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Use of soils and palaeosols on volcanic materials to establish the duration of soil formation at different chronological scales

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ABSTRACT

In this paper, we present an overview of the Mexican volcanic palaeosol sequences, as a valuable tool to establish the duration of soil formation at different chronological scales. We have selected four study cases which cover time intervals from decennial, centennial, to millennial pedogenesis. The first case corresponds to the soils in El Chichón volcano, where the short interval between the eruptions gives the opportunity to study the soil formation in periods less than 500 years. In this interval, the transformation from Regosol to Andosol is observable. In El Nevado de Toluca, pedogenesis of longer duration (4000 to 6000 y), characterizes a vitric Andosol stage. In this area, the transformation of Andosol to Luvisol is also shown, in periods longer than 10,000 years. The third study case corresponds to the Tlaxcala palaeosol sequence, where pedogenesis in intervals from 10,000 to 100,000 years is observable. In this case, no Andosols are present, and a complete set of Luvisols showing different properties is found. This differentiation is not only related to the duration of the pedogenesis, but also to the climatic conditions, which lead to changes in specific properties (clay content, weathering of the primary minerals, Fed content). In this way, these soils are valuable for palaeoenvironmental reconstruction. The fourth case is related to faster pedogenesis in the volcanic regions of Mexico, where highly developed Luvisols are found, formed in intervals less than 15,000 y. In this case, the influence of a pre-weathered volcanic material as a source of clay allows the rapid transformation.

1. Introduction

Recent soils and palaeosols developed in the volcanic geosystems, derived from and incorporated in the tephra sediments, are receiving increasing interest in various research aspects. During recent years, new tephra-palaeosol records have established the landscape history in different volcanic regions (e.g. von Suchodoletz et al., 2009; Inoue et al., 2011; Zembo et al., 2011). The organic-rich volcanic palaeosols are widely used as source of radiocarbon dates to develop tephrostratigraphic schemes (e.g. Tonneijck and Jongmans, 2008), and also as possible carriers of novel molecular proxies for palaeovegetation reconstruction (Zech et al., 2014). They are also considered as important carbon storage-regional hotspots (Batjes, 1996; Chaopricha and Marín-Spiotta, 2014; Zech et al., 2014). On the other hand, it is well known that volcanic soils suffer transformations related to the fast weathering evolution and mineral neoformation, which control the pedogenetic processes of the unconsolidated volcanic materials, as pyroclastic ejects, pumice, scoria, or lahar deposits (Shoji et al., 1993) under uniform climatic conditions (Delvaux et al., 1989; Zamotaev and Targulian, 1994; Nieuwenhuyse et al., 2000).

The transformation of volcanic soils goes through several stages. The "normal" trend of alteration of volcanic ash was firstly proposed by Fieldes (1955). This author as well as Shoji et al. (1985), Nanzyo et al. (1993), van Breemen and Buurman (2002), and Dahlgren et al. (2004) considered allophane as the initial product of weathering, followed by halloysite. Many recent papers concur with this sequence. Perhaps the model includes different pathways, as the transformation depends on a wide variety of factors as precipitation, drainage, composition of the tephra, type of vegetation, and even human activities (Lowe, 1986; Parfitt, 2009; McDaniel et al., 2011). These factors control the weathering environment and consequently the leaching, the pH, and the organic cycle (Churchman and Lowe, 2012). For instance, allophane formation occurs under the following conditions: pH values ranging from 5 to 7, a low amount of complexing organic compounds

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(Ugolini and Dahlgren, 1991), and a high availability of Al (Lowe, 1986). Allophane formation is limited in environments with a high amount of organic matter and pHs <5, promoting the formation of Al-humus complexes, and limiting the availability of the Al. In consequence, non-allophanic Andosols are developed (Shoji et al., 1985; Dahlgren et al., 2004; McDaniel et al., 2011). In both cases (allophanic and non-allophanic soils), the percentage of Si is lower than 10 ppm. In environments where Si is higher, mostly due to restricted leaching, halloysite is formed (Parfitt, 2009).

Time and climate are the main factors which control the relative weathering degree and soil development (Ugolini and Dahlgren, 2002). In humid climates, the development sequence proceeds from initial soils, to clayey soils as: Regosols − > Andosols − > Cambisols − > Luvisols − > Acrisols (Parfitt and Saigusa, 1985; Delvaux et al., 1989; Shoji et al., 1993; Sedov et al., 2003a). In semiarid climates, the sequence changes from Regosols − > Andosols − > Phaeozems − > Vertisols (Shoji et al., 1993).

The question arises about how much time is needed to transform the original tephras into allophanic soils and further to clayey or other kind of soils. Many authors have addressed this question in surface soils under several climate conditions, for instance, Yamada and Shoji (1983) as well as Wada (1985), in Japan; Miehlich (1991), in Mexico; Nieuwenhuyse et al. (1993), in Costa Rica; Jahn and Stahr (1996), in the Canary Islands; Gracheva et al. (2001) in the Tonga Islands; Chorover et al. (2004), in Hawaii; and Vilmundardóttir et al. (2014) in Iceland.

