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Rates of pedogenic processes in volcanic landscapes of late Pleistocene to Holocene age in Central Mexico

Victor Peña-Ramírez [a], Lorenzo Vázquez-Selem [b], Christina Siebe [a, *]

[a] Instituto de Geología, Universidad Nacional Autónoma de México, Cd. Universitaria, México DF, CP 04510, Mexico
[b] Instituto de Geografía, Universidad Nacional Autónoma de México, Cd. Universitaria, México DF, CP 04510, Mexico

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ABSTRACT

The Transmexican Volcanic Belt and its many volcanic fields of different ages offer good opportunities to study soil development on volcanic tephra of intermediate to basaltic composition. We studied a soil chronosequence within the Sierra Chichinautzin volcanic field (SCVF), south of the basin of Mexico, and aimed to establish the rates of pedogenic processes. This field has been active for around 50,000 years, and produced 221 cinder cones with their respective lava flows. We selected 11 sites located on ^{14}C dated lava flows of ages between 1800 and 30,500 BP, at 3100–3200 m above sea level, covered with pine–fir forest, with an ustic soil moisture regime and an isomesic soil temperature regime. We also included a younger site (1000 BP) and three older sites (>100,000 years), two at 3100 masl and one at 2600 masl, from nearby volcanic fields to widen the time frame of the chronosequence. Soil profile samples were analysed for total organic carbon as well as for mineral neoformations related to clay contents, selective chemical extractions, and X-ray diffraction analyses.

Within the SCVF the total soil thickness, carbon accumulation and Al, Si and Fe extracted with acid ammonium oxalate increased linearly with age on surfaces up to 10,000 years old at rates of 19 cm ky^{-1}, 4.1 kg C m^{-2} ky^{-1}, 4.6 kg Al, 2.7 kg Si and 2 kg Fe m^{-2} ky^{-1}, respectively. Crystalline clay and iron oxide formation reach a maximum at the oldest site located at 2600 masl of 1650 kg clay m^{-2} and 70 kg Fe$_d$ m^{-2}. Their increase is linear up to ages of 10,000 years at rates of 22 kg clay m^{-2} ky^{-1}, and 2.8 kg Fe$_d$ m^{-2} ky^{-1}. Thereafter the rates are much slower. Allophane and allophane-like minerals dominate in the clay fraction at all sites of the chronosequence, and small amounts of halloysite can be identified in soils older than 6200 years, while kaolinite was only identified at the three oldest sites (>100,000 years).

The linear increases of all indicators of pedogenesis in the first 10,000 years are presumably driven by recurrent tephra deposition during this time frame. Thereafter, erosion and colluviation processes seem to disturb pedogenesis, changing its rates and redistributing its products in the landscape.

1. Introduction

Soil forming processes have very slow rates in relation to human lives. Therefore our current knowledge on their rates has been dominantly investigated by selecting study objects affected by the same or at least very similar soil forming conditions over different time spans, from few hundreds to tens of thousands and up to millions of years, i.e. by quantifying indicators of pedogenic processes along so called soil chronosequences (Stevens and Walker, 1970; Yaalon, 1975; Huggett, 1998). To conform a soil chronosequence all study sites should ideally be located on stable landform positions, have the same parent materials, and similar climatic conditions and thus vegetation cover over time (Bockheim, 1980; Jenny, 1980; Crews et al., 1995; Schaetzl and Anderson, 2005). Additionally the parent material should offer a clear reference of its age, particularly of the age since it has been exposed to weathering at the earth's surface. However, it is well known that environmental conditions are not stable at millennial time scales, and that vegetation changes in response to climate (Heine, 1975; Harden, 1982; Kitayama and Mueller Dombois, 1995; Kitayama et al., 1995; Vitousek et al., 1997). Also, in volcanic landscapes, tephra deposits are seldom homogeneous over larger distances, as coarser particles

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* Corresponding author.
E-mail address: siebe@unam.mx (C. Siebe).

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are deposited close to the source, while smaller size particles can travel much farther (Schmincke, 2004). Recurrent volcanic activity will add fresh material to adjacent locations in variable amounts depending on the meteorological conditions (e.g. Jackson et al., 2005). In several landscapes the inputs of airborne allochthonous materials have been evidenced to alter soil properties significantly (McFadden et al., 1987; Herrmann et al., 1996; Yaalon, 1997). Also, volcanic ash redeposited by wind has been recognized as a source for loess-like soils (Jackson et al., 2005; Iriondo and Kröhling, 2007).

Nevertheless, soil chronosequence studies in which successive stages of one or more pedogenetic processes over several time-scales are recorded, have allowed to calculate rates and direction of pedogenetic change during the Quaternary (McFadden and Weldon, 1987; Karlstrom, 1988; Scarciglia et al., 2015) in very different landscapes, as glacial moraines (Hall, 1999), landslide scars (Krasilnikov and Targulian, 2007), old mining areas (Ramos-Arroyo and Siebe, 2007), fluvial landforms such as fans, flood-plains and terraces (Howard et al., 1993), marine terraces (Sauer et al., 2010, 2012), and lava flows and volcanic ash deposits of differing ages (Crocker and Major, 1955; Harden et al., 1991; Manner and Morrison, 1991; Miehlich, 1991; Merritts et al., 1992; Crews et al., 1995; Van den Bygaart and Protz, 1995; Zarin and Johnson, 1995; Jahn and Stahr, 1996; Nieuwenhuyse et al., 2000).

