high weathering status is explained by interaction between the intensive pedogenesis and vertical transport of soil material towards karst sinkholes. In wetlands, biochemical secondary calcite precipitation occurs, accompanied by surface accumulation of algal residues (periphyton crust). In the transitional area, a polygenetic profile (Calcisol over Cambisol) was developed, indicating recent advance of wetlands. Because of specific pedogenesis, the upland soils lack many disadvantages of other soils of humid tropics, such as acidity,

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low humus content, and poor structure. However, ancient land-use practices had to be adjusted to thin soils, low P availability and soil loss due to karst erosion.

Keywords Pedogenesis · karst erosion · soil toposequence · micromorphology · Maya civilization

1 Introduction

Pedogenesis on calcareous parent materials is known to differ significantly from that of soils developed on silicate minerals. While soils formed on carbonate rocks in Mediterranean and Temperate regions (in particular, Terra Rossa, Terra Fusca, and Rendzinas) have been studied extensively, knowledge about tropical soils derived from carbonates is rather limited. Singer (1988), who studied soil diversity in South-Eastern China, describes shallow profiles formed on limestone, with low weathering status and mollic epipedon, quite different from profound, red, deeply weathered "latheritic" soils on shales and Pleistocene sediments. However other studies in the tropical islands of the Pacific and Caribbean demonstrated vast variety of soil types formed on limestones. Besides relatively "young" Entisols and Mollisols, those in an advanced stage of development like Alfisols and Ultisols were reported (Bruce 1983). Even deeply weathered ferrallitic profiles are known to form on limetones, e.g. kaolinitic "Red Ferrallitic" or "Latosolic" soils in Cuba (Ortega Sastriques 1984) and Oxisols associated with the karstic bauxites in Jamaica (Scholten and Andriesse 1986). The factors and processes controlling this high soil diversity as well as the origin of the carbonate-free soil materials are still poorly understood.

Ahmad and Jones (1969) favor the hypothesis of "residual" origin of soils on the Pleistocene limestones of Barbados, however Borg and Banner (1996) point to domination of "non-regolith eolian components" in their parent material, relying on neodymium and strontium isotopic compositions and Sm/Nd ratio. Muhs et al. (1990) state that transatlantic transport of Saharan dust, with minor input of volcanic ash deposition from local volcanoes provided the substrate for soils on calcareous rocks on Carribean islands. Brückner and Schnütgen (1995) demonstrated volcanic origin of soil parent material on the coral reef terraces of New Guinea.

Soil age is thought to be an important, but not unique factor controlling diversity. Study of a chronosequence of reef terraces on Barbados, with a reliable time scale provided, has shown that some pedogenic properties, in particular weathering status, depend upon landform age (Muhs 2001). At the same time, soil diversity within a single terrace was found to be rather high, especially regarding solum, and A and B horizon thicknesses.

The Yucatán Peninsula in southeastern Mexico presents a perfect area for studying tropical pedogenesis on calcareous parent materials. This extensive, flat, slightly uplifted limestone platform is occupied by humid to subhumid tropical forest ecosystems, in many cases with little contemporary human impact. The surface and subsurface karst forms are abundant and variable, indicating intensive and recent karstification processes.

The study of soil mantle formation and evolution in Yucatán also has an important archaeological significance. Soils of this region were once involved in long-term agroecosystems of ancient Maya civilization, perhaps the most developed prehispanic society of the Americas, which flourished for over a thousand years before declining for still unknown reasons around A.D. 900 (Sharer 1994). The high population of the region could only have been supported through intensive agriculture and resource management (Culbert and Rice 1990, Fedick 1996).

Many studies of ancient Maya intensive agricultural practices have now been conducted (Harrison and Turner 1978, Pohl 1985, Flannery 1982, Fedick 1996, White 1999), however, there has been relatively little research on how soil fertility was maintained under such intensive cultivation systems. Assessment of soil properties and soil fertility characteristics in Yucatán was conducted by Aguilera-Herrera (1963) and by Hernández et al. (1985) in relation to traditional slash-and burn agriculture. Recently Bautista-Zúñiga et al. (2003, 2004) studied soil diversity in Yucatán state, linking it to microrelief development and building up soil evolutionary schemes.

In this work we performed a pedogenetic study of most wide spread soils in the northeastern Yucatán Peninsula, based mainly in micromorphology, in order to (1) understand how different soil formation and geomorphological processes interact in generating the soil mantle in a tropical karst landscape and (2) characterize this mantle as a resource for productive and sustainable agroecosystems of the ancient Maya.

2 Environmental Conditions

We studied the soil cover distribution along a topographic transect (toposequence) in an area of northern Quintana Roo, Mexico, where ongoing archaeological survey by the Yalahau Regional Human Ecology Project is documenting dense Maya settlement dating primarily to portions of the Late Preclassic and Early Classic periods (ca. 100 B.C.–A.D. 350), with a widespread reoccupation of the region dating to the Late Postclassic period (A.D. 1250–1520) (see Fedick et al. 2000). The soil study focuses on land within and around the El Eden Ecological Reserve, which is located 38 km WNW of Cancun (21°3'N, 87°11' W) (Fig. 1).

