Neosols, relict paleosols, and alterites in the Transmexican Volcanic Belt, Morelos state: Characterization and regional spatial distribution

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ABSTRACT

Investigations concerning the pedological linkages between modern soils and paleosequences, as well as the research regarding their spatial distribution and variability dynamics along the landscape are unfortunately very scarce. Both studies can provide, in a geochronological scale, a very useful paradigm to decipher the present and past biotic and abiotic environmental conditions that prevailed in many regions of the world.

The aim of this paper is: (1) to characterize the environment as well as the soil groups and paleosequences located in landscapes of the Transmexican Volcanic Belt, Morelos state, and (2) to explain, relate, and visualize in two dimensions and at a reconnaissance scale, the spatial distribution of soil groups within these landscapes. Such knowledge can provide the basis to establish a unique paleopedological record of late Pleistocene to Holocene environmental conditions in the Transmexican Volcanic Belt.

In our study, the interpretation of thematic cartography and the application of sophisticated methods like remote sensing and laboratory automated image analyses combined with field transects, provided a unique set of tools for generating and synthesizing data. These data were invaluable in order to obtain the spatial predictions about soil and paleosequence distribution.

Our research results reveal that: (a) in the study area there are seven different soil groups, 19 subgroups, one group of relict paleosols, and two genetic types of alterites; (b) the phenomenon of topography-induced environmental differences, and the slope-profile position commonly have a notable influence on the spatial distribution and variability of soil groups; (c) all studied paleosols meet many of the taxonomic requirements for Luvisols, while some alterites satisfy the diagnostic characteristics of Fragipans or Duripans; (d) the pattern of paleosequence spatial distribution in the Morelos landscapes is closely parallel to the distribution of late Pleistocene–Holocene volcanic geomorphic elements. In addition, many of the studied soils and paleosequences show distinctive spectral properties that allow their accurate identification by means of automated image analyses. These results suggest that the spatial distribution of these soils and paleosequences in Morelos state are geographically predictable.

Key words: relict paleosols, alterites, spatial distribution, soil spatial predictions, automated image analyses.

RESUMEN

Los estudios acerca de las relaciones pedológicas entre los suelos modernos y las paleosecuencias, así como las investigaciones relacionados con su distribución y variabilidad espacial en el paisaje, son desafortunadamente muy escasas. Ambos tipos de estudios potencialmente pueden proveer, en una escala geocronológica, un paradigma muy útil para descifrar las condiciones ambientales, bióticas y abióticas que prevalecieron en diferentes épocas en muchas regiones del mundo.

Los objetivos de este artículo son: (1) caracterizar a nivel regional el medio ambiente así como los grupos de suelos modernos y paleosecuencias localizados en paisajes del Cinturón Volcánico Mexicano en el Estado de Morelos; (2) explicar, relacionar y representar en dos dimensiones y en escala de reconocimiento, su distribución espacial dentro de esos paisajes. Tal conocimiento puede delinear las bases para establecer un importante registro paleopedológico de las condiciones ambientales que se presentaron en el Cinturón Volcánico Mexicano durante el Pleistoceno tardío al Holoceno.

En este estudio, la interpretación de la cartografía temática del área, así como la aplicación de métodos sofisticados como la tetedetección y el análisis automático de imágenes, combinados con transectos en campo, resultó una valiosa herramienta para generar y sintetizar información. Dicha información resultó invaluable para realizar algunas predicciones sobre la distribución espacial de los suelos y paleosecuencias que se presentan en el área de estudio.

Los resultados obtenidos muestran que: (a) en el área de estudio existen siete diferentes grupos taxonómicos de suelos modernos (Neosoles), 19 subgrupos, un grupo de paleosuelos y dos tipos genéticos de alteritas ('tepetates'); (b) el fenómeno de diferencias ambientales inducidas por la topografía, así como la posición de los perfiles de suelos en las pendientes, son factores muy determinantes en la distribución y variabilidad espacial de los suelos, paleosuelos y alteritas; (c) todos los paleosuelos detectados en este estudio reúnen los requisitos necesarios para ser clasificados como Luvisoles, mientras que algunas alteritas muestran propiedades diagnósticas para fragipanes y duripanes; (d) el patrón de distribución espacial que muestran las paleosecuencias está estrechamente relacionado con la distribución de las geoformas volcánicas de edad Pleistoceno tardío–Holoceno. Además, muchos de los suelos y paleosecuencias estudiados muestran propiedades espectrales muy distintivas que permiten su identificación a través del análisis automátizado de imágenes. Todos esos resultados sugieren que la distribución de suelos y paleosecuencias presentes en el Estado de Morelos son geográficamente predecibles.

Palabras clave: paleosuelos relictos, alteritas, distribución espacial, análisis automátizado de imágenes.

INTRODUCTION

The traditional two-dimensional soil landscape studies probably started with V.V. Dokuchaev's zonality schemes in 1899–1900. These studies demonstrated that both soil distribution-variability patterns and landscape elements often coincide, and that knowledge of one allows predictions to be made on the other (Yaalon, 1971). This coincidence of spatial distribution-variability and landscape elements can occur on any scale and at any time (Adams *et al.*, 1975; Gerrard, 1995).

From a pedological point of view, it is generally accepted that the combination of soil-forming factors within landscape, produces selected zonal soils in this landscape (Gerasimova *et al.*, 1996). Each soil zone is supposed to have one or several zonal genetic soil types that are specified by the soil profile composition.

Generally, the composition, properties, and evolution status of a soil profile gradually vary through space with soil position in the landscape to form catenas (Jenny, 1941; Olson and Hupp, 1986; Sommer and Schlicting, 1996). In such catenas, soil properties and development are mainly related to geomorphic processes (Huggett, 1975; Hall, 1983; Birkeland, 1999) and topography effects (Berry, 1987); for example, the shape of a slope can influence moisture distribution and sediment transport (Birkeland, 1999).

This zonality doctrine may be briefly formulated as the hierarchical system of geographical regularities governing the spatial distribution and variation of soils, and as specific regular combinations of soil-forming agents in large areas accounting for basic trends of pedogenesis (Gerasimov, 1975; Gerasimova, 1987).

In a more specific concept, Ruhe (1975), Targulian and Sokoloba (1996), and Birkeland (1999) establish that the systematic spatial distribution and variability of soils depend on the following four factors: (1) landforms and environment, (2) soil-forming factors, (3) pedogenic-geomorphic processes and soil slope profile positon, and/or (4) soil management by humans.

In contrast to this systematic soil distribution and variability, Wilding *et al.* (1983) argue that some of the main causes of vertical and lateral soil anisotropy that yield spatial distribution and variability of a random nature include: (a) differential lithology, (b) contrasting variations in the

intensity of weathering, (c) increase in erosion and accretion, (d) natural or induced perturbation of the tessera ecosystem, and (e) differential hydrology.

We consider that all of these statements involve important dynamic interrelations of biological, geological, geomorphological and pedological processes that are multi-scaled in both time and space. Consequently, such statements must be also utilized on the reasonable study of the properties, spatial distribution, and variation of relict paleosol–alterite sequences (paleosequences) located on the geomorphic components of the landscape.

We also argue that the knowledge of the spatial distribution and variation of recent soils, or neosols (Reuter, 2000), and paleosequences on a landscape scale is necessary for extrapolation from point results to greater areas, not only in paleopedological research but also for the present or past environmental reconstruction purposes. Regarding this, Charles Lyell, a nineteenth-century geologist, promoted the principle that "the present is the key to the past". The past and the present are also keys to the future.

Unfortunately, an unresolved problem in modern paleopedology research is that very few studies consider the identification and interpretation of paleosequence dynamics critical to understanding the spatial distribution and variability of soil properties across the landscape (Gama *et al.*, 2001).

