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Weathering and clay formation in semi-arid calcareous soils from Northeastern Brazil

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ABSTRACT

Despite the great number of studies exploring the inter-profile genetic relationships in a catena, the microrelief and microtopographic features have been overlooked. This study investigated the role of microrelief surfaces (convex, flat and concave) on the mineral formation and pedogenesis in soils derived from limestones in NE Brazil. Soil profiles were studied in different micro-landscape surfaces, and soil samples were taken by horizon for chemical (weathering indexes) and mineralogical analyses. Mineralogy was determined in samples from diagnostic subsurface horizons, which were subjected to the proper chemical treatment for identification (X-ray diffraction - XRD) and quantification (Newmod II and Thermogravimetry - TG) of the phyllosilicates. The XRD patterns showed similar composition among the parental material of the studied profiles. The chemical also showed similar dynamics along the surfaces; however, the concave surface had soils with a higher degree of weathering, when compared to others. The clay minerals identified on the convex and flat surfaces were vermiculite, illite, smectite and kaolinite; while on the concave surface, only illite and kaolinite were found. Based on the information generated by the Newmod II, there was an increase in the amount of kaolinite towards the concave surface, from 21%, on the convex surface, to > 50% of pure kaolinite crystals on the concave surface. These data were supported by the TG curves. Our results evidence that microrelief features, marked by low topographic amplitudes, are determinant for the formation and distribution of phyllosilicates in calcareous soils; and, thus, may be of key importance for predicting the occurrence of contrasting mineralogy in soils derived from calcareous rock.

1. Introduction

The notion that the local relief and its forms (slopes and curvatures; both vertically and laterally) control water dynamics and the processes of material redistribution (i.e. colloidal material and solutes) on a landscape dates back to the catena concept coined by Milne (1935); which was complemented by others (Conacher and Dalrymple, 1977; Huggett, 1975; Ruhe, 1975). Several studies explored the inter-profile genetic relationships in a catena, and how they govern the distribution of different soils on landscapes. However, historically, the vast majority of these studies, including those on calcareous material (Atalay, 1997; Silva et al., 2017; Van de Wauw et al., 2008), have focused and high slope gradients, while microrelief and microtopographic features have been often overlooked.

The origins of these small-scale landforms may be diverse and complex, and several different processes have been proved to create them, such as treethrow disturbances (tree uprooting; Embleton-Hamann, 2004; Schaetzl, 1990), faunalturbation (pedoturbation promoted by animals; Soyer, 1983; Phillips, 2007), argillipedoturbation (shrinking and swelling of clays; Knight, 1980; Schaetzl, 2008), and cryoturbation (freeze–thaw activity; Bockheim and Tarnocai, 1998). However, irrespective of its origins, microrelief features may trigger or hinder certain pedogenetic processes, depending on local conditions (i.e. climate, drainage, water table behavior) and govern the soil distribution patterns at local and regional scales.

In northeastern Brazil, where the semi-arid region covers an area of about 750,000 km^2 (Ab'Saber, 1977), pedogenesis is mostly governed by the combination of high temperatures and irregular rainfall, acting

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predominantly on rocks from the crystalline basement (Precambrian Era).These conditions usually lead to the formation of slightly weathered soils, with high-activity clays and high base status.

Despite the prevalence of low weathering rates in the Brazilian semiarid region, there are some exceptions where the typical processes from tropical humid environment take place (i.e. altimontane soils; see Barbosa et al., 2015). Among these unique environments is the Apodi Plateau, a vast geomorphological unit in NE Brazil, where the flat relief with dominant slopes of < 2% shows no dissection. Although the soil survey of the Apodi Plateau (Brasil, 1973) indicates a predominance of high-activity clay mineral (e.g. smectite and vermiculite; Ernesto Sobrinho, 1980; Lemos et al., 1997) and high base status (e.g. Cambisols), recent studies have reported the occurrence of low-activity clay minerals in soils mostly dominated by kaolinite; i.e. Lixisols and Ferralsols (Alencar, 2002; Ferreira et al., 2016; Mota et al., 2007). These contrasting soils form a continuum on the regional landscape with unclear boundaries, mostly due to the absence of clear landform distinction.

The determination of relative abundance of each mineral as a function of the different (micro)relief features can serve as an important tool for predicting the occurrence of different soil types on these fairly flat, monotonous, karst landscapes. Additionally, it may assist with decision making for the management systems to be adopted, and can generate valuable information for the evaluation of pedogenesis. Thus, the aim of the present study is to assess how weathering rates, clay formation and hydrological conditions are ruled by rather slight variations in (micro)relief in these environments.

2. Material and methods

The Apodi Plateau covers 2146 km^2 between the states of Ceará and Rio Grande do Norte (NE Brazil; Fig. 1). This geomorphological unit belongs to the Potiguar Basin that is composed stratigraphcally, at emerged portion by the Jandaíra Formation (250–300 m thick) above the Açu formation. The first is composed by calcitic and dolomitic limestone rocks, whereas the. Açu Formation is composed of fine-grained sandstone, with micaceous and kaolinitic clay mineralogy (Girão et al., 2014; Brasil, 1973; Sampaio and Schaller, 1968). The climate in the region is BSw'h, hot and semi-arid, with a mean annual temperature of approximately 28 °C and relative air humidity varying from 50 to 84%, with a mean rainfall of 750 mm (Fig. 1; Ceará, 1980). The native vegetation in the studied area was composed of hyperxerophilic Caatinga; however, the studied area is currently under banana cultivation.

The studied site covers an area of 102 ha, located the municipality of Limoeiro do Norte (state of Ceará, NE Brazil). The terrain contains slope gradients predominantly < 3%, which covers 97% of the studied area, with a slight inclination in a northwest-southeast direction (Fig. 1). At the northwest end of the study site the higher elevations were recorded (~103 m) while minimum elevations (~101 m) were obtained at the opposite end (southeast). In previous studies by Oliveira (2009) and Oliveira et al. (2013), both a detailed soil survey and a (micro)topographic survey were conducted at the study site. A digital elevation model was produced (DEM) and based on the shape of the contour lines (microslope features) the studied area was divided into three different surfaces (Fig. 1): convex (42 ha), flat (22 ha) and concave (38 ha). Based on the chemical and physical data and morphological descriptions (according to Schoeneberger et al., 2012). The particle-size analysis was determined by the pipette method (Gee and Bauder, 1986). The total organic carbon was determined by wet oxidation (Walkley and Black, 1934). The soil pH was measured in water (1:1.25) using a glass electrode. The calcium carbonate equivalent (CCE) was determined according to Allison and Moodie (1965). The soils were classified according to WRB (IUSS Working Group WRB, 2015). Although the profiles were classified as Calcaric Cambisol (loamic) (convex and flat surfaces) and Calcaric Cambisols (clayic) (concave surface), soils showed a wide variation with respect to their morphological characteristics (i.e. soil depth) and mineral composition of clay fraction; with shallower soils and high-activity clays occurring in the convex surface. According with criteria established by WRB (IUSS Working Group WRB, 2015), the soils profiles do not show diagnostic properties that characterize a lithological discontinuities.

Al_2O_3 and Fe_2O_3 were determined in the air-dried fine earth (< 2 mm; ADFE), using