Geologically the northern peninsula consists of Cretaceous age uplifted fossiliferous limestone. These rocks, mainly included in the Yucatán Evaporite Formation (López-Ramos 1975), reach a depth of 3,500 m and rest over a Paleozoic basement. Overlying evaporates, a sequence of limestones, sandstones and evaporitic deposits of Paleocene-Eocene age are found. The landscape is characterized by a relatively smooth plain broken through numerous karstic sinkholes (known locally as "cenotes"). The altitude of the platform averages 25–35 m (Lugo-Hupb et al. 1992). Pool (1980) described (using Yucatán Mayan terminology) four geomorphic elements of the relief: heights or ho´lu´um, plains or kan kab, depressions or k´op, and cenotes or dzoonot. Climate is hot and humid. Mean annual temperature is 25°C and the

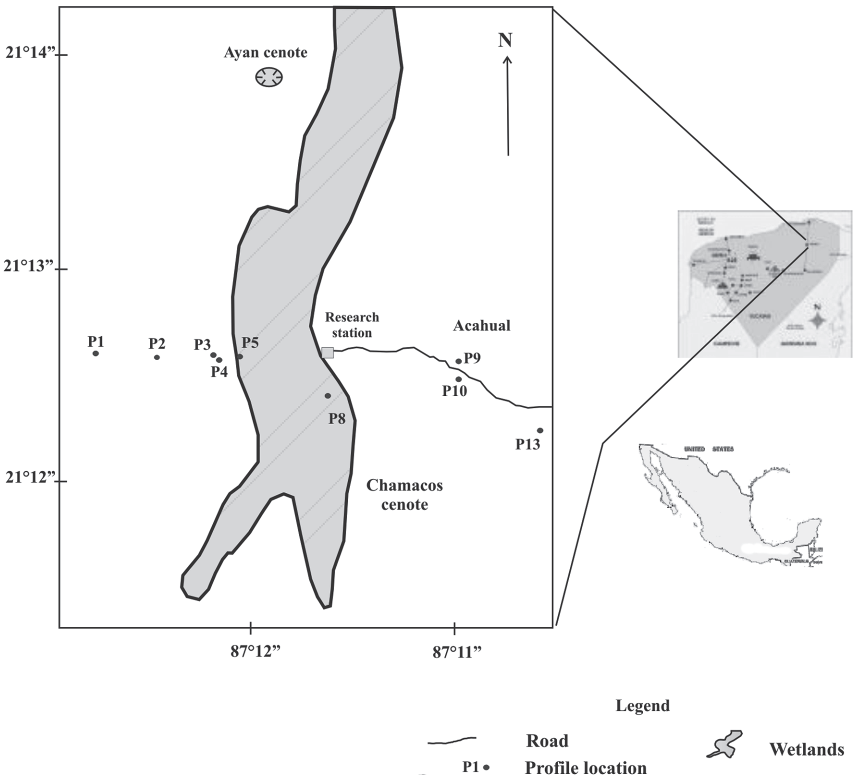

Fig. 1 Location of study area and soil profiles

annual precipitation is 1126 mm. The highest temperature, during May, is 28°C. The maximum precipitation is concentrated in summer, from May to October, reaching 915 mm (García 1988).

Natural vegetation is a moist, medium-high broadleaf, evergreen forest (Miranda 1959); the areas recently (less than 10 years ago) affected by fire are occupied by pioneer associations dominated by ferns. Tropical savanna vegetation dominates the wetlands.

3 Materials and Methods

This study was conducted along an E-W transect in order to identify soil variety and distribution across the landscape. This transect crossed the main geomorphological elements and related vegetation types: uplands with tropical forests, small karst pits, and extensive flat depressions with wetlands. Additional profiles were studied and sampled in the areas, affected by forest fires.

Soils were classified according to the World Reference Base (WRB 1998). Bulk samples for physical and chemical analyses, as well as undisturbed samples for thin sections, were collected from genetic horizons. Soil colors were determined according to the Munsell Soil Color Charts (1975). Thin sections were prepared from undisturbed soil samples impregnated with resin, and studied under a petrographic microscope with descriptions following the terminology of Bullock et al. (1985). Selected chemical properties, including organic carbon, available P, and pH were evaluated according to guidelines of the United States Department of Agriculture (USDA 1993).

We quantitatively separated particle size fractions: sand (2–0.05 mm) by sieving, silt (0.05–0.002 mm) and clay by gravity sedimentation, with previous destruction of microaggregation agents: carbonates (treatment with diluted HCl with pH 3) humus (10% H_2O_2) and iron oxides (DCB). We separated particle size fractions: sand (2–0.05 mm) by sieving, silt (0.05–0.002 mm) and clay by gravity sedimentation, with previous destruction of microaggregation agents: carbonates (treatment with diluted HCl with pH 3), humus (10% H_2O_2) and iron oxides (DCB). X-ray diffraction patterns of the oriented specimens of clay fraction were obtained with a diffractometer (Philips 1130/96) utilizing Cu K_radiation following pretreatments of air drying, heating to 400°C, and saturation with ethylene glycol. To identify neoformed crystalline components in the soil affected by forest fire, we studied soil materials under electron microscope equipped with an EDX microprobe, and obtained powder X-ray diffractogramms from the material enriched with the neoformed component to be identified.

4 Results

4.1 Soil Morphology

In uplands, the soil cover is discontinuous; rock outcrops are rather frequent and limestone looks strongly weathered, with dissolution pits and etched zones. In all geomorphological positions, including wetlands, we observed typical results of karstic alteration, forming fractures and sinkholes. In the uplands (Ho´lu´um) under mainly undisturbed forest, thin soils dominate (less than 30 cm depth), with an Ah/AC/C profile. They have a dark reddish brown (5YR 3/3, dry) Ah horizon, 10–15 cm thick. This horizon has a very well developed granular structure, and a high root density. The AC horizon is reddish brown (5YR 4/4, dry), with a fine granular structure, and is softer than the previous horizon.

Weathered limestone fragments are common; however, there is no reaction to HCl, indicating that soil matrix is free of carbonates. The C horizon is composed of 90% fractured limestone, infilled by soil material. It was classified as Leptic Calcaric Phaeozem (profiles 1 and 2). Other upland soils are thinner and more stony (profile 3). The Ah horizon (less than 10 cm thick), with a less developed granular structure, rests directly on limestone. In this case, they were classified as Rendzic Leptosols.