Having this in mind, over the past two years, our attention has been focused on paleosequence properties, as well as in their association with neosols and spatial distribution dynamics within the Quaternary landscapes of Morelos State, located in the central Transmexican Volcanic Belt (TMVB).

In this paper, an overview of the current state of knowledge regarding the pedogenetic characteristics and spatial distribution of neosols and paleosequences over landscapes of Morelos state is presented. The goals of this study are: (1) to characterize the environment as well as the neosol groups and paleosequences located in the TMVB landscapes of Morelos state, and (2) to explain, relate, and visualize in two dimensions and at reconnaissance scale the spatial distribution of neosols and paleosequences within these landscapes. In agreement with Birkeland (1999), we consider that the use of environmental correlation for predicting soil spatial distribution and variation is most effective when an *a priori* environmental–pedogenic model is proposed for a region.

Finally, in order to obtain such a model and objectives we decided to use the following methodological strategy: (1) the utilization of thematic maps and, in accord with Bruin and Stein (1998), a digital elevation model for the region; (2) the generation of new thematic information using remote sensing and automated image analyses; and (3) the field collection and verification of ground truth data by means of transects.

For practical reasons, we utilized the Morelos state digital elevation model published by the Instituto Nacional de Estadística, Geografía e Informática (INEGI, 1999). This model was used to provide the basis for spatial representation of environmental factors and coverage present in the study area. On the basis of the model, we also designed a sampling method and evaluated the adequacy of neosol and paleosequence data and their environmental correlation.

REGIONAL SETTING

Morelos state (Figure 1) is located in central Mexico. The extreme coordinates that limit the state are: 19°08´ to 18°20´ north latitude, and 99°30´ to 98°38´ west longitude. According to INEGI (1999), the state covers an area of 4,958 km^2, with 2,811 km^2 located in the TMVB physiographic province and 2,147 km^2 in the Sierra Madre del Sur (SMS) province.

The TMVB landscape is mainly characterized by tectonic, structural, and volcanic landforms, and probably by a few periglacial landforms (Pasquaré *et al.*, 1987; Márquez *et al.*, 1999). In addition, certain mass movement landforms (lahars and other flows), and some anthropogenic tillage/management features like hillslope terraces (archeological features) are also present. Erosional, depressional, fluvial, mass movements, along with slope and solution landforms are typical characteristics of the SMS province. In both areas, the surface morphometry is highly variable and contrasting; for instance, the elevations range from 880 m to 5,500 m, and the slopes have gradients that vary from <0.5 to >95% (Figure 2).

In the TMVB, Pleistocene–Holocene igneous-efusive (*e.g.,* basalt, andesite, dacite) and pyroclastic rocks (*e.g.,* fine and coarse ash, pumice, lapilli, and tuffs) are dominant (Fries, 1960), while in SMS, Tertiary volcanic rocks and Cretaceous clastic sedimentary (*e.g.*, mudstone, conglomerate, calcareous shale) as well as interbedded rocks (*e.g.* limestone–shale, limestone–sandstone) are common (Martin del Pozzo *et al.*, 1997).

From the physiographic point of view, Morelos altitude and topography account for their highly varied range of climates and vegetation. The adiabatic cooling phenomenon characterizes this area. Figure 3 shows that climate oscillates from warm, with annual mean temperatures above 26°C, to cold, with annual mean temperatures under 8°C. Annual precipitation ranges from <1,000 to 1,500 mm (García, 1988).

The current vegetation and land use includes pine forest and oak-pine mix (8%), subtropical deciduous seasonal forest (30%), grass/herbaceous and shrub cover (6%), and crop cover (53%). About 3% of the Morelos state area is occupied by urban constructions and roads (INEGI, 1999).

Vertisols and Phaezoms are among the most important agricultural soils in Morelos state. The main products are vegetables, maize, rice, sugar cane, and ornamental flowers,
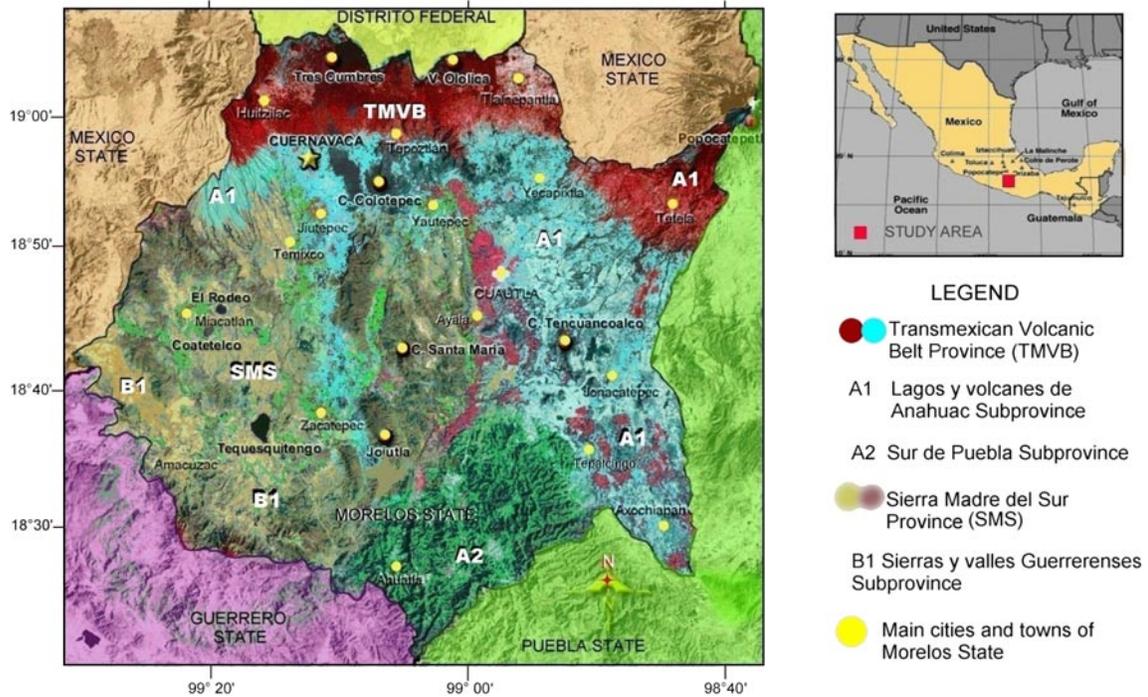
Figure 1. Location of the study area in the Morelos state.
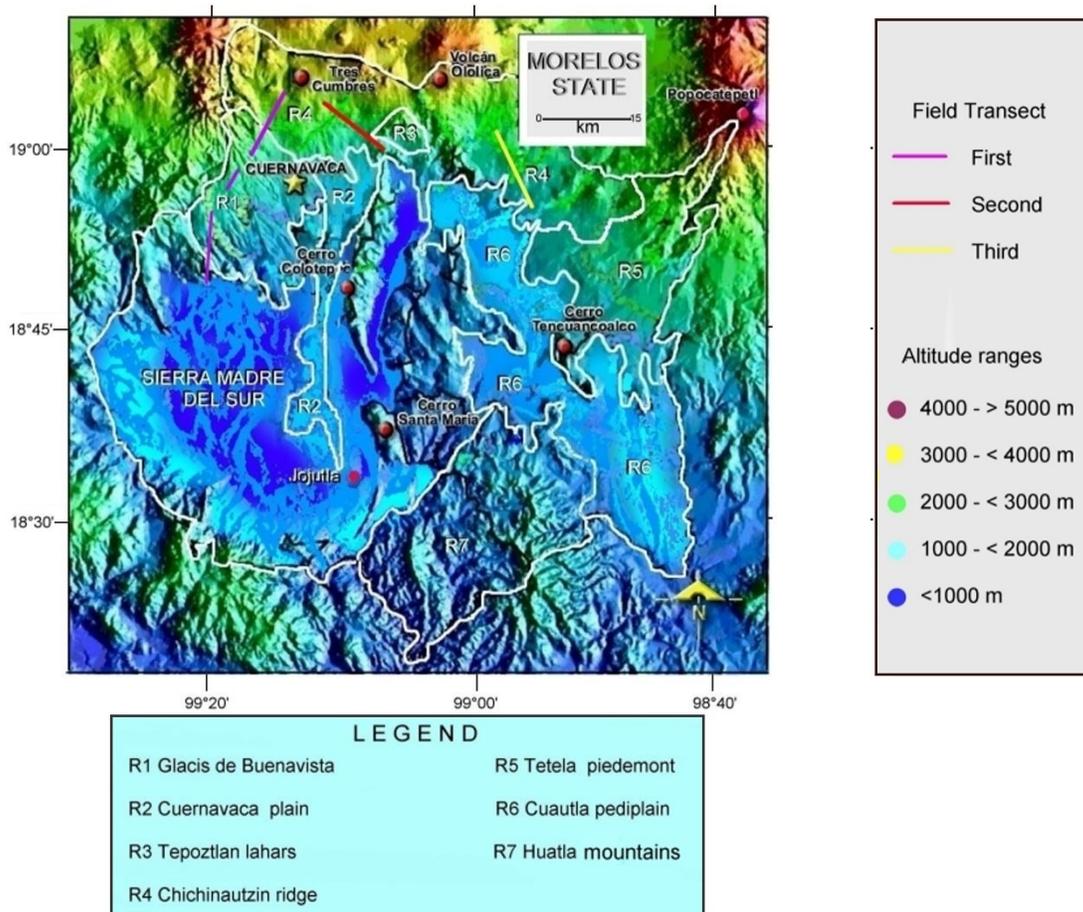
Figure 2. Spatial location of physiographic regions of the Morelos state belonging to the Transmexican Volcanic Belt province.

