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Spatial arrangement of soil mantle in Glacis de Buenavista, Mexico as a product and record of landscape evolution

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ABSTRACT

Factors controlling spatial soil organization have recently attracted the attention of soil scientists because they can contribute to regional management of soil resources. We present here a case study in the Glacis de Buenavista (Mexico), an extended volcanic piedmont, in order to develop an integral understanding of its soil cover as a product and, at the same time, as a record of the main stages of landscape evolution. Three phenomena were considered: Luvisol and Vertisol type soils, and pedosediments, all of them analyzed in terms of their development degree (clay content, macro and micromorphology, selective extractions of Fe (Fe_d, Fe_o), silicon (Si_o) and aluminum (Al_o), weathering index and clay mineralogy). Luvisols, represented in the Ahuatenco, Mexicapa and Buenavista sections, are located in the northern and central part of the area. They are red-clayey, polygenetic soils that show strong weathering (with high kaolinitic clay content and high weathering index values), clay illuviation, and reductomorphic processes, combined with vertic features in some parts of the profiles. Vertisols dominate the central and southern portion of the Glacis. They exhibit cracking, angular blocks with wedge-like shapes, slickensides and stress-cutans. The pedogenesis of the Vertisol type is clearly associated with the presence of smectitic minerals in the clay fraction as a product of neoformation. Factors controlling this pedodiversity are: relief, which affects bioclimatic differentiation within the studied landsurface and defines the lateral redistribution of moisture and dissolved substances; and time. Luvisols represent a longer pedogenetic phase that started in the Late Pleistocene, according to the age of buried paleosols, while Vertisols mainly originated in the Late Holocene (according to the age of buried organic horizons). Pedosediments are located in the central area of the Glacis. Here, past and present geomorphic processes interact to produce the greatest soil diversity. The recent human-induced erosion partly destroyed polycyclic Luvisols and exposed ancient subsurface pedosedimentary strata. At the same time it produced patches of unconsolidated pedosediments consisting mostly of redeposited Luvisol materials.

1. Introduction

Soils on all landscape positions are formed and developed under a changing environment and are influenced directly or indirectly by soil forming factors and accompanying complex interactions between hydrologic and geomorphic processes (Phillips and Marion, 2005). This concept follows the factor model formulated by Dokuchaev (1967) and Jenny (1994) where soil properties and their spatial distribution are seen as a function of soil forming factors, and define the trends of pedogenesis; meanwhile, pedogenetic processes drive and govern soil formation and development (Bockheim and Gennadiyev, 2000). This approach is abbreviated in the "Neo-Dokuchaevian" concept of the factor–process–property triad, formulated by Gerasimov (1973). According to Johnson and Watson-Stegner (1987), soil evolution continues through the complex interaction of progressive and regressive pedogenetic pathways as well as exogenic or endogenic factors, processes, and conditions. It can result in divergent (evolution increases soil diversity) or convergent (evolution increases soil homogeneity) tendencies of soil cover development (Phillips, 2001). In consequence, soil property distribution has a non-linear behavior, making the interpretation of pedogenetic trends difficult. Sommer (2006) proposes that the comprehension of both soil spatio-temporal variability and the dynamic of processes leads to a better understanding of soil landscapes.

The factor–process–property triad as applied to the humid/semihumid tropics usually focuses on the great pedogenetic potential of the bioclimatic conditions that provide the highest rates of various soil forming processes, especially those related to the mineral transformation and migration of weathering products (alteration of primary components, mineral neoformation, leaching, clay illuviation). Together with long-term development it makes the tropics a region of deep mature soil and regolith bodies, with a maximum

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tendency towards convergence. In climatic geomorphology it is widely accepted that weathering in the tropical regions is faster than denudation (Büdel, 1982).

However, this view seems to be valid mostly for the old stable landsurfaces which are dominant on the vast platform plains. Young landsurfaces (Late Pleistocene–Holocene) rejuvenated by erosion or formed by fresh sediment weathering, usually does not reach the advanced ferrallitic stage. The resulting regolith demonstrates only partial alteration of unstable primary minerals and domination of 2:1 clays among secondary components (e.g. Stoops et al., 1994; Bronger, et al., 2000). Geomorphological studies in these dynamic geosystems have demonstrated that erosion–sedimentation processes could be compatible with pedogenesis and weathering even in the humid tropics (Rhodenburg, 1983), giving rise to the spatial variations of the weathering status and maturity of soil bodies (Schaefer et al., 2002). This variability is most complex and contrasting mountainous landscapes with high intensity and heterogeneity of geomorphic processes (Krasilnikov et al., 2005). Local climatic variations related to altitude, slope exposition, etc. contribute to producing the soil diversity of these landscapes.

The reasons for soil mantle differentiation in tropical mountains are not limited to the modern geomorphological and climatic factors. Paleoecological research demonstrates that the tropics had a complex recent environmental history linked to the global cyclic climate changes of the Quaternary (e.g. Farrera et al., 1999; Sarnthein, 1978). This creates the possibility that relict soil bodies or features, generated under past environmental conditions different from the present ones, could be incorporated in the soil cover. In particular, the origin of the mature soils with high weathering status often found in tropical mountains is questioned from this perspective. Are they products of the recent advance of pedogenesis which locally "overtakes" erosion (Krasilnikov et al., 2005)? Are they likely paleosols, fragments of an ancient soil mantle that developed under more stable geomorphological conditions and/or under more favorable bioclimatic factors?