We associate both upland soil units with the traditional concept of "Rendzina" meaning shallow humus-rich soils on calcareous parent material. Similar soils in areas recently affected by fire and currently occupied by ferns, have signs of disturbance and turbation (profiles 9 and 10). Dark grey humus-rich material, typical for Rendzina Ah horizon, are mixed with red mottlesb and charcoal Powdery white material, showing clear reaction with HCl, is distributed unevenly over all above mentioned morphological elements. Another soil type was identified in a similar upland position, to the north-west of the transect (Fig. 1) where it occupies a small area about 10 m^2. In this location, soils are thicker (35 cm), and more clayey (profile 13). The Ah horizon (15 cm thick) is dark reddish brown (5YR 3/3, dry) and has a granular structure with a high root density and moderate contents of organic carbon. The B horizon, 15 cm thick, has a subangular blocky structure, is very hard when dry, and very clayey. The C horizon is rich in weathered limestone fragments, although the complete profile has no reaction to HCl. It was classified as Chromic Cambisol.

Within the relatively flat upland terrain, small depressions can be found (k´op in Yucatec Mayan). Within these depressions, soils are somewhat deeper and clayey. They show an A/Bg/C profile (profile 4). The Ah horizon is very dark grayish brown (10YR 3/2, dry), 11 cm thick, with a granular to subangular blocky structure and the highest content of organic carbon (15.3%). The Bg horizon is grayish brown (10YR 5/2, dry), clayey, with thin clay cutans over aggregates. Bioturbation is strong and the presence of Fe concretions is common. Some peds break into angular blocks with 60° angles, indicating vertic characteristics, although not very well expressed.

Weathered limestone fragments are found at a depth of 24 cm, but horizons have no reaction to HCl. The soil was classified as Leptic Gleyic Phaeozem. In the wetlands, periphyton appears, forming a soft patchy crust on the surface. Periphyton is a complex community of algae and other aquatic microorganisms that form in seasonal bodies of water such as wetlands (see Wetzel 1983) and are deposited on the land surface in the dry period. Surprisingly, soils in some portions of the wetlands are also thin (profile 8), with 1 cm of a very dark gray (10YR 3/1, dry) horizon and rich, highly decomposed organic material. Below we found a rather thin (less than 10 cm thick) gray Bk horizon, consisting mainly of fine secondary calcite and containing mollusk shells. It was classified as Leptic Calcisol. In the wet season this soil is flooded, however in the dry period (when the description was made) it was saturated with water.

In intermediate positions, between uplands and the lower areas of wetland, where forest is restricted to gentle slopes, periphyton appears again. Under the periphyton, a 5-cm pale Bk horizon was found with light gray color when dry (10YR 7/1) that becomes brown when humid (7.5YR 4/2). It is sandy and rich in carbonates. Below, a well developed soil profile was found. The buried A horizon is dark brown (7.5YR 3/4, dry), 10 cm thick, with a well expressed granular structure and with abundant charcoal fragments. Its organic carbon content is low (1.04%), and it does not react with HCl. The Bw horizon, 10 cm thick, is similar in color (7.5YR 3/4, dry), but coarser in texture (more silty), with abundant content of carbonates. The underlying C horizon has many weathered limestone fragments. This soil can be regarded as polygenetic, because two different cycles of pedogenesis and sedimentation were recognized.

4.2 Soil Micromorphology

Groundmass of Rendzic Leptosols (profile 3) is mainly formed by dark-colored (brown or black) isotropic organic material. Under higher magnification, a large part is dominated by fine detritus. Larger fragments of plant tissues in different stages of decomposition are also abundant. This material is organized in rather coarse subangular blocks or in small crumbs of irregular shape. Carbonate particles of various sizes are frequent in the groundmass. On the contrary, all kinds of silicate materials, and in particular clay, are scarce. We found only few clay-rich rounded aggregates with lighter yellow-brown color and speckled to granostriated b-fabric, embedded in the dark isotropic predominantly organic groundmass (Fig. 2a,b). Despite the macromorphological similarity with Rendzic Leptosols, the micromorphological properties of the two Leptic Calcaric Phaeozem profiles (1 and 2) are quite different. Only very few large (>2 mm) fragments of limestone with biogenic structure (numerous mollusk shells) could be found. Groundmass is completely free of carbonates and very rich in fine clay material with scarce silt-size quartz grains embedded in it. Clay has stipple-speckled b-fabric and rather low birefrigence, groundmass has a reddish-brown color; due to staining with iron oxides. Organic materials are present in different forms. Fragments of plant tissues are rather frequent, with signs of decomposition by microbes or mesofauna.

Mottles of dark gray-brown organic pigment and tiny black specks are abundant within groundmass. The material is remarkably well aggregated: granules of various size and small subangular blocks, all of coprogenic origin, are partly welded, to form the porous aggregates of higher order, and all together produce spongy fabric with a dense void system (Fig. 2c). Soils formed in the small karst depression have a quite specific set of micromorphological features of the Bg horizon. It is compact, and its structure is dominated by subangular to angular blocks separated by fissures. The color of soil material is brown-yellow, with dark- brown areas corresponding to frequent ferruginous nodules and mottles (Fig. 2d). The groundmass is rich in clay, having porostriated, granostriated (thick envelopes of oriented clay round the ferruginous nodules) and mosaic-speckled b-fabric. Stress cutans are rather frequent along open and closed fissures (Fig. 2e). A few deformed clay illuvial pedofeatures was found only in this horizon. Few charcoal fragments are embedded in the groundmass (Fig. 2f).