along with improved pastures that supports a dairy industry on these soils.

METHODS

The study area comprises the portion of the TMVB located in the Morelos state (Figure 1). Research, was carried out in six methodological steps. The methods and materials employed are briefly summarized below.

Step A. Integration of the data base

The documented and cartographic information generated by DETENAL (1981) and INEGI (1999) was used to integrate our database and, in some cases, for the thematic illustration of this work.

The Morelos database includes: (1) topography map at 1:250,000 scale, (2) geology map at 1:250,000 scale, (3) vegetation map at 1:250,000 scale, (4) map of physiographic provinces at 1:250,000 scale, (5) digital elevation model at 1:250,000 scale, (6) maps of mean annual precipitation (mm) and mean annual temperature (°C) at 1:100,000 scale, (7) pancromatic aerial photographs at scale 1:50,000, and (8) satellite images TM 5 at 1:250,000 and 1:1,000,000 scales. In addition, we also compiled and utilized the Morelos state soil profile descriptions and associated data

elaborated by Ortiz-Pérez (1977), Solleiro-Rebolledo (1992), Flores-Román *et al.* (1996), and Jasso-Castañeda (2000).

Step B. Preliminary stereoscopic study of the area

In accordance with the procedures outlined by the United States Department of Agriculture (Soil Survey Staff, 1998), the TMVB area was scanned with a stereoscope for a general impression of the landscapes, including relief, landforms, geomorphic components, geology, hydrology, kind of soil to be expected, farming, and additional features, for instance archeological features, drainageways, roads and buildings.

Step C. Fieldwork

A first topographic transect was made, which crosses representative landforms of the TMVB in all parts of the landscape (Figure 2). The digital elevation model and the false color composite image Landsat TM 5 were used as base maps for collecting environmental information. A total of 63 points were surveyed according to the field guide of the U.S. Department of Agriculture (Schoeneberger *et al.*, 1998). However, on the basis of field studies and pedological analysis, only 12 representative neosols and
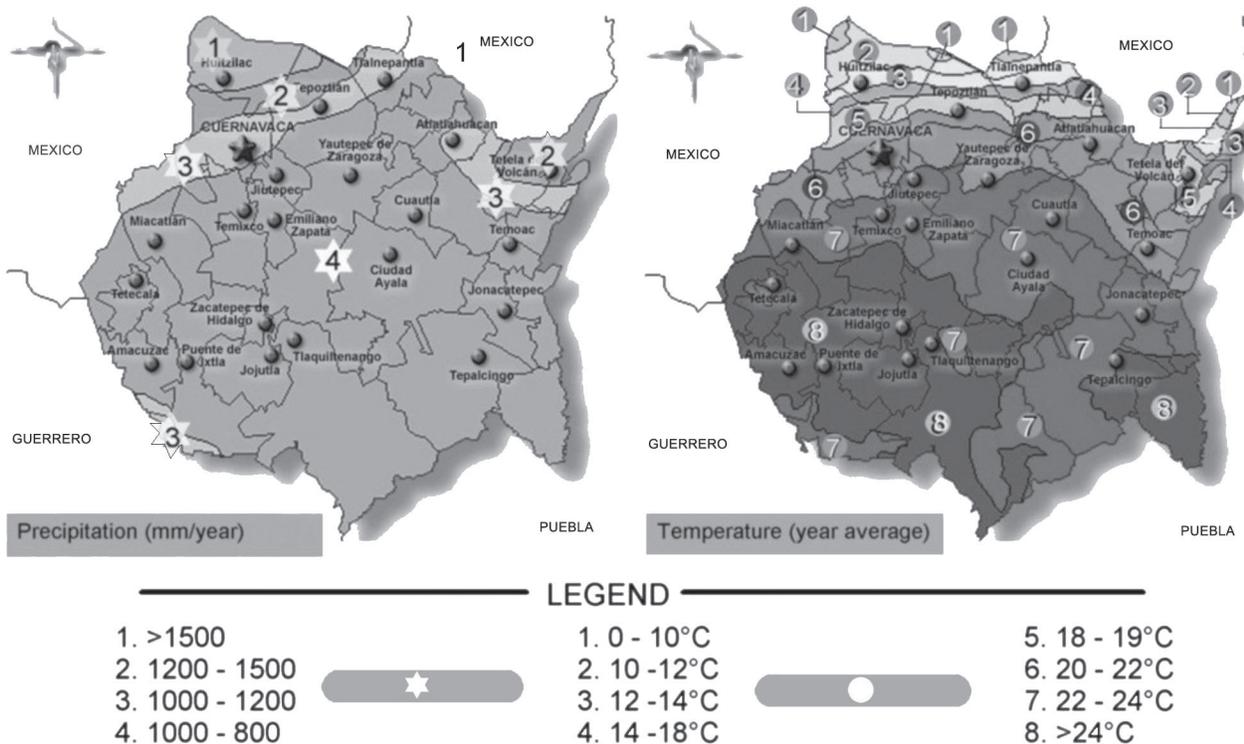
Figure 3. Climatic characteristics of the Morelos state.

one paleosequence were selected for analysis and discussion in this paper (S1–S13).

The following properties were recorded for each point: (1) location in the hillslope profile position (HSP); (2) slope percent; (3) elevation (m a.s.l.); (4) climate: temperature (°C) and precipitation (mm); (5) parent material; (6) type of land cover/vegetation; (7) soil total depth (cm); (8) number and type of horizons; (9) thickness, color, structure, consistence and field texture of each horizon. The landforms were denoted according to the Glossary of Landform and Geologic Terms (NSSC, 1997). A Global Positioning System (GPS) was used to determine the coordinates of each soil survey point.

Step D. Qualitative visual analysis of Landsat 5 image.