Ancient and modern human impacts are another important factor that shaped the soil cover of these tropical mountainous regions, which hosted various agricultural civilizations over thousands of years. Slaymaker (2010) considers that destruction of natural vegetation and agricultural activity is now the key factor controlling the slope processes in these regions. However the effect of different types of cultivation on erosion and slope mass movement is estimated primarily from studies of modern land-use. Much less is known about the impacts of long-term traditional cultivation on tropical mountain soils; the research in this field is focused mostly on ancient terrace systems (Borejsza et al., 2008; Kemp et al., 2006). It is not well known which elements of the soil mantle ancient farmers preferred and what identifiable effects they had on it.

2. A case of study: Glacis de Buenavista

For more than 10 years we have studied the key area of Glacis de Buenavista in order to understand how the past and present interplay of pedogenesis and geomorphic processes, controlled by natural and human-induced environmental change, has shaped soil distribution and properties. The Central Mexican highlands provide an extremely complex background for this interplay. This region, located at the northern limit of the tropical belt, is characterized by great variability in local climatic conditions as well as elevated levels of biodiversity and endemism in vegetation types (Ramamoorthy et al., 1993). Additionally, it is an area of active tectonics and volcanism due to its proximity to the Transmexican Volcanic Belt. The region's Late Quaternary environmental history, based on various lacustrine, glacial and paleopedological records, demonstrates contrasting changes linked to global climate processes (Lozano-García, 1996; Metcalfe et al., 2000). Finally, the palynological data indicate large-scale human impacts during at least last 3000 years. (Lozano-García et al., 2005), while abundant archeological materials illustrate the development of sedentary agrarian communities from the Formative period to the Classic and then Postclassic civilizations.

Glacis de Buenavista was the area where the pedological research on the Mexican volcanic paleosols was initiated (Solleiro-Rebolledo et al., 1999). Following these initial investigations, we focused on the specific paleosol and pedosediment bodies formed by the sharp environmental fluctuations of the Pleistocene–Holocene transition. In particular, we were the first to suggest that the indurated subsoil horizons—"tepetate" of Buenavista—are relicts of this dynamic landscape (Solleiro-Rebolledo et al., 2003; Díaz-Ortega et al., 2010). However this research left several important questions unanswered: for example, what is the origin of the anomalous high weathering status of the Holocene Luvisols?

Subsequent research has demonstrated that the soil mantle of Glacis is the result of a much longer and more complex interaction of past and recent, natural and human-induced processes. This paper is an attempt to develop a comprehensive interpretation of the soil cover of Glacis de Buenavista as a product and record of the main stages of landscape evolution since the formation of this geoform.

2.1. Site conditions

Glacis de Buenavista is located 85 km SW of Mexico City (18°45′–19°00′ North latitude and 99°25′–99°05′ West longitude), at the boundary of two physiographic regions: the Transmexican Volcanic Belt (TMVB) and the Sierra Madre del Sur (SMS) (Fig. 1). TMVB consists of Cenozoic volcanic materials while SMS has a complex mixture of sedimentary, volcanic and metamorphic rocks of different ages. Glacis is an extended piedmont with morphology similar to an alluvial fan. The northern limit is the Sierra de Zempoala, formed by basaltic andesites; to the west lahar deposits are present; on the eastern side a basaltic plateau is found (Mesa la Gloria); to the south limestones occur (Fig. 1). The substrate of Glacis consists of Pleistocenic conglomerates of the Cuernavaca Formation (Fries, 1960), which are formed by volcanic rocks from the Sierra de Zempoala. These rocks are interlayered with lava flows, lahar deposits and volcanic materials from Sierra Chichinautzin.

Glacis covers an area of 202.7 km^2 (Martínez-García and Lopez-Blanco, 2005), with differences in altitude of 1500 m. The highest point is found in the north (2400 m) and the lowest in the south (900 m). Relief is strongly dissected, especially in the north and east, by gullies that run NNW–SSE. These gullies are separated by less than 1 km. Slope varies from 15–40° in the north, to 3–15° in the center, to <7° in the south (Guerrero, 2007). Tectonically, Glacis is located within the graben of Cuernavaca, which is oriented NW–SE (Macías, 2006) and bounded by two fault systems (Chalma and Cañón de Lobos) (Fig. 1).

The present day climate is warm and humid; however there are climatic differences according to changes in altitude. At higher elevations (2550 m) the climate is humid with a mean annual temperature of 12.1 °C. Annual rainfall is 1510 mm (García, 1988), most of which falls during summer months (1310 mm, June to September). At altitudes below 1850 m, temperature is higher (20.7 °C) and precipitation lower (1150 mm).

Natural vegetation varies according to altitudinal gradients (Rzedowski, 1978). The highest elevations are dominated by *Abies*, *Quercus* and *Alnus* (>2100 m) (Martínez-García and Lopez-Blanco, 2005). The mixed forest (between 1900 and 2100 m) is represented by deciduous and evergreen species such as *Quercus magnoliifolia*; and oak forest (1500 to 1900 m), both growing inside the gullies and perennial streams. The Juniperus forest (1700 to 1900 m), represented by *Juniperus flaccida*, is distributed over the foothills in small stands, with induced grassland. The low forest (1000–1900 m) is dominated by Burseraceae and *Pseudosmodingium perniciosum*, which has been