The micromorphology of the Leptic Calcisol in the wetland implies a quite distinct mode of pedogenesis. The major part of groundmass consists of carbonates – in contrast to highland Phaeozems and Cambisols, in which groundmass is dominated by silicate clay. However, these carbonates are represented not by fragmented parent limestone, as in Rendzic Leptosol, but exclusively by neoformed micritic calcite. Micrite (with admixture of microsparite) forms blocky and granular aggregates, often welded to build up spongy fabric with high porosity. Frequently the micrite accumulations have specific biogenic microstructure: ooids (Fig. 3a), channeled clusters, related to the activity of algae (Fig. 3b) (Vogt 1987). Granules are often colored with dark-brown organic pigment – the presence of which lowers the material birefrigence. Partly decomposed plant tissues, as well as shell fragments (Fig. 3c) of terrestrial mollusks, are common. Soils on the gentle slope towards the wetland

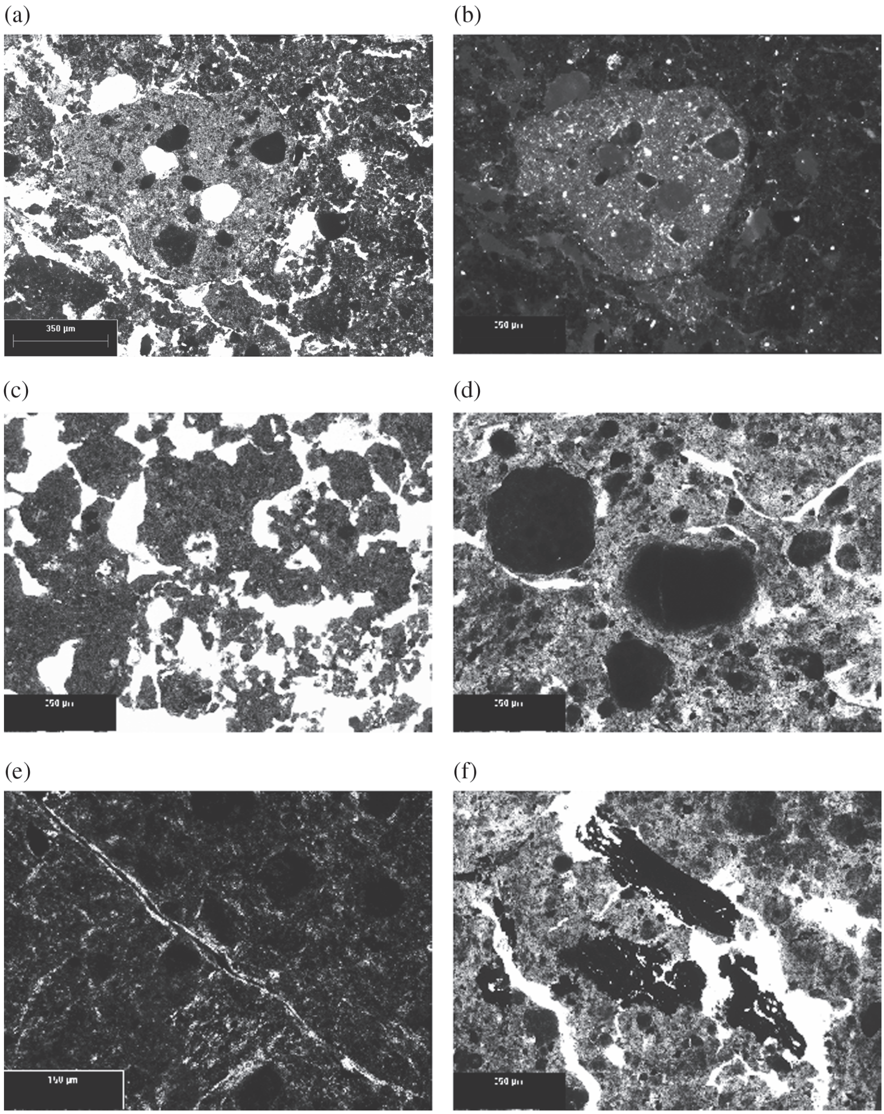

Fig. 2 Micromorphology of the upland soils from El Eden toposequence. PPL – plane polarized light, XPL – crossed polarizers. (**a**) Clay aggregate, Ah horizon of Rendzic Leptosol, PPL, (**b**) Same as (**a**), XPL, (**c**) Complex structure (subangular blocks and granules) and spongy fabric of Ah horizon of Leptic Phaeozem, PPL, (**d**) Compact material with fey fissures, frequent ferruginous nodules; Bg horizon of Gleyic Phaeozem, PPL, (**e**) Stress cutan, Bg horizon of Gleyic Phaeozem, XPL, (**f**) Charcoal fragments, Bg horizon of Gleyic Phaeozem, PPL

(profile 5) demonstrate a peculiar adn contradictory combination of micromorphological properties. According to earlier observations, some of the soils (profile 5) are typical for the wetlands, and others, for the upland soils. The surface carbonate