According to the procedures outlined by Congalton (1991) and Barrett and Curtis (1992), the visible characteristics of the Landsat TM 5 subscenes considered in the transect were accurately analyzed in the field to notice their spatial variations in the scene. The acuity (visual) analysis (Drury, 1990) was based on their distinctive visible radiation characteristics in bands 1, 2, and 3 (energy at wavelengths from 0.4 to 0.7 μ), as described by Chuvieco (1990).

Based on Chuvieco (1990), we employed the following fundamental recognition elements in the image dissection: (1) spatial frequency and contrast of the variations, (2) shape and size, (3) tone/color/texture, (4) pattern, and (5) site and association. Subsequently, some of the selected subscenes (paleosol-alterite areas) were condensed into gray-level histograms by means of computer image analysis (Castleman, 1996).

Step E. Automated image analyses

The automated analyses of the selected Landsat subscenes (Step D) were performed with the software *Image-Pro Plus version 4.1*, a very useful tool in studies of two-dimensional images that includes automated selection filters and image enhancement and measurements. With this software, the spectral properties of the paleosol and alterite subscenes previously determined in the field through Landsat 5 acuity analysis were recognized, digitized, and automatically extrapolated to similar areas (predicted areas) present in the rest of the Landsat scene.

Step F. Accuracy evaluation of the predicted spatial distribution areas of paleosequences

The strategy employed was analogous to step C, and consisted of field verification through two new transects (second and third in Figure 2) in order to evaluate the realistic representation grade of the predicted areas with paleosequences (step E) located in the Morelos landscapes.

RESULTS AND DISCUSSION

General regionalization of the study area

Gerrard (1995) and Birkeland (1999) stated that the geomorphological regionalization of land systems is a useful attempt to show the systematic distribution and variation of soils across landscapes. The stereoscopic study of the area, the field work, as well as the interpretation of the thematic maps and digital elevation model of the Morelos state (DETENAL, 1981; INEGI, 1999), led to regionalization of the study area. This was made on the basis of physiographic patterns and surface morphometry that included: elevation, slope aspect, gradient and complexity, as well as geomorphic and geological components.

At a reconnaissance scale (1:250,000), we identified seven physiographic regions, which are determined by some of the natural boundaries of the Morelos ecosystem, as shown in Figure 2. According to local names, the regions are named for convenience as follows: Glacis de Buenavista (R1), Cuernavaca plain (R2), Tepoztlan lahars (R3), Chichinautzin ridge (R4), Tetela piedmont (R5), Cuautla pediplain (R6), and Huautla mountains (R7). Table 1 summarizes some of the main environmental factors that characterize each of these regions.

The cartographic information of INEGI was used to prove that each region have a common history and is a mappeable area of the TMVB province in the Morelos surface. Each area is of similar age, relief, soil associations, hydrology, and lithology, and is formed by a set of erosional, constructional or both processes during an episode of Quaternary landscape evolution.

In agreement with INEGI (1999), we consider that the first six regions meet the geomorphological requirements to be regarded as representative elements of the Lagos y Volcanes de Anahuac Subprovince, while R7 is a geographical portion of the Sur de Puebla Subprovince (Figure 1).

First topographic transect

Having covered the creation of image regions of Morelos state (Figure 2), the stereoscopic study of the area, and the acuity analyses of Lansat TM 5 image, the transect line was planned. The transect was followed as closely as possible, and environmental features were observed and described at predetermined regular intervals.

In terms of understanding the geomorphological and pedogenetic processes involved in landscape evolution and
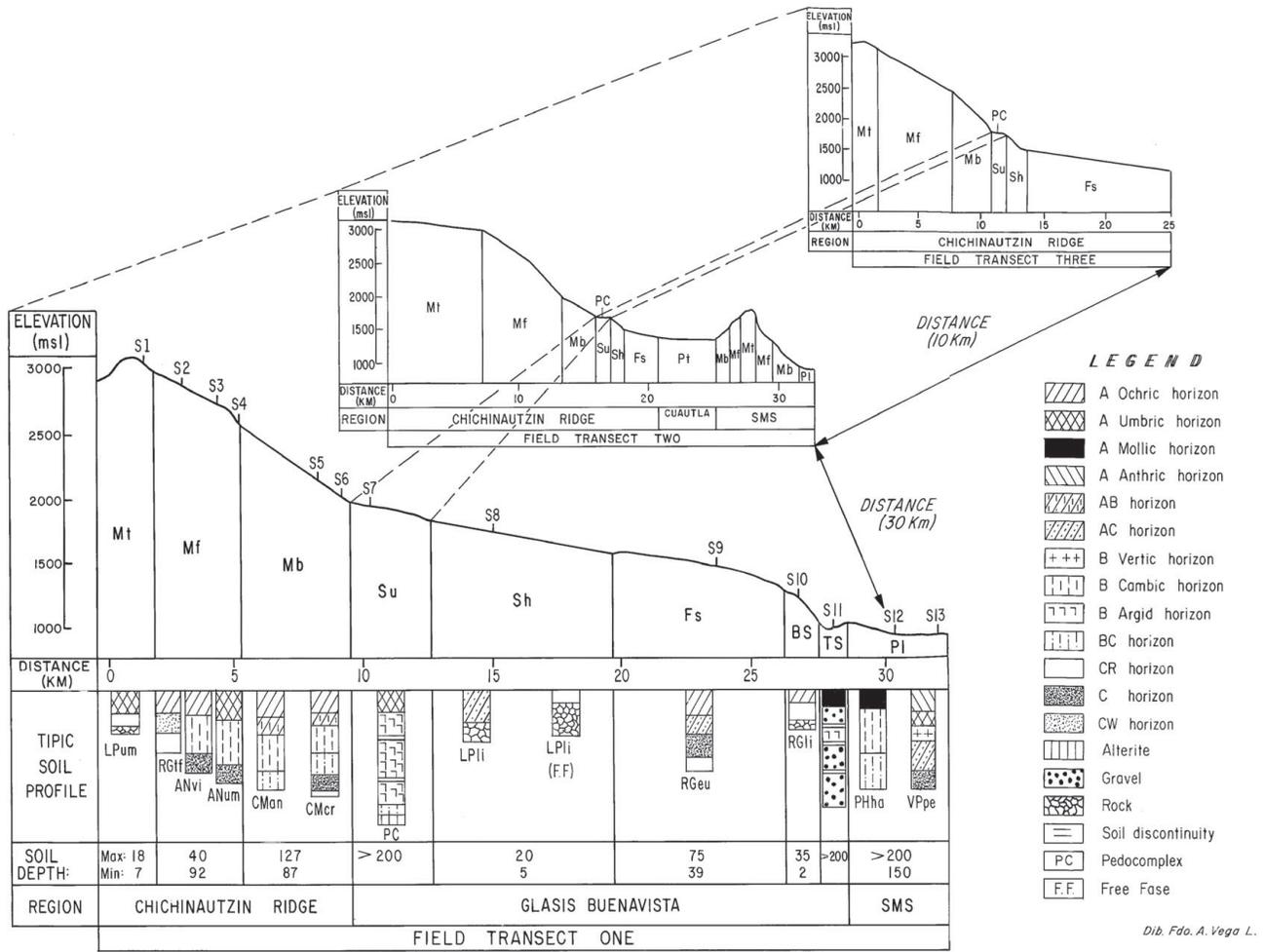
Figure 4. Field transects in the Morelos state showing the subdivision in slope profile positions, the location of studied neosols (S1–S6, S8–S13) and paleosols (S7), as well as the corresponding soil profiles.

in the spatial distribution and variability of neosols and paleosequences, the transect line was subdivided into nine separate working segments or positions (hillslope profile position, HSP). For the subdivision, the model of simple and complex slopes outlined by the Field Book for Describing and Sampling Soils (Schoeneberger *et al.*, 1998) was followed. Figure 4 schematizes a transect route that includes part of the R4 and R1 regions and a small area of the alluvial valley of Miacatlan, located in the Sierra Madre del Sur (SMS) province. This cross-section also illustrates, in two dimensions, the spatial distribution of mountain and pediment slope positions, and the distribution of neosol groups and paleosequences in these segments or positions.

