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Spatial distribution and development of soils in tropical karst areas from the Peninsula of Yucatan, Mexico

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A B S T R A C T

Better understanding of soil formation requires knowing the spatial distribution of the soils that allows constructing models of soil sequences in multiple directions along various types of gradients. This approach was applied to comprehend the soil formation from the soil distribution in the tropical karst areas of the Peninsula of Yucatan, Mexico. For soil mapping, a two-step methodology was followed. First, a geomorphic analysis was performed; subsequently, 382 soil profiles were reclassified and integrated into a geopedologic map. Additional soil survey was carried out in areas where soil information was lacking (123 soil profiles). Satellite images were used to identify flooded areas. After conducting numerous field verifications and analyses, landforms and soils were combined to make a soilscape map. Based on field observations and the soilscape map, soil development was analyzed on soil sequences. Four geomorphic environments were identified, karstic plains and hills with Leptosols, Cambisols, Luvisols, and Vertisols; coastal plains with Arenosols, Regosols, Solonchacks, and Histosols; fluvio-paludal plains with Gleysols, Histosols, Leptosols and Solonchacks; and tectono-karstic plains and hills with Leptosols, Cambisols, Luvisols, and Vertisols. Relevant soil forming factors in the Peninsula of Yucatan include time of emersion of the limestone platforms, climate, rock type, and macro- and micro-relief. Other factors such as groundwater level, fractures, also have an influence on soil formation. Karst development can be considered as a complex soil and relief forming factor. Terra Rossa soils as Leptosols, Cambisols, Luvisols, Nitisols and Vertisols in the Peninsula of Yucatan may be polygenic. In some cases, the theory of residual origin fits better the data than the theory of allochthonous origin; in other cases, it is the other way around.

1. Introduction

Limestone and dolomite rocks are often covered by reddish clay soils called Terra Rossa that forms a discontinuous layer ranging in thickness from a few centimeters to several meters. These soils are classified as Cambic Leptosols, Cambisols, Luvisols, Nitisols and Haplic Vertisols (Chromic) according to the World Reference Base for Soil Resources (IUSS working group WRB, 2006). Several hypotheses have been used to explain Terra Rossa formation: (a) rock and climate as principal soil forming factors and dissolution of limestone as the main process that produces lime-free residues (Kubiëna, 1953; Bronger et al., 1983; Scholten and Andriesse, 1986); (b) the contribution of allochthonous materials, mainly of eolian origin, in the USA (Olson et al., 1980), Israel (Danin et al., 1983), Turkey (Aydinalp, 1997), the Mediterranean region (Yaalon, 1997; Durn, 2003; Muhs et al., 2010), Croatia (Durn et al., 1999), Jamaica (Muhs and Budhan, 2009), and México (Cabadas et al., 2010); (c) the residual dissolution of red limestone formed by debris mud, ash or eolian dust, principally in the Bahamas, Antilles, México, USA (Florida, Texas, and Kentucky), Spain, Israel and Australia (Merino et al., 2006ab; Merino and Banerjee, 2008). The latter hypothesis refers to the replacement of limestone by authigenic clay along a narrow reaction front.

The studies on the formation of Terra Rossa soils in the karst of the Peninsula of Yucatan can be grouped into three types: (a) regional studies with intensive fieldwork, description of soil profiles and relief (Aguilera, 1959; Isphording, 1978; Duch, 1988; Bautista et al., 2003a, 2005a), (b) site studies with intensive fieldwork but restricted spatially (Bautista et al., 2004; 2005b), and (c) case studies (point or small areas) including geochemical and micromorphological analyses (Sedov et al., 2007; Cabadas, in press; Cabadas et al., 2010; González, 2010).

The first two study types adopted the hypothesis of residual origin through limestone dissolution, while the third type adopted the

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hypothesis of the contribution of allochthonous materials. In fact, only in two cases allochthonous materials were detected in the soils (Sedov et al., 2007; Cabadas et al., 2010). Other studies argue that Leptosols are essentially products of soil degradation (Sedov et al., 2008) or result from a mixture of allochthonous and autochthonous materials (Cabadas, in press).

According to SEMARNAP (2000), soil information in Mexico is considered old and incomplete, thus usually not appropriate for most current applications. Official soil maps (INEGI, 1984abcdef) used a geologic approach that provides limited understanding of soil distribution and formation.

In this work, we analyze the spatial distribution and development of soils in the tropical karst of the Peninsula of Yucatan using a geomorphopedologic mapping approach and we discuss soil formation according to time of platform emersion and in the light of current hypotheses on the origin of Terra Rossa soils.

