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Paleosols beneath a lava flow in the southern basin of Mexico: The effect of heat on the paleopedological record

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ABSTRACT

Volcanic activity affects past and present landscapes. Here we present a case study related to the heat impact of the Xitle lava flow on the former soil cover. The eruption occurred 1670 years B.P., in south Mexico City. The evaluated properties include those related to the "soil memory", used as tools of paleoenvironmental interpretation in volcanic paleosols: macro and micromorphology, color, grain size distribution, magnetic susceptibility, and carbon and nitrogen contents. Changes of these properties by the heat influence are relevant for an adequate paleoenvironmental reconstruction. Two sites and three soil profiles are selected to show soil modifications by the volcanic activity. The two sites represent the following: 1) slightly transformed paleosol buried by the lava flow, but separated from it by a 10 cm thick volcanic ash layer (site Cuicuilco-ENAH); 2) moderately and strongly transformed paleosols (two profiles inside the Copilco archeological zone). One of the Copilco profiles represents a buried paleosol with a very thin (3 cm) ash layer on top, at the contact with the lava; the second profile is the most affected by the lava flow, as it is directly beneath the lava. All studied paleosols are sandy, have a low amount of organic matter, narrow C/N ratios, and very high values of magnetic susceptibility. The strongest modifications are observed in the upper horizons, which are in contact with the lava. However, the presence of the ash layer minimizes the heat effect. Despite the observed modifications, it is possible to establish three cycles of soil formation in the paleolandscape. The first, and the oldest, related to the development of a Luvisol type soil, indicates a longer time of landscape stability. During the second cycle a pedosediment with a high concentration of artifacts was formed. The last and the youngest cycle includes the Ab and the AEb horizons (present only in Copilco). They form by an Andosol type pedogenesis, which reflects a shorter time of soil development. The presence of the AEb horizon is interpreted as the result of the degradation of the Ab horizon, either due to the heat effect of the lava, or to cultivation and irrigation practiced by the pre-Hispanic communities.

1. Introduction

Volcanic paleosols are proven to register the landscape transformations in different regions (e.g. Inoue et al., 2011; von Suchodoletz et al., 2009; Zembo et al., 2011). They are as well good paleoenvironmental archives (e.g. Bäumler and Zech, 2000; Campbell, 1986; Sayyed, in press; Sedov et al., 2001, 2003; Solleiro-Rebolledo et al., 2007). Additionally, these tephra paleosols can record past human activities and provide a good understanding of the relationship between humans and their environment (McClung de Tapia, 2012; Sánchez et al., 2013).

It is well known that the paleoenvironmental interpretation is based on selected properties that constitute the "soil memory" (Targulian and Goryachkin, 2004). However, these properties can be modified by the effect of the volcanic activity. Consequently, the changes in particular properties have to be accounted to reliably reconstruct both, the paleoenvironment and the ancient land use.

There is little information about the changes in soil properties by the effect of the lava. Most of the works deal on the influence of high temperatures during forest fires, where temperatures can reach 1500 °C during a short period, if sufficient combustible material is available (Neary et al., 1999). Temperature is lower in the soil litter (850 °C), but in the soil mineral phase, the average is 150 °C, because of the soil isolating effect (DeBano et al., 1979). Mataix-Solera et al. (2011) report a range between 200 and 400 °C. These fires reduce significantly the total organic carbon/organic matter content and the soil aggregation stability (DeBano et al., 1979; Zavala et al., 2010), but the effect is most important in the first centimeters. Badía-Villas et al. (2014) show in a mollic A horizon that the heat intensity is reduced with

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depth, e.g. if the superficial soil material is heated up to approximately 500 °C, the temperature in a depth of 2 cm does not exceed 100 °C.

With respect of soil colors, Lockwood and Lipman (1980) in a study conducted in Hawaii, observe that at temperatures higher than 500 °C, in the presence of abundant oxygen, the soil become orange-pink or brick-red color, with any organic matter after complete burnt. At lower temperatures, the soil has brown or yellow-brown colors. Terefe et al. (2008) also observe a soil color change in chroma and redness index, with high temperatures, between 200 and 500°.

Concerning the grain size distribution, Terefe et al. (2008) observe an increase of the sand content, due to the effect of aggregation lost, which rises the erosion of the finer particles, while Kletetschka and Banerjee (1995) report that fires produce an enhancement of the soil magnetic susceptibility, attributed to the oxidation of ferromagnetic minerals.

Mexico City is located in the basin of Mexico, a region with high tectonic activity, affected by several Holocene volcanic eruptions (e.g. Martin del Pozzo et al., 1997; Siebe, 2000). Cuicuilco and neighboring sites as Copilco, located at the south of the basin, were affected by the eruption of the Xitle volcano, which occurred 1650 years B.P. (AD 245–315) (González et al., 2000; Siebe, 2000). The effusion of lava flows changed the landscape and affected the flora, fauna, soils, and water flows, as well as the population of the region. Besides the research conducted to establish the nature and behavior of the lava flows from Xitle volcano, several works have been published to identify the effect of the eruption in the former cultures who lived in the southern part of Mexico City (Córdova et al., 1994; Lugo-Hubp et al., 2001; Martin del Pozzo et al., 1997; Siebe, 2000). Most of these investigations focused on the impact of the lavas on the landscape. They identified the compact, black soil beneath the lavas, and used it for dating, however, no particular analyses have been done in the paleosols covered by these volcanic materials.

In this work, we analyze different paleosol profiles buried by the Xitle lava flow, in order to evaluate the transformation of soil properties due to the impact of the Xitle eruption. We further use this information to reconstruct soil and landscape evolution of the region, and infer the possible effects of the human impact in the paleosol cover.