The R4 mountain hillslope profile positions that we proposed and recognized in the field transect are named in this paper: (1) mountaintop (Mt), (2) mountainflank (Mf), and (3) mountainbase (Mb). Regarding R1 pediment slope positions they were called: (4) pediment summit (Su), (5) pediment shoulder (Sh), (6) pediment backslope (Bs), (7) pediment footslope (Fs), (8) pediment toeslope (Ts), and

(9) plain (Pl). However, not all of these segments were present along the second and third transects (Figure 4).

Field observations revealed that the Mb, Su and Pl segments are the most stable positions with the oldest and most developed residual soils. However, argic horizons only occur in the Su position soil profiles. These profiles show substantial clay accumulations that vary from 55 to 80% in Bt diagnostic horizons (Paleosequences, PC in Figure 4).

On the contrary, the Mt, Mf, and mainly Sh and Bs positions are predominantly unstable areas highly subject to soil erosion and mass movements (*i.e.*, creep, flow, fall, and avalanche deposits). Such areas present a moderate to poor soil profile development index, respectively. In areas subjected to that processes, free faces (rock outcrops) are very frequent. It is evident that the differences between Mb, Su, Pl, and Mt, Mf, Sh, Bs soil profiles can be mainly attributed to their difference in position morphometry and geomorphological processes.

In addition, some deposition (*i.e.*, pedisediment, colluvium) is present in the Fs position, but it is a dominant

Table 1. Characteristics of the physiographic regions identified in the Morelos state within the Transmexican Volcanic Belt (TMVB) province.

Subprovince		Lagos y Volcanes de Anahuac (LVA)						Sur de Puebla
Physiographic Region	Glacis de Buenavista (R1)	Cuernavaca valley (R2)	Tepoztlan lahars (R3)	Chichinautzin ridge (R4)	Tetela piedmont (R5)	Cuautla plain (R6)	Huatla mountains (R7)	
Predominant landforms	EL, ML, WL	EL, FL, VL, AF	ML, EL, VL, AF	VL, SP, PL, ML	VL, SP, ML, EL, PL	FL, EL, ML, VL, AF	EL, ML, VL, DL	
Elevation (m a.s.l.)	Max: 2,100 Min: 1,100	Max: 1,550 Min: 900	Max: 2,300 Min: 1,500	Max: 3,300 Min: 1,500	Max: >3,500 Min: 1,500	Max: 1,500 Min: 900	Max: 1,650 Min: 1,000	
Slope aspect (°)	Downslop 135−160	Downslop 180−185	Downslop 180−185	Downslop 180−203	Downslop 200−220	Downslop 155−165	Downslop 0−315	
Slope gradient (%)	Max: 9 Min: >3	Max: 18 Min: <2	Max: 90 Min: <1	Max: >65 Min: <2	Max: >50 Min: <4	Max: <6 Min: <1	Max: 40 Min: 5	
Slope complexity	Simple	Simple	Simple to complex	Complex to simple	Simple to complex	Simple	Complex	
Precipitation ranges (mm)	<1,400−900	<1,200−900	1,100−>90	>1,500−1000	1,500−1,000	1,000−800	800−<700	
Temperature ranges (°C)	16−22	20−24	18−22	0−16	0−22	20−>24	>24	
Land cover/vegetation	Frf, Grs, Scs, Rag, Opm, Aru, Aur	Iag, Rag, Grs, Aru, Aur, Ddf, Tcr	Iag, Ddf, Opm, Aru, Aur, Frf	Tcd, Opm, Grs, Rag, Iag, Frf, Aur, Aru	Tcd, Opm, Grs, Rag, Tcr, Thw, Aru, Aur	Iag, Rag, Tcr, Aru, Aur, Grs, Ddf, Bci	Ddf, Scs, Rag, Bci, Aru, Aur	
Predominant lithology	Cg, Cl, Cr, Dr, Ds, Ef, Me, Pf	Al, Bl, Cg, Cl, Pf, Vc, Va	Lh, Df, Me, Pf	Pl, Br, Pf, Vc, Va	Dl, Bl, Df, Ef, Id, Rf	Al, Cg, Cl, Cr, Id, Ll, Me, Pf, Va	Al, Cg, Cl, Cr, Ef, Ds, Me, Tr	
Formation (Age)	Cuernavaca (Quaternary)	Chichinautzin (Quaternary)	Tepoztlan (Tertiary)	Chichinautzin (Quaternary)	Tlayecac–Popocatepetl (Quaternary)	Popocatepelt–Cuautla (Quaternary/Cretacic)	Tilzapotla (Tertiary)	
Predominant soils	Leptosols Regosols	Vertisols Phaeozems	Phaeozems Vertisols	Andosols Regosols Leptosols Phaeozems Luvisoil	Andosols Leptosols Regosols	Vertisols Phaeozem	Regosols Leptosols Phaeozems	
Erosion	ST; WL, g, r; 3, 4, 5	SL, MO; WL, s, r; 1, 2	SL; WL; 1	SL; WL, s; 1	MO; WL, s, g; 2	MO; WL, s, r; 2, 3	MO, ST; WL, r, g; 3, 4, 5	

Predominant landforms. AF: antropogenic features; DL: depressional; EL: erosional; FL: fluvial; ML: mass movement; PL: periglacial; SP: slope; VL: tectonic, structural, and volcanic; WL: water.
Land cover/Vegetation. Aru: rural transportation-roads; Aur: urban and built up, cities, and industry; Bci: mines and quarries; Ddf: dry deciduous forest; Frf: free face (rock outcrop); Grs: grassland; Iag: irrigation agriculture; Opm: oak-pine mixed forest;Rag: rain-fed agriculture; Scs: native shrubs; Tcd: conifers; Tcr: trees (nuts), Thw: hardwoods (oak).
Predominant lithology. Al: slope alluvium; Bl: basaltic lava flow; Br: breccia; Cg: conglomerate; Co: colluvium; Cr: creep deposit; Df: debris flow deposit; Dl: dacitic lava flow; Ds: debris slide deposit; Ef: earthflow deposit; Id: in-place deposits (non-trasported); Lh: andesitic lahars; Ll: lacustrine layers; Me: mudflow; Pf: pyroclastic flows; Rf: rockfall deposit; Vc: volcaniclastics; Tr: travertine; Va: volcanic ash.
Erosion class: SL: slight; MO: moderate; ST: strong. Erosion kind: WL: water; s: sheet; r: rill (small channels); g: gully (big channels). Erosion magnitude: (estimated % loss of the original A and E horizons)
1: >0 up to 25%; 2: 25 up to 75%; 3: 75 up to 100%; 4: total removal of A and E horizons, including part of B horizon; 5: total removal of soil.

process in the Ts position. Thus, soil horizons increase in thickness at the Ts because of colluvium deposition. We observed that the Ts soil profiles may also incorporate soil flow deposits (reworked Bt soil horizons), which may explain their greater 'pedogenic' clay content (Figure 4, S11). In some places, pedogenic carbonate not leached from other sources can be found.