The studies in several modern soil chronosequences in volcanic regions of the world show that during the first hundreds years the accumulation of organic matter occurs, not only under the cool humid climate of Japan (Wada, 1985) or Iceland (Vilmundardóttir et al., 2014), but also under humid tropical conditions as in the Tonga islands (Gracheva et al., 2001) or Costa Rica (Nieuwenhuyse et al., 1993). The development of Bw horizons needs longer times, in the range of $n \times 100$ to $n \times 1000$ years (hundreds to several millennia). In temperate climates as in Japan, Bw horizons requires more than 1000 years (Wada, 1985; Shoji et al., 1993), while in the tropical conditions of Costa Rica, they form in shorter periods (Nieuwenhuyse et al., 1993). Bt horizons require more than 10,000 years in the semiarid climates of the Canary Islands (Jahn and Stahr, 1996) as well as in the tropical humid climates of the Tonga islands (Gracheva et al., 2001). However, the formation of a Bt horizon can be faster if the parent material has clay originally (Birkeland, 1999; Díaz-Ortega et al., 2011). In Mexico, the classic study of the chronosequences in the volcanic areas of the Sierra Nevada by Miehlich (1991) demonstrates the progressive development of Andosols during the Holocene. Transformation of Andosols into clayey soils occurred over periods longer than 10,000 y.

The mentioned works have been done in modern volcanic soils, with the limitation that pedogenesis is an ongoing process. According to Birkeland (1999), the time of soil formation is better estimated in buried soils, because the interval is constrained by the events of pedogenesis and sedimentation. Thick tephra deposits are able to stop the pedogenesis of the buried soil, and at the same time, to create a new surface to start the soil formation, resetting the pedogenic "clock" to zero (Lowe, 2010).

At the same time, the understanding of the duration and evolutionary succession of pedogenetic processes and phases, independent from climate, has key importance for the palaeoecological interpretation of tefra-palaeosol sequences. Deposition of pyroclastic materials occurs at variable frequencies, resulting in changes of the pedogenesis duration of different buried soils. In consequence, palaeosols within a sequence could present diverse properties and even belong to several groups, at the highest taxonomic level, which are not related to any considerable change of bioclimatic factors. Volcanic palaeosol diversity, controlled by time, is a specific phenomenon, quite different from the evolutionary pathways of classical "zonal" soils, and palaeosols of loessic sequences. In addition, profiles formed at different evolutionary stages provide quite different proxies that could be used for palaeoecological reconstructions, and thus have decisive influence in the design of the "record decoding".

The objective of this work is to show different duration of pedogenesis in volcanic areas of Mexico, in palaeosols showing different degrees and time scales of development, from decennial to several millennia. After identifying these evolutionary phases, we intend to develop guidelines of how to involve temporal aspects in palaeoecological studies, and how to interpret at the volcanic palepedological records. In this approach, we use the information from palaeosols buried by tephras of different ages, bracketing the time of soil formation. For this purpose, we compare and summarize the earlier results on the individual tephra-palaeosol sequences with well-established chronologies, based on instrumental dates.

2. Site conditions of the selected objects

We have selected four sites affected by volcanic activity in Mexico, on different time scales: El Chichón, El Nevado de Toluca, the Tlaxcala Block, and the Glacis de Buenavista. In El Chichon, we illustrate changes in a decennial to centennial scale; in El Nevado de Toluca, palaeosols show evolution over several millennia. In the Tlaxcala Block, the cases of the Grey, Brown, and Red Units are presented as an example of >10,000 y palaeopedogenesis. The last study case exhibits an anomalous fast development of clayey soils over short (millennial) intervals in the Glacis de Buenavista.

The palaeosols of the four sites have been studied and the results have published (Sedov et al., 2001, 2003a, 2003b, 2009; Solleiro-Rebolledo et al., 2007; Díaz-Ortega et al., 2011). In this work, we consider selected information which can be related to the weathering status and soil evolutionary trends: macro- and micromorphology, total organic carbon (TOC), clay content, Alo, Sio, Feo (aluminum, silicon, and iron extracted with acid oxalate), Fed (iron extracted with dithionite-citrate-bicarbonate), clay mineralogy, and amorphous minerals content evaluated by using the formula of Parfitt and Wilson (1985). The selection of the palaeosols is done on the basis that they represent different stages of soil formation as the first criterion, and that the same set of analyses have been done to characterize them.

Palaeosol classification is based on the morphological and analytical properties, following the IUSS Working Group WRB (2014). However, in palaeosols it is not possible to comply with all diagnostic criteria necessary for a correct classification (Retallack, 1990; Krasilnikov and García-Calderón, 2006). In consequence, the proposed classification considers the morphological characteristics as well as the more stable properties, as proposed by Mack et al. (1993).

2.1. Palaeosols in El Chichón

The first site corresponds to El Chichón which shows the case of decennial to centennial soil formation. El Chichón is an active volcano located in southern Mexico (Fig. 1). It has a long history of eruptions during the last 200,000 years, with a marked phase of activation in the Holocene, when more than 12 eruptions have been recorded (Espíndola et al., 2000). The last explosive eruption occurred in 1982 producing large-scale devastation in the surrounding area and some climatic effects on the global scale (Sigurdsson et al., 1984). The site conditions in the area of El Chichón are dominated by a very humid (more than 4000 mm annual precipitation) and hot climate (22.5 °C mean annual