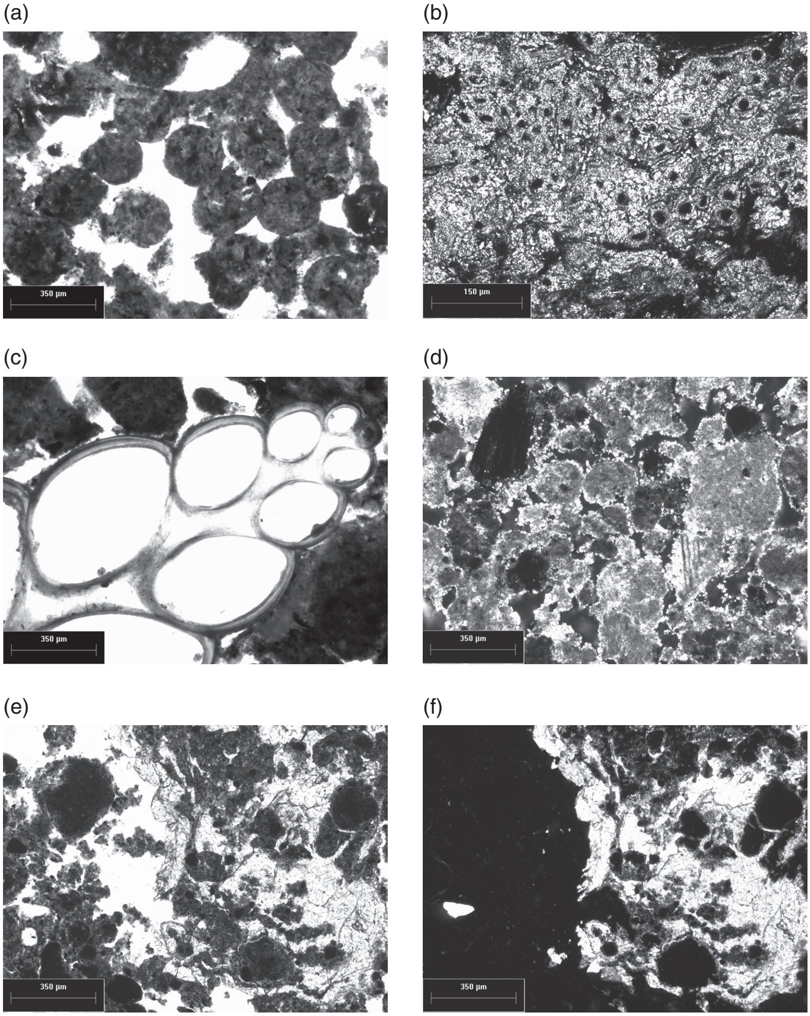

Fig. 3 Micromorphology of the wetland soils from El Eden toposequence. PPL – plane polarized light, XPL – crossed polarizers. (**a**) Micritic ooids, Bk horizon, Leptic Calcisol, PPL, (**b**) Channeled micritic aggregate, Bk horizon, Leptic Calcisol, XPL, (**c**) Mollusk shell, Bk horizon, Leptic Calcisol, PPL, (**d**) Granular structure, micritic groundmass with high birefringence in Bk horizon of upper Calcisol member of polygenetic profile, XPL, (**e**) Microarea cemented by coarse crystalline calcite (*center to right part*), Ah horizon of the lower Cambisol member of polygenetic profile, PPL, (**f**) Same as (**e**), XPL, note high birefrigence of calcitic cement

horizon is an analogue of laguna Calcisols; its material is dominated by neoformed biogenic calcite (3d). However, the underlying Ah and Bw horizons resemble the Phaeozems of elevated landsurfaces. Their groundmass is free of carbonates and contains abundant silicate clay. The Ah horizon has a granular structure and is enriched with organic material, although it also has some clusters of biogenic micrite that may be derived from the overlying carbonate horizon. The micromorphology of Bw is somewhat similar to the Bg horizon of the Phaeozem in karst depression, being rather compact, clayey, having blocky structure and containing frequent ferruginous nodules. A peculiar feature observed from both Ah and Bw horizons are micro-zones, cemented by large crystals of calcite, filling all pore spaces and "trapping" the soil aggregates (Fig.3e and 3f).

The upland soil, recently affected by fire, is heterogeneous: dark grey-brown humus-rich clods are mixed with red aggregates, enriched in iron-clay fine material; large black charcoal particles, often with the cell wall structure preserved, are very frequent (Fig. 4a). A peculiar feature of this material is the presence of loose concentrations of silt-size crystalline particles with high interference colors, and of irregular or rhombohedral shape in the pores and on the surfaces of the charcoal particles. Some of the rhomboids, being observed under crossed polarizers at higher magnifications, demonstrate non-uniform, undulating extintion patterns, indicating that they are not monocrystals but rather aggregates of minor crystals (Fig. 4b).

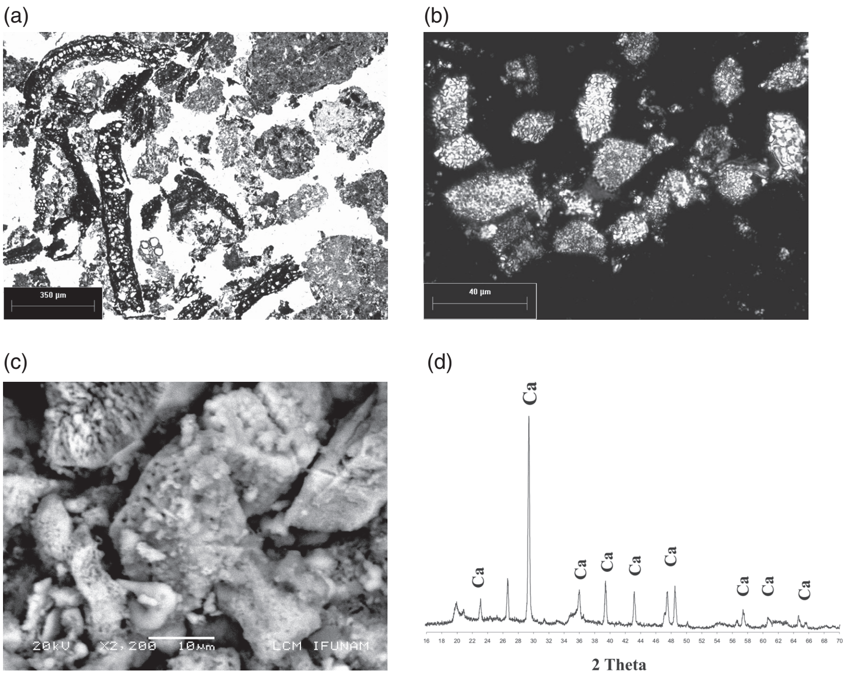

Fig. 4 Micromorphology and mineralogy of Rendzina, affected by forest fire. (**a**) Micromorphology of A horizon: clay and humus-clay aggregates (*right*), charcoal particles (*left*), PPL, (**b**) Neoformed carbonate grains in A horizon of irregular and rhombohedral shape. Note irregular extinction pattern, XPL, (**c**) Scanning electron microscopy of neoformed carbonates: note aggregative morphology of the rhombohedral grain, (**d**) Powder X-ray diffraction pattern of the soil material, enriched with neoformed grains; Maxima corresponding to calcite are marked with Ca

Under SEM we observed the rhombohedral grains which consist of tiny (about 1 μ) compactly packed particles that confirms the aggregative nature of at least part of the rhomboids (Fig. 4c), that could be micritic pseudomorphs after large whewellite (calcium oxalate) crystals (Canti 2003). About 10 particles of this shape that were subjected to EDX microprobe analysis showed the presence of Ca as the dominant element. An X-ray diffractogram from the material enriched with white powdery particles indicated calcite as the only crystalline non-silicate phase (Fig. 4d). This calcitic material is not derived from limestone fragmentation since its morphology is completely different from micritic or biomorph limestone carbonates.