2. Site description

2.1. Geology and volcanic activity

The basin of Mexico is located in central Mexico, in the Transmexican Volcanic Belt. It is hemmed by volcanic mountain ranges: in the north by the Sierra de Tezontlalpan, in the east by the Sierra de Nevada, in the south by the Sierra Chichinautzin, and in the west by the Sierra de Las Cruces (Mooser et al., 1974). The basin was completely closed during the Middle Pleistocene, because of the intensive volcanic activity in the south caused by the Chichinautzin volcanic field (Mooser et al., 1974) conforming an endorheic system, with five interconnected water bodies: Zumpango, Xaltocan, Chalco, Texcoco, and Xochimilco (Fig. 1). However, most of these lakes dried out due to the construction of several drainage systems during the XVII, XVIII and XIX centuries, to avoid the floods, which affected frequently the city (Gurría, 1978). Today only small lake bodies are still preserved. Xochimilco, near the study area, is one of the biggest (Fig. 1).

The southern part of the basin has been affected by the volcanic activity of the Sierra Chichinautzin, where more than 200 Quaternary volcanoes are present (Martin del Pozzo et al., 1997; Siebe, 2000; Morales-Casique et al., 2014). The eruption of the monogenetic Xitle volcano is the most recent event with an intense influence in the study area (Fig. 2). It is formed on the slope of the Ajusco volcano (3950 m a.s.l.), which is more than 700,000 years old. The altitude of Xitle is 3150 m a.s.l. and the diameter scales 500 m (Martin del Pozzo et al., 1997). Its eruption occurred 1670 $\pm$ 35 years B.P. (AD 245–315) according to Siebe (2000). The eruption of ash followed by lava flows covered an area of 70 km^2 named as “El Pedregal” (Siebe, 2000).

The various mafic Xitle lava flows consist of olivine basalt (Córdova et al., 1994; Urrutia-Fucugauchi, 1996) containing plagioclase and olivine phenolcrysts. Most of the lavas exhibit a pahoehoe morphology, varying from highly vesicular to non-vesicular (Cañón-Tapia et al., 1995). This material was of low viscosity, which in contact with water bodies produced pillow-lavas. The time interval among the different events varied from some hours up to a few years (<10 years), which is also evidenced by the lack of soil formation in between the corresponding layers (Urrutia-Fucugauchi, 1996). The lavas first moved north and then north-east following former river valleys (Fig. 1). In total Xitle produced 0.96 km^3 of lava and 0.12 km^3 of ash (Cervantes and Molinero, 1995).

2.2. Geographic setting

The southern part of the basin of Mexico has a subhumid temperate climate Cb (wl) (w), with summer rainfall (García, 1988). The mean annual temperature of 16.9 °C is beneath the typical value for subtropical latitudes, and is affected by the altitudinal effect (from 2150 to 3150 m a.s.l.). The annual precipitation reaches 833 mm, with a dry season between November and May followed by a rainy season, from June to October (Castillo-Argüero et al., 2007). The modern soil cover in “El Pedregal” is thin and discontinuous. The soil thickness is on average only 4.5 cm (Santibañez-Andrade, 2005). These soils show an acid pH (5 to 6), and low contents of P, N, Ca, and K (Santibañez-Andrade, 2005). The typical vegetation of the highlands is pine forest, however today the primary vegetation is hard to recognize due to the high urban impact. Despite of the relatively high precipitation, a xerophytic shrub community dominates (Rzedowski, 1954) in “El Pedregal”, with a great variety of plants (Castillo-Argüero et al., 2007), since the lava flows are extremely porous and fractured and the rain infiltrates readily.

2.3. Cultural development

The basin of Mexico played a leading role in the history of Mesoamerica (geographical and cultural region that includes Central and Southern Mexico, Guatemala, Belice, Honduras, and El Salvador) due to its central position, its large extension, and the richness and diversity of its ecosystems (Kirchhoff, 1943).

First societies based on agriculture settled in the basin of Mexico around 3000 years ago (López-Camacho, 1991; Parsons et al., 1982). Examples of these societies were found in Copilco and Cuicuilco, both of them affected by the Xitle lava flows.

The Copilco archeological site was discovered by Zelia Nutall, in 1902. In 1917, Manuel Gamio constructed seven tunnels beneath the lava flows, where he found burials, pottery, lithic and stone alignments (Gamio, 1920).

Cuicuilco represented one of the first urban centers in the basin of Mexico, according to the materials obtained in the excavations (Heizer and Bennyhoff, 1958; Piña-Chán, 1967). The city reached a population of 20,000 inhabitants, during the Middle Pre-Classic (900 to 500 BC) (Sanders et al., 1979; Serra-Puche and Lascano, 2009). The development of Cuicuilco was related to its strategic position in the western margins of lake Xochimilco, where rivers and fertile soils in the surrounding areas were present. The site had multiple religious and residential buildings and a hydraulic system that supplied water to its inhabitants. In the last stage of the Late Pre-Classic (600 to 150 BC), Cuicuilco and Copilco disappeared, probably before the Xitle eruptions (Córdova et al., 1994). The reasons of the abandonment are still unknown. Siebe (2000) suggested that an eruption of pyroclastic flows from the Popocatépetl volcano (located at the SE of the basin), occurred between 250 and 50 BC, destroyed the site. However, Plunket and Uruñuela (2006) concluded that the eruption did not affected directly the sites, but it caused a severe impact in the landscape, and consequently in the