2. Materials and methods

2.1. Study area

The Peninsula of Yucatan is located in the southeast of Mexico between 18° and 21° 30′ North. It is a region of low relief with elevations generally below 50 m a.s.l. (Bautista et al., 2005a). The highest area lies in the center of the peninsula and from there elevation decreases eastward and westward by abrupt steps. In the southern part of the Yucatan state are the hills of Ticul and Sayil, with altitudes of up to 250 m a.s.l. Two main geomorphic units are recognized: (1) recent plains of less than 50 m elevation with minimal karst development, and (2) older plains and hills with less than 400 m elevation (Lugo et al., 1992). Three phases of tectonic uplift, dating back to 5.3 Ma, 3.6 Ma and 18 ka (Lugo et al., 1992; Lugo and García, 1999; Padilla, 2007), have caused terrain emergence and raised the surface of Yucatan (Fig. 1). Based on the former dates, the emerged platform surfaces can be called old, intermediate and young, respectively. The processes of platform emersion include differential uplift, generalized tectonic tilting and eustatic movements. Tectonic fractures are frequent, generating significant geomorphic features such as hill alignments and doline groups (Fig. 2). The northern coast is the driest area of the Peninsula of Yucatan with a semi-arid climate of the subtypes BS_1(h')w and BS_0(h')w. On the island of Cozumel, the climate is warm humid of Am(f) subtype with abundant winter rainfall. The rest of the Peninsula of Yucatan has a warm subhumid climate with three subtypes including Aw_0, Aw_1 and Aw_2 of increasing moisture. The driest areas are located in the west and the wetter ones in the east (Fig. 2) (García, 1990). Forest cover includes various types from tropical deciduous to tropical evergreen forest. In coastal and other low-lying areas, vegetation is savannah, petenes (i.e. tropical forests on residual hills), mangroves, coastal dune scrub, sedge, cattail marshes and tulare (Flores and Espejel, 1994)

2.2. Soil mapping

A two-step methodology was followed for soil mapping (Fig. 3). First, an analysis of the geomorphic environments and landscapes was carried out. Subsequently, the available soil information including field and laboratory data was collected. Soil profiles were re-classified and, after numerous field verifications, the updated soil information was integrated into a geomorphic landscape map to form a soilscape map (1:250,000). Additional soil survey was carried out in areas where soil information was lacking in order to cover the entire Peninsula of Yucatan.

Relief features were identified at subregional level based on the nature and functioning of the morphogenetic environments. The concept of terrain unit or homogeneous map unit was applied to differentiate among geomorphic landscapes. The geomorphic landscape is a portion of terrain that contains environmental conditions physiognomically and functionally distinguishable from those of adjacent units through well-defined boundaries (Hansen, 1984). Its characterization and delineation are based on the correlation of morphostructural, morphometric, morphodynamic and environmental criteria of the same functional and genetic order using digital elevation models (Table 1).

Analog maps from the National Institute of Statistics, Geography and Informatics (INEGI), digital maps from the National Forest Inventory, and Landsat and Spot satellite images were used as bases for soil mapping. A digital model was used to separate hills and plains, and a fracture map allowed identifying their tectono-karstic origin, especially in the case of aligned hills. Grouped sinkholes were identified on satellite images and their spatial relationship with fractures provided strong evidence that the fractures had contributed to their development.

Landsat images were processed using a principal component analysis called tasseled cap to create a 7–4–2 false-color composite image. This was used via visual interpretation to detect the distribution of surface moisture, vegetation cover and the occurrence of exposed soils in fluvio-paludal and coastal plains. The satellite images were used to delimit the humid surface of Gleysols in fluvio-paludal plains. The first emerged karstic plains with poor drainage and coastal zones were identified using a vegetation cover map and satellite images. The maps were produced with the ArcGIS 9.3 software (ESRI, 2004).

2.3. Soil database and soil analyses

The Multilingual Soil Database (SDBm Plus) software was used to handle and store georeferenced soil data, including the attributes of individual soil profiles (De la Rosa et al., 2002). Profile information of 382 sites was taken from official data (INEGI, 1984a,b,c,d,e,f) and from the literature (Bautista et al., 2003a, 2004, 2005a; Amaya et al., 2005; May and Bautista, 2005). Additional data were collected between 1999 and 2007 (Fig. 4). Multiple revisions were made to check the existing information in the field. The classification of the soil profiles was updated according to the framework of the World Reference Base for Soil Resources (IUSS working group WRB, 2006).

In areas of limited soil information, 123 soil profiles were described according to Siebe et al. (1996). Features described in the field included dry and wet color, texture, size, shape and stability of aggregates, carbonates, root distribution, pH and electrical conductivity. Soil samples were taken by horizon in 50 profiles for physical and chemical analyses. The following tests were performed: separation and quantification of fine earth, percentage of gravel by sieving at 2 mm, particle size distribution (Okalebo et al., 1993), bulk density, pH 1:2.5 (Lean, 1982), calcium carbonate equivalent using the calcimeter method (USDA, 1996), organic matter by acid dichromate oxidation (Nelson and Sommers, 1982), cation exchange capacity by the ammonium acetate pH 7 method, with the exchangeable cations measured in the percolate (USDA, 1996).

2.4. Mineralogical analysis

The mineralogy analysis was made on B horizon samples from principal soil groups belonging to four geomorphic environments, in order to obtain the mineralogical components of the untreated random powders and the fine fraction of the lime-free residue. The selected geomorphic environments are: coastal plain, tectono-karstic plain, karstic plains and karstic hills.

X-ray diffraction analysis (XRD) of the soil matrix (untreated samples with lime) and the lime-free clay fraction was carried out to identify the minerals to support soil classification and interpretation of soil formation. Soil samples were dried and sieved at 2 mm. From each of the untreated powder soils, a sub-sample of 100 g was taken and grounded in an agate mortar to be homogenized.

In the case of lime-rich soils, the clay fraction (<2 μm) was obtained upon dissolution of the carbonates with HCl (5%) and sedimentation in water (Moore and Reynolds, 1989). The carbonate-free dry soil (5 mg)