4.3 Texture, Chemical Properties and Clay Mineralogy

All soils have pH values close to 7, somewhat lower in the upland Phaeozems and Cambisol, and a bit higher in the Leptosol and lowland Calcisols (Table 1). A horizons of the upland Rendzinas show pH values close to neutral, and with high values of humus (above 8% of organic carbon) and clay content (more than 70% in the Phaeozems about 50% in Leptosol). More than 15% of organic carbon (!) are found in the Leptic Gleyic Phaeozem in the small karst depression. The wetland, water-saturated with Calcisol, has much less humus than the upland Rendzinas (about 5%). This is a rare case of a soil toposequence in which well drained upland

Table 1 Selected properties of the studied soils

Horizon	Depth (cm)	Color dry	Color wet	OC* (%)	pH	P** ppm
Profile 1, Leptic Calcaric Phaeozem						
Ah	0–15	5YR 3/3	5YR 3/2	8.93	6.8	7.31
AC	15–27			6.10	6.8	3.50
Profile 2, Leptic Calcaric Phaeozem						
Ah	0–13	5YR 3/3	5YR 3/2	9.15	6.8	10.10
Profile 3, Rendzic Leptosol						
Ah	0–14	10YR 3/2	10YR 2/2	11.15	7.1	7.35
Profile 4, Leptic Gleyic Phaeozem						
Ah	0–11	10YR 3/2	10YR 2/2	15.3	6.3	7.31
Bg	11–24			0.97	6.9	7.31
Profile 13, Chromic Cambisol						
A	5–20	5YR 3/3	5YR 3/2	5.05	6.5	2.24
B	20–35			2.69	6.5	1.12
Profile 5, Polygenetic profile						
Bk	0–5	7.5YR 7/1	7.5YR 4/2	2.59	7.5	7.31
Ah	5–14	7.5YR 3/4	7.5YR 3/2	1.04	7.6	3.50
Bw	14–24	7.5YR 3/4	7.5YR 3/2	0.68	7.6	3.50
Profile 8, Leptic Calcisol						
Bk	1–3			5.20	7.5	3.01

* Organic carbon.

** Available phosphorus

members demonstrate higher accumulation of organic materials, than hydromorphic lowland members. Clay content of wetland soils is also lower.

X-ray diffraction patterns of all upland soils and lower subprofile of a two-phase profile in the forest-wetland transition are rather uniform. They show high and sharp 14 Å and 7 Å maxima, staying unchanged after glycolation; in heated specimens, 14 Å peak shifts to 12–13 Å peak with a shoulder to larger angles and 7 Å maximum disappears (Fig. 5). We suppose that this set of peaks is diagnostic of dioctahedral vermiculite. Incomplete contraction after heating (to 12–13 Å and not to 10 Å) points to formation of a fragmental additional Al-hydroxide interlayer between 3 layer

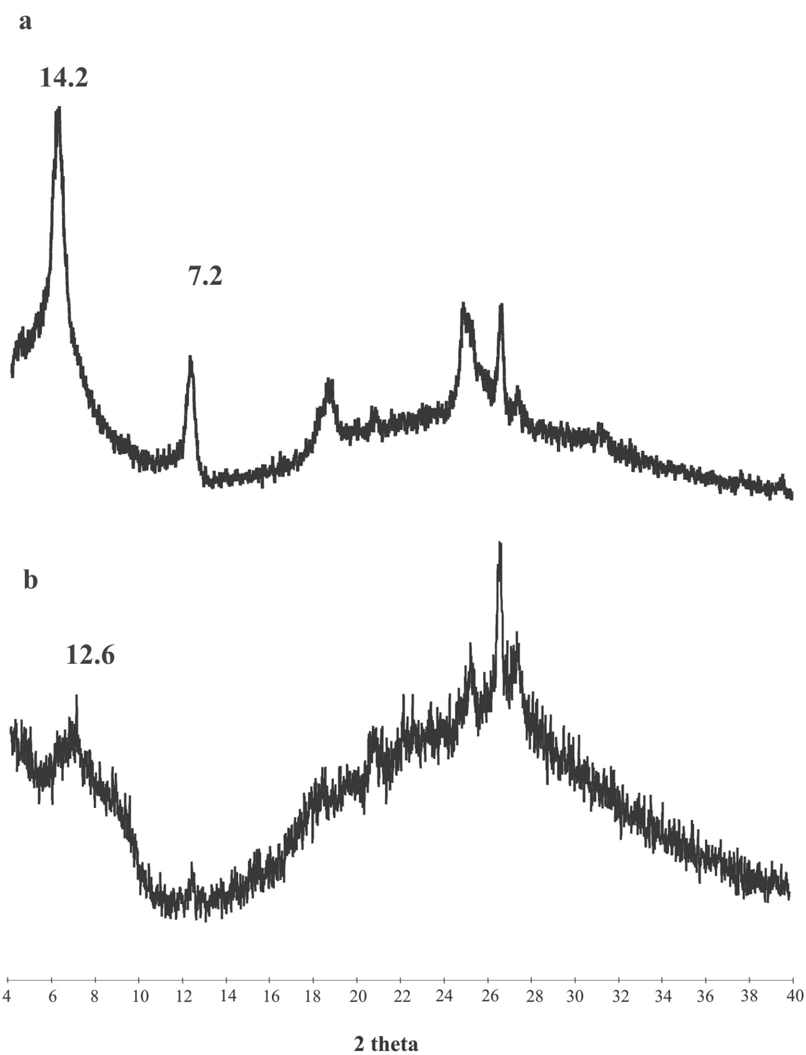

Fig. 5 X-ray diffractogram from the clay fraction of the Leptic Calcaric Phaeozem Ah horizon. Above: specimen saturated with ethylene glycol, below: specimen heated to 400°C

units (Dixon and Weed 1989). The 7 Å peak is likely a second order maximum of vermiculite, rather than a first order of kaolinite. The reason is that it disappears after heating to 400°C – temperature too low for destruction of kaolinite lattice, but enough for vermiculite contraction and transformation of its diffraction pattern.