Several authors report changes of specific indicators of pedogenic processes measured at sites of different age and in which they assume that all other soil forming factors have suffered similar changes. In chronosequence studies, the rate and direction of pedogenetic change can be calculated by correlating soil ages with distinct properties, and by adjusting for example a linear or logarithmic equation to the data (Levine and Ciolkosz, 1983). These chronofunctions are very useful for testing theories of pedogenesis, and to determine the necessary time for certain pedogenetic features or horizons to form (Birkeland, 1990, 1992; Crews et al., 1995; Chadwick and Chorover, 2001; Holzschuh, 2004).

Weathering processes have also been studied in the laboratory, by modifying temperature and pressure conditions to force the advance of pedogenesis (Schnoor, 1990; Swodoba-Colberg and Drever, 1993; Sverdrup and Warfvinge, 1995; White and Brabtley, 2003). However the rates calculated in these experiments do not coincide with those inferred from field chronosequences. This discrepancy is attributed to the difficulty of estimating a reactive surface area of field soil minerals, and also to macropore water flow in aggregated natural soils, which alters the reaction contact times between the solid phase and the soil solution (Nahon, 1991; Lasaga, 1998; Chadwick and Chorover, 2001).

For this reason, chronosequence studies are still widely used to infer rates of pedogenic processes. However, considering that soil forming factors do not remain constant in time, the data analysis considers a multidirectional rather than a unidirectional driving force of pedogenesis (Phillips, 1993). This recognizes that soil development occurs in episodes during which the soil forming factors are relatively constant, and which are then taken over by a following phase in which the rate of a process changes due to a change in one or several soil forming factor conditions. In some cases, the process can slow down and the expression of an indicator diminishes in consequence. Also, it is now well recognized that the rates of pedogenesis tend to decline as soil development increases, due to the self-limiting nature of some processes, such as the depletion of weatherable minerals, or the decline in weathering rates at the weathering front as regolith thickness increases.

In active volcanic fields, soil development is affected by recurrent tephra fall as new eruptions occur at the same or in adjacent volcanoes (Bertrand and Fagel, 2008). As loose ash deposits have a large specific surface and their mineral components are easily weathered, this can lead to soil aggradation. However, if the ash fallouts have a larger thickness, former soils are buried beneath them, and pedogenesis is interrupted. Often, the ash fallout severely affects vegetation, and subsequent rain events lead to soil erosion. These differences in soil chronosequences have been recognized by Vreeken (1975) and Huggett (1998), who differentiate soil chronosequences as “pre-incisive” or “post-incisive”, depending on whether the starting point of soil formation coincides at all studied sites, or it started at different moments, and according to the time overlap during which all studied sites were subject to pedogenesis (i.e. “time transgressive chronosequences with and without historical overlap”).

Many chronosequence studies have been performed in volcanic landscapes, under different moisture regimes, from xeric, i.e. arid and semiarid climates (Jahn and Stahr, 1996; Vaughan, 2008), to udic and perudic, i.e. humid climates (Crews et al., 1995; Nieuwenhuyse et al., 2000; Egli et al., 2008). However, few studies document rates of pedogenic processes under ustic soil moisture regimes (i.e. seasonal climates).

The Transmexican Volcanic Belt (TMVB) crosses Central Mexico from the Pacific Coast to the Gulf of Mexico. It offers excellent opportunities to study genesis of volcanic ash soils, as volcanic activity has been more or less constant throughout the Quaternary. One example is the Sierra Chichinautzin volcanic field (SCVF), located south of the Basin of Mexico, where volcanic activity has been recurrent in time intervals of <1700 years over the last 50,000 years (Siebe et al., 2004). It is composed of more than 221 monogenetic cones, which were active for a few years and produced lava flows of dacitic to basaltic composition, as well as ash fallouts, many of which originated during the latest part of the eruptions and covered the lava flows.

Similarly, the strato-volcano Popocatépetl (5450 masl), located in the Sierra Nevada in the southeast part of the Basin of Mexico has had three major episodes of activity during the last 25,000 years (Siebe and Macías, 2006), offering excellent sites for chronosequence studies. This was acknowledged by Miehlich (1991), who did a very detailed study on soil formation in the Sierra Nevada covering a time span from 1000 to 10,000 BP at altitudes between 2500 and 3000 masl, with soil moisture regimes ranging from ustic/isomesic (2500–3000 m), to udic isomesic/isofrigid (3000–4000 m) and ustic/isofrigid (>4000 m).

The objective of this study was to establish rates of pedogenic processes, such as the accumulation of humified organic matter and the neoformation of secondary minerals at 3000 m altitude under coniferous forests. Our aim was to distinguish particularly the rate of neoformation of short-range order minerals, humus-Al and Fe complexes on the one hand, and the formation of crystalline clay minerals and iron oxides on the other hand. We also aimed to investigate whether these indicators of pedogenic processes could provide hints on climate change during the last 100,000 years at this altitude, and whether they are affected by changes in the mineralogical composition of the parent materials. In addition, we investigated if the recurrent inputs of ash fallout deposits can be identified in the field and through various laboratory analyses and to what extent they might affect the overall pedogenic development in relation to the other soil forming factors.

2. Materials and methods

2.1. Study site description and selection of study sites

The studied sites are located in the surrounding volcanic mountains of the basin of Mexico, within the central part of the Transmexican Volcanic Belt (TMVB) (Table 1 and Fig. 1, Peña-Ramírez et al., 2009). All sites are between 3000 and 3200 m