During the field transect survey we also found that the breaking down of the continuous Landsat scene into discrete spatial elements (subscenes) allow us to recognize and classify many spectral distinctive patterns of the different land covers and soil boundaries. Such patterns are mainly caused by climatic, topographic and vegetative reflective differences. For instance, paleosequences only were located in anomalous highlights image subscenes (pattern class: partial eroded sites and some free faces) that differ from the surrounding subscenes (Figure 5). Moreover, we found that some soil properties (*e.g.*, organic matter, soil color, sand, silt, and clay content, and possibly iron oxide content) are highly correlated with specific visible spectral patterns of the Landsat image

These spectral differences of land elements and their relationships with physiographic regions and hillslope profile positions were a useful complement to visualize, in a first approach, the spatial configuration of neosols and paleosequences.

Characterization of neosols and paleosequences

The results of field work indicate the presence of seven different neosol groups, 19 lower level units (subgroups), one group of paleosols, as well as two genetic types of alterites. The neosols and paleosequences were classified in accordance to FAO (1994). However, in terms of their mode of soil-forming processes, soil profile features, the environment in which they form, and landscapes upon which they occur we propose to group these soils in seven provisional classes. Below, a brief description for each reference soil class is given.

Class 1. Volcanic residual soils which are not bound to specific zonal climatic conditions: Lithic (li), Umbric (um) and Eutric (eu) Leptosols (LP), associated with Lithic (li) Eutric (eu) and Tephric (tf) Regosols (RG). Their representative horizon sequence is A-C.

Class 2. Volcanic residual soils with Andic or Vitric horizons in which soil formation is conditioned by the parent material and the climatic characteristics: Vitric (vi), Arenic (ar), Melanic (me), Umbric (um) and Luvic (lv) Andosols (AN). With a few exceptions, their representative horizon sequence is A-Bw-C, or A-BCw-C.

Class 3. Volcanic residual soils with initial soil formation of various kinds, more strongly expressed than in other soils: Vitric (vi), Andic (an), Chromic (cr) and Eutric (eu) Cambisols (CM). The representative horizon sequence is A-Bw-BC-C.

Class 4. Volcanic polycycle soils (relict paleosols) characterized by a marked subsurface accumulation of illuvial clay and cutanic properties. They are analogous to Albic (ab), Stagnic (st) and Cromic (cr) Luvisols (LV). Their common representative horizon polysequence is A-pedocomplex (PC)

Class 5. Soils essentially formed by recent alluvial and colluvial deposition and sometimes *in-situ* pedogenesis. These soils are not bound to specific zonal-climatic conditions: Tephric (tf), Mollic (mo), Skeletic (sk) and Eutric (eu) Fluvisols (FL), associated with Lithic (li) Leptosols (LP) and with Calcaric (ca), Skeletic (sk) and Eutric (eu) Regosols (RG). Their frequently representative horizon sequence is A-C or A-C-2A-2C.

Class 6. Old alluvial soils characterized by a marked surface accumulation of base-saturated organic matter: Vertic (vr), Calcaric (ca) and Haplic (ha) Phaeozems (PH). Their representative horizon sequence is A-Bw-Cca or A-Bt-Cca.

Class 7. Old alluvial soils characterized by the presence of a Vertic horizon: Calcaric (ca), Pellic (pe), Cromic (cr) and Eutric (eu) Vertisols (VR). Their representative horizon sequence is A-Bss-C.

Based on their pedogenetic characteristics, we consider that (with the exception of Class 4) the Classes were formed as so-called genetic soil types/horizons under the present pedogenetically effective environmental conditions. These Classes are all neosols that exhibit from very weak (Class 1 and 5) to moderate (Class 2 and 3) and strong (Class 6 and 7) soil formation and development. Thus, Class 2 and 3, frequently show diagnostic horizons that include ochric, umbric and mollic epipedons, as well as cambic horizons. Commonly, some of these soils also have andic properties and redox features. Andisolization is a dominant soil-forming process present in Class 2.

Regarding Class 6 and 7, they include soils that are mainly characterized by the presence of a mollic epipedon, and slickensides and cracks features, respectively. Melanization and, in some cases, argilluviation are representative soil-forming processes of Class 6, while vertization is a typical process inherent to Class 7.

Class 4 include the representative pedocomplex of paleosols and alterites sequences in Morelos state (Figure 6). The studied paleosols are Pleistocene relict polycycle soils characterized by redder hues, very similar in their morphology to Luvisols. Radiocarbon data indicate ages of these paleosols older than 11,000 yr BP.

According to Sedov *et al.* (2001) and Solleiro *et al.* (2003), Class 4 paleosols were formed by argilluviation processes and have some distinctive diagnostic horizons and properties that include: (1) ochric or umbric epipedons, (2) albic horizons (argilluviation base cation leaching), (3) argillic horizon, and in some cases (4) albeluvic tongues and (5) stagnic properties. In accordance with Soil Survey Staff (1998), such soils meet the requirements for Paleudalfs Great Group. However, such paleosols were classified by
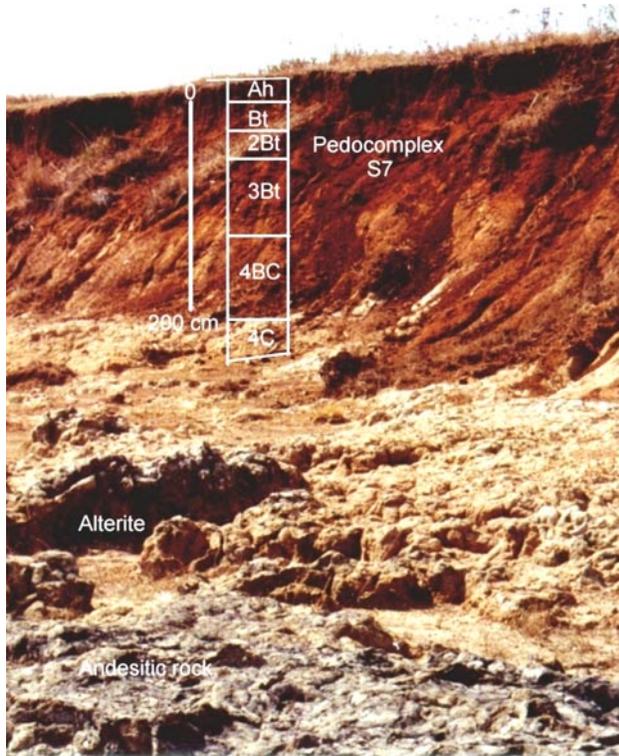
Figure 6. Typical pedocomplex of the study area.

DETENAL (1981) as Orthic Acrisols, and/or Ferric Luvisol, and/or Argillic Phaeozems.

In all of these paleosols, the Bt horizon is characterized by extensive 1:1 clay accumulation due to *in-situ* weathering and clay illuviation, high content of free iron oxides, and redoximorphic pedofeatures. All of these properties indicate long-term pedogenesis under past humid forest environments and periods of great landscape stability (Jasso *et al.*, 2002).

Regarding the alterites, they only were found in eroded areas associated with soils representatives of Class 4, or outcrop in areas where Class 5 is present (Figures 4 and 5). In both cases, the alterites frequently show a physical phenomenon analogous to hydroconsolidation (Bryant, 1989; Assallay *et al.*, 1998). Only a few of these alterites clearly show evidence of silicification processes (Duripans). At present, their genesis is still a matter for investigation and discussion, but the micromorphological analyses of these materials revealed the presence of two genetic types of alterites: (1) alterites that were formed by mass movement processes (debris, pyroclastic, and mud flows) linked to Pleistocene eruptions; and (2) alterites that were formed by pedogenic processes. Locally, the alterites are named 'Tepetates' and some of them frequently satisfy the requirements for Fragipans (Flores *et al.*, 1996).