No clay minerals were identified in the clay fraction of the Bk horizon of the wetland Leptic Calcisol. Only weak peaks of calcite are present, indicating, that this mineral, forming major part of the fine materialpartly remains after the HCl pretreatment.

5 Discussion

5.1 Interplay of Pedogenesis and Karst Erosion – the Reason of Pedodiversity in North-Eastern Yucatán

It is clear from first glance that soils formed on limestone in the northern Yucatán Peninsula differ greatly from the "central image" of humid tropical pedogenesis, perceived as thick, deeply weathered Ferralsols or soils with illuviation of kaolinitic clay (Acrisols-Lixisols). Leptic Phaeozems are shallow, discontinuous and often stony. Their pH values are neutral to slightly acid (Table 1), indicating incomplete leaching. They give an impression of very young, underdeveloped profiles. Their groundmasss shows the presence of primary carbonates and weatherable minerals and is dominated by clay and iron oxides, with few resistant quartz grains.

We still do not have enough data to detect the origin of the precursors of these components. At least, a volcanic source is unprobable. We found neither rests of primary volcanic minerals, nor allophanes or halloysite – typical weathering products of pyroclastic deposits. Further speculations are limited by the lack of knowledge about composition of non- carbonate components of limestone. The results of Aguilera-Herrera (1963) and Bautista-Zúñiga (2003) (both propped the residual genesis of the Yucatán soils) are few and contradictory. The former states that the limestones of Yucatán contain smectites, whereas the latter detected halloysite.

However, independent from the primary origin of the groundmass material (from limestone weathering or allochtonous sediment, as discussed above), properties clearly indicate the advanced weathering stage, which is not expected for a primitive soil. We further speculate that this property resulted from mineral transformation in situ and not from the deposition of pre-weathered sediment. Our reasoning is related to the geomorphological distribution pattern of weathering products. The most altered soil materials were found on elevated land surfaces which provide a leaching environment, and not in lower wetlands, which present better conditions for accumulation of any kind of sediment but less opportunities for advanced in situ mineral alteration, because of poor internal drainage.

Having rather high weathering status, the upland soils however do not reach the most advanced "ferrallitic" weathering stage. Their clay material is dominated by 2:1 mineral – Al-hydroxide interlayered vermiculite known to be an intermediate product of weathering in humid environments, resulting from incongruent dissolution of illites and chlorites (Dixon and Weed 1989). They do not contain Al hydroxides and kaolinite – the "end members" of the weathering products sequence, characteristic for Ferralic diagnostic horizon. This differentiates the soil mantle of the Yucatán from that of the neighbour Carribean islands (Jamaica, Cuba) where Ferrallitic soils are frequently found on limestones.

Contrary to undisturbed upland soil, we found abundant neoformed calcite in the Rendzina, recently affected by forest fire. Components of similar composition and morphology are described in the burned plant materials (Canti 2003, Courty et al. 1989) This observation points to the discontinuity of the process of carbonate leaching in the upland soils. It is interrupted by the periods of carbonate addition with plant ash produced by forest fires, the latter becoming more frequent due to present and past human activities.

We arrived at what seems to be a contradiction between high weathering status of soil materials from one side, and soil thinness, uneven distribution, and abrupt contact with the limestone, from the other. The interaction of pedogenetic and geomorphological processes is supposed to be responsible for such a situation. In general, we believe that considerable soil redeposition occurs in geomorphologically unstable karst environments of the northern Yucatán Peninsula. However, our studies of the soil catenary sequence at El Edén revealed no signs of lateral sheet erosion, natural or man-induced, which would transport fine material from the uplands to the wetlands. In the latter we have not found thick pedosediments. Wetland soils are often thinner than upland counterpart. The evidence, even more convincing, is that the groundmass composition of the Calcisols in wetland is very specific and cannot result from redeposition of materials, originating either from upland Phaeozems or limestone outcrops.

Calcisols lack the silicate clay, which could serve as a marker of Phaeozem-derived pedosediments. Their groundmass consists mostly of carbonates; however, those are not the products of limestone fragmentation, but rather the result of biochemical calcite precipitation from dissolved carbonates, mostly by algae. We relate this process directly to the functioning of algal community developed in wetlands during the rainy season. This conclusion agrees with results reported by Leyden et al. (1996). These authors also found low erosion rates and absence of anthropogenic lateral soil transport enhancement. The erosional dynamics in the northern Maya Lowlands seems to differ remarkably from that in the southern Maya Lowlands, where various authors report the strongest evidences of intensive lateral soil transport corresponding to ancient Maya occupation periods. Evidence for erosion in the southern lowlands includes thick layers of redeposited soil on lower land surfaces (Beach 1998a; Beach et al. 2003, Dunning et al. 2002) as well as enhanced sediment accumulation in lakes (Rice 1996). Both phenomena are lacking in our study area. We agree with Leyden et al. (1996) that this difference isrelated to the character of relief.

However, although we did not find evidence of long distance lateral soil redeposition we assume that short-distance, mostly vertical soil transport is quite intensive towards cracks, hollows, and small but steep depressions of karst origin.