Spatial distribution of neosols and paleosequences

Notwithstanding the volcanically active and tectonically unstable nature of the study area (Márquez *et al.*, 1999)*,* we assumed that the neosols associations and paleosequences, as well as their landscape distribution, follow some principles of the idealized geomorphic models established by Ruhe (1975), Conacher and Dalrymple (1977), and Hall (1983). These models are a good influence
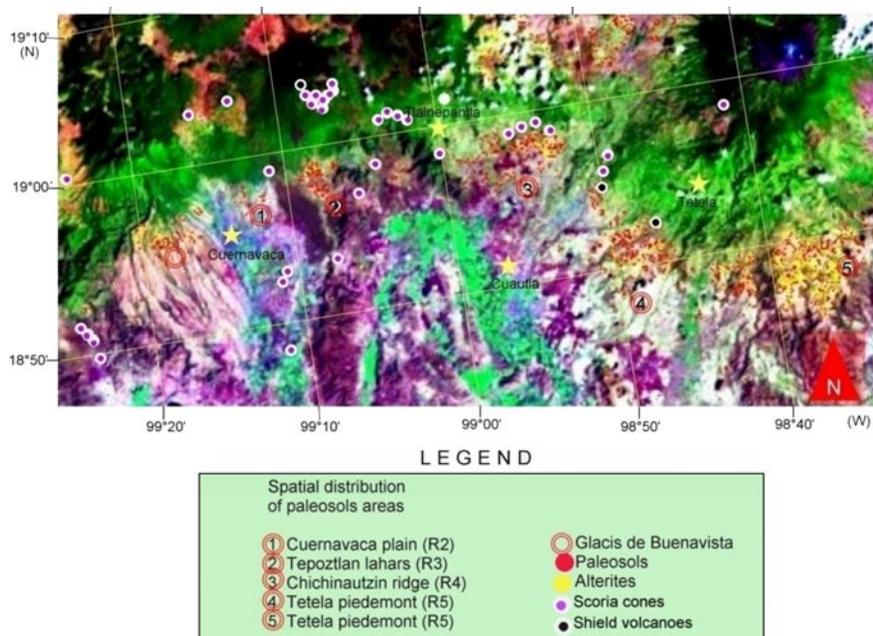
Figure 5. Predicted spatial distribution of paleosols and alterites in the Morelos state.

for furthering the integration of pedology and geomorphology.

Such models estimate that soils play an integral role toward understanding and unraveling landscape evolution. However, these models also estimate that relief is a factor that modifies the effects of the other factors of soil formation, and emphasize erosional and depositional patterns when going from high places to low places in the landscapes. It means that the hillslope profile position dynamics generally determines the relative stability of land surfaces and the general nature and evolution grade of the neosols and paleosequences that may be expected on a landsurface. Theoretically, it also means that the effects of relief and hillslope profile position upon spatial distribution and variation of neosols and paleosequences located in the study area are predictable.

The spatial distribution of the 12 representative neosol groups (S1–S6, S8–S13) and one paleosequence (S7) can be observed in Figure 4. Table 2 shows some of the environmental factors and morphological characteristics of the representative soils present in each hillslope profile position (HSP).

Such soils tend to be specific for each one of these positions. Thus, soil classes 1, 2, and 3 are spatially distributed in Mt (S1), Mf (S2, S3, S4) and Mb (S5, S6) positions respectively, while Class 4 (pedocomplex), was only located in the boundary of the positions Mb and Su (S7). Class 5, was dominant in the position Sh (S8), Bs (S10) and Fs (S9). Classes 6 and 7 are restricted to the position Pl (S10, S11).

However, for purposes of discussion, we assumed that these results are not still enough to fully confirm the proposed HSP model for spatial distribution of neosols and paleosequences in the studied area. To do a thorough examination of the spatial distribution and variation dynamics of Morelos neosols and paleosequences, we need to increase our experience not only about soil-geomorphic forming factors but also about the processes operating to change existing and ancient soils.

Predicted spatial distribution of paleosol–alterite sequences and field verification: Transects two and three

Results of the paleosol–alterite pattern recognition by means of automated image analyses indicate the probable occurrence of paleosols in five different geographical sites (predicted areas) of the studied area. These sites are located in the R4, R5 and R6 regions. Their extreme coordinates are lat 19°00′ to 18°50′ N and long 99°15′ to 98°38′ W (Figure 5). The analysis of computed histograms of these predicted areas are evidenced by many similarities between them, and were analogous to the histograms obtained from the R1–R4 paleosequences (transect one)

In Figure 5, the predicted paleosols areas (five

geographic areas) appear in red color, while the alterite areas are yellow because of a predetermined color code of the software. Also, it is possible to observe that these areas only occur at determinate altitudes (1,700 to 2,000 m), precipitation ranges (1,000 to 1,200 mm), and temperature zones (18° to 19° C), as well as in a specific position in the landform (pediment summit). Thus, their spatial location in the slope profile is similar to the spatial location of the paleosequences area detected in the first transect.

In Figure 5 is also shown that the environmental context of these paleosol–alterite areas is closely parallel to the distribution of Late Pleistocene–Holocene volcanic geomorphic elements of the Chichinautzin Group (scoria cones, shield volcanoes, basaltic lava flows interdigitating with pyroclastic flow deposits and lahars).

Finally, as mentioned earlier, two new field transects (predicted areas 2 and 3; Figures 2, 4 and 6) were carried out to validate the accuracy grade of the generated data shown in Figure 5. We obtained the following results in this topic: (1) in these new transects the environmental conditions and the spatial distribution of neosols in the HSP were identical to the first transect; (2) paleosol-alterite sequences were present in the predicted areas; (3) the detectability grade of the paleosols by means of automated image analyses were acceptable, but not enough to distinguish the paleosols from some red clayey colluvium put together with them; and (4) alterites were well recognized from the other materials associated with them; for instance tephra deposits, lahars, mud flows, and volcanogenic alluvium

CONCLUSIONS

The analysis of thematic maps of Morelos state, combined with field transect information and enhancement through remote sensing technology, provided the necessary geospatial data to propose an environmental-pedogenic model for the region. This model allowed us to describe and study geomorphology in relation to pedogenic processes. Such a model was recognized as a toposystem formed by seven natural physiographic regions.

This toposystem is characterized by cyclical landscape stability due to volcanism, tectonic activity, rejuvenation, and probably several paleoclimatic fluctuations. Moreover, the presence in this area of some well-developed pedocomplexes suggests that the changes in the landscape take place rapidly over a short-time period and that short periods of change were separated by longer periods of relative stability.

In this toposystem, the relief factor has a prominent influence in the vertical zonation regarding precipitation, temperature, vegetation, and parent material distribution. The research results from soil properties also suggest that this phenomenon of topography-induced environmental differences could be considered as one of the main, but not

Table 2. Transect one: representative environmental and morphological characteristics of soils.

Site, Region, (Soil profile)	Altitud(m)/ HSP	P (mm)/ T (°C)	Slope (%)/ Aspect (°)	Land use	Soil Classification	Horizon	Depth (cm)	Structure	Color matrix (moist)	Field Texture	Moist consistence	Parent Material
S1, R4, (P1)	3,100/Mt	1,500/12	>1/200	Opm, Frf	Umbric Leptosols (LPum) Class 1	A CR	0 – 9 9 – 14	2, m, sbk	10YR3/1 10YR6/3	Silt L	so,po	Va
S2, R4, (P3)	2,850/Mf	1,400/15	20/255	Thw	Tephric Regosols (RGtf) Class 1	A Cw CR	0 – 18 18 – 33 33 – 55	2-3, m, abk 1, f-m, abk sg	10YR3/2 10YR5/3 10YR6/4	Loam Silt L Sandy L	ss, ps ss, po so, po	Va
S3, R4, (P5)	2,720/Mf	1,200/17	14/205	Opm	Vitric Andosols (ANvi) Class 2	A Bw C	0 – 23 23 – 52 52 – 67	2, f, gr-sbk 2, m-c, abk sg	10YR5/8 10YR6/6 10YR7/3	Loam Silt L Sandy L	ss, ps ss, ps so, po	Va
S4, R4, (P6)	2,650/Mf	1,200/18	11/190	Opm, Rag	Umbric Andosols (ANum) Class 2	A Bw C	0 – 38 38 – 61 61 – 82	3, m-f, gr 3-2, m, sbk 1-2, m, abk	10YR3/1 10YR5/3 19YR6/6	Loam Silty C L Silt L	ss, ps ss, ps so, po	Va, Pu
S5, R4, (P8)	2,150/Mb	1,100/19	8/170	Opm, Rag	Andic Cambisols (CMan) Class 3	A AB Bw BC	0 – 33 33 – 45 45 – 84 84 – 103	2, m, gr-sbk 3, m, sbk 3, m-c, sbk 2, f-m, sbk	10YR5/6 10YR6/6 10YR6/8 10YR7/8	Silt L Silty C L Silty C L Sandy L	ss, ps ms, ps ms, ps ss, po	Va, Pf
S6, R4, (P9)	1,980/Mb	1,100/20	5/165	Tcd, Rag	Chromic Cambisols (CMcr) Class 3	A AB Bw BC C CR	0 – 29 29 – 38 38 – 63 63 – 78 78 – 96 96 – 110	3, m, gr-sbk 3, m, abk 3, m-c, abk 2, m, abk 1-2, m, abk 1, f, abk	5YR4/2 5YR4/4 5YR5/4 5YR5/8 5YR6/6 5YR7/6	Clay L Clay L Clay L Silty C L Silty L Silty L	sx, mp sx, pm sx, p ms, mp ss, ps so, po	Pf, Va
S7, R1, (P11)	1,900/Su	1,000/20	3/158	Opm, Rag, Frf	Pedocomplex: (Luvisols) Class 4 "Tepetate" (Alterite) –	Ah Bt 2Bt 3Bt 4BC 4C	0 – 25 25 – 70 70 – 145 145 – 205 205 – 259 >259	3, m-f, gr 3, f-m, abk 3, m, abk 3, m-c, abk 2, m-c, abk M	5YR2/2 5YR3/4 5YR3/4 5YR5/6 10YR5/6 –	Clay Clay Clay Clay Clay L Sandy L	sx, p sx, vp sx, mp sx, mp ms, mp ss, ps	Lh, Me, Pf

Table 2. Continued.

Site, Region, (Soil profile)	Altitud(m)/ HSP	P (mm)/ T (°C)	Slope (%)/ Aspect (°)	Land use	Soil Classification	Horizon	Depth (cm)	Structure	Color matrix (moist)	Field Texture	Moist consistence	Parent Material
S8, R1, (P16)	1,750/Sh	950/21	3/150	Frf, Grs, Scs	Lithic Leptosol (LPli) Class 5	AC	0 – 11	1, f-m, sbk	10YR2/1	Sandy L	so, po	Br
S9, R1, (P20)	1,630/Fs	950/22	2/150	Grs, Scs, Ddf, Bgs	Eutric Regosols (RGeu) Class 5	A AC C	0 – 31 31 – 43 43 – 65	2, m, sbk 1, m, sbk sg	10YR5/6 10YR6/6 10YR6/4	Silt L Silt L Silt L	ss, ps ss, ps ss, ps	Co, Mm
S10, R1, (P25)	1,230/Bs	950/22	12/145	Frf,Grs	Lithic Regosol (RGli) Class 5	A C R	0 – 17 17 – 35	1, m-f, sbk sg	10YR5/6 10YR6/4	Silt L Sandy L	so, po so, po	Co, Al
S11, R1, (P26)	1,100/Ts	900/23	2/160	Ddf, Scs	Mollic Fluvisols (FLmo) Class 5	A C 2C 3C 4C	0 – 29 29 – 65 65 – 83 83 – 160 160 – 225	2, m-c,sbk 1, f-m, sbk 2, m, abk 2, m, sbk sg (gravel)	10YR3/1 10YR6/6 5YR3/4 7.5YR4/4 10YR7/8	Loam Silty L Clay Clay L Sandy L	ss, ps so, po sx, mp sx, p so, po	Al, Co
S12, SMS, (P30)	1,020/Pl	900/23	<2/180	Iag, Ddf	Haplic Phaeozem (PHha) Class 6	A Bw₁ Bw₂ BC	0 – 30 30 – 63 63 – 93 93 – 150	3, m-f, abk 3, m, sbk 3, m-c, sbk 2, m, sbk	10YR3/2 10YR4/3 10YR4/4 10YR5/4	Loam Silty C L Silty C L Silty C L	ss, ps sx, p sx, p sx, p	Al, Co, Pe
S13, SMS, (P33)	990/Pl	850/24	<1/180	Iag	Pellic Vertisol (VPpe) Class 7	Ap A11 Bss AC C	0 – 33 33 – 51 51 – 75 75 – 120 120 – 150	3, m-c, abk 3, m-c, abk 3, m-c, abk 3, m-c, abk 2, m, abk	10YR2/1 10YR3/1 10YR3/2 10YR5/2 10YR6/2	Clay Clay Clay Clay Clay L	sx, p vs, vp vs, vp vs, vp vs, vp	Al

HSP: Hillslope profile position; Mt: mountaintop, Mf: mountainflank, Mb: mountainbase, Su: pediment summit, Sh: pediment shoulder, Bs: pediment backslope, Fs: pediment footslope, Ts: pediment toeslope, Pl: Plain.

Land use. Bgs: gravel and sand, Ddf: dry deciduos forest, Frf: free face (rock outcrop), Grs: grassland; Iag: irrigation agriculture, Opm: Oak–pine mixed forest, Rag: rainfed agriculture; Scs: native shrubs; Tcd: conifers; Thw: hardwoods (oak).

Structure. 1: weak; 2: moderate; 3: strong; f: fine; m: medium; c: coarse; M : massive; sg: single grained; gr: granular; sbk: subangular blocky; abk: angular blocky.

Field texture. L: loam; C: clay.

Moist consistence. So: not sticky; ss: slightly sticky; ms: moderately sticky; sx: sticky; vs: very sticky; po: not plastic; ps: slightly plastic; mp: moderatly plastic; p: plastic; vp: very plastic.

Parent material. Al: slope alluvium; Br: breccia; Co: colluvium; Lh: andesitic lahar; Me: mudflow deposit; Mm: mass movement deposit; Pe: pedisediment; Pf: pyroclastic flows; Pu: pumice; Va: volcanic ash .

the only, reasons for the spatial distribution and evolutionary variation of neosols and paleosequences in the study area. For instance, in some cases parent material variability and time commonly appear to overshadow the effects of topography, mainly in areas with great landscape stability (summit). Thus, older age, ash, pyroclastic and lahar deposits, as well as greater landscape stability produced a more mature soil with a thick argillic horizon and well expressed clay films classifying it as a Luvisol (Paleudalf).

Consequently, we hypothesized that the neosol and paleosequence genesis, as well as their spatial distribution and variation are not only and totally intertwined with the classic geomorphic models of the evolution of landscapes. In addition, catastrophic events occurring in the study area have altered or destroyed much preexisting relief and soils and/or otherwise produced a fresh land surface.

Finally, the teledetection analyses and field studies related to the geomorphic components of the study area disclose that relict or exhumed paleosols and alterites have many typical spectral patterns, and also that their distribution is closely parallel to the distribution of Late Pleistocene–Holocene volcanic landforms in this area. We conclude that the spatial distribution of volcanic paleosols and alterites in Morelos state is geographically predictable.

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