We found a lot of such forms, empty as well as partly filled with fine pedosediments in all parts of our toposequence. Adjacent to these karstic forms, limestone outcrops are often free of soil. The Gleyic Phaeozem in the small karst depression has enhanced thickness, due to addition of redeposited soil from above, as indicated by the presence of charcoal fragments, even in its lowest Bg horizon. The higher soil thickness is accompanied by the manifestation of redoximorphic processes (frequent ferruginous nodules) indicating that these locations receive both additional fine material and moisture. Only here we found profiles with vertic properties, which are reported to be much more common in depressions of the southern Maya Lowlands (Beach et al. 2003) and the signs of the incipient clay illuviation.

Since many karst sinkholes are connected to a vast underground fissure and solution system, part of the soil material is probably transported deeper, contributing to cave and cenote sediments. In fact, each profile on the land surface is the result of a balance between pedogenesis and soil loss due to vertical transportation towards karst sinkholes. Rate differences between these two processes cause the variety of in situ formed soils, from the thick red Chromic Cambisols to the thinnest Rendzic Leptosols, and finally bare rock. It should be noted that the groundmass of Rendzic Leptosols, although dominated by plant detritus and primary carbonates, still contains some clay-rich aggregates – most probably the last remnants of an earlier continuously weathered horizon, such as those in the neighboring Phaeozems. We think that these Leptosols are not young, but rather a result of degradation of a previous well developed profile, due to unbalanced soil loss caused by enhanced karst erosion. High intensity of karstification processes in Yucatán could be also be responsible for the absence of deeply weathered ferrallitic soils in this region. Similar "balance" models for soil cover development in karst regions were proposed for other natural zones such as boreal forests (Goryachkin and Shavrina 1997) and Mediterranean environments (Atalay 1997).

5.2 Two-Storeyed Soil in the Wetland Periphery: An Indicator of Recent Environmental Change

A soil profile formed in the marginal part of the wetland, close to the upland forest has signs of the overlapping of two different pedogenetic events. The upper unit, similar to wetland Calcisol, is superimposed on a Cambisol, which is typical for upland soil formation. We interpret this as a result of the extension of wetland area, affected by the regular floods towards the territories earlier occupied by the upland forest ecosystem. We also attribute partial cementation of the Cambisol groundmass (originally carbonate-free) by large crystals of secondary calcite to the same landscape dynamics, which caused periodical saturation of a soil with surface water, from which calcium carbonate could precipitate. The timing of this environmental change is unknown and we have no instrumental or archaeological dating for either of the two soil units. The driving force of this dynamic is also uncertain and could imply climatic change as well as groundwater table rising, related to sea level fluctuations.

The data on the stratigraphy of paleosol-sedimentary sequences of the southern Maya Lowlands give some hints for the preliminary correlation and interpretation of the Calcisol-Cambisol. In a number of papers where such data are presented (Pohl and Bloom 1996, Pope and Pohl 1996, Voorhies 1996), the following stratification regularity is described: well developed humus-rich paleosols are overlain by pale "gray clay," or "gray silt," often with carbonates and gypsum, sometimes accompanied by layers of freshwater mollusk shells.

The lower paleosols indicate a phase of relative geomorphological stability, while the overlying layers "are the result of natural deposition representing both alluviation and colluviation in floodplains and associated backswamps, accentuated by deposition of calcium carbonate and gypsum from ground and surface water" (Pohl and Bloom 1996). We suppose that the Cambisol unit (profile 5) could be associated to organic-rich paleosols and the Calcisol, the overlying carbonate-rich sediments. If this association is correct, then the two-storeyed profile of the wetland periphery reflects landscape processes which took place within the ancient Maya occupation period.

5.3 Pedogenetic Properties in Relation to Ancient Land Use

Fray Diego de Landa, a Franciscan missionary who arrived to Yucatán soon after the Spanish occupation and left informative descriptions about various aspects of Maya life wrote: "Yucatán is the country with the least earth that I have seen… it is marvelous that the fertility of this land is so greaton top of and between the stones" (Tozzer 1941, p. 186; original 1566). In this passage he refers to the extraordinary fertility of thin calcareous soils of Yucatán (Leptic Phaeozems and Rendzic Leptosols) which, from the contemporary standpoint, seem to be so unsuited to agriculture. In fact, these soils lack the majority of disadvantages common to the usual, thick but extremely leached, humid, tropical soils. The characteristics of Yucatán soil are developed by the unique combination of weathered groundmass, rich in silicate clay of 2:1 type and iron oxides, and limestone located quite near the surface. The permanent dissolution of the latter (evidenced by various corrosion forms) gives sufficient dissolved calcium carbonate to provide pH values close to neutral and to avoid the problems of typical tropical soils, related to excessive acidity and Al toxicity. It also provides the stabilization and accumulation of dark disperse humus.

Already Kubiëna (1970) in his classic study of soil development on limestone in the Vienna Woods underlined that formation of the Mull Rendzina with abundant dark colloidal humus is conditioned by accumulation of sufficient quantities of clay components in the topsoil above calcarious rock. In the studied soils, humus, vermiculitic clay, and iron oxides are the agents of stable aggregate formation which provide favorable physical properties, regarding soil moisture availability, aeration, and root penetration. There is no tendency to compaction and hardening, that is usual for cultivated tropical Acrisols and Lixisols (Van Wambeke 1992). These pedogenetic features could also be responsible for relatively rapid recovery of calcareous soils in humid tropics of Mexico during fallow period, recently reported by Mendoza-Vega and Messing (2005).

We agree with Beach (1998b) that the major soil limitations for agriculture are its thinness and uneven surface distribution, as well as very low available P contents (Table 1), showing deficiency in this nutrient. An important way to match cultivation to such soil conditions was planting in natural karst features filled with soil material (Kepecs and Boucher 1996) and fertilization of the upland soils, for which purpose P-rich periphyton evidently was used, being collected and transported from the wetlands (Fedick et al. 2000, Palacios et al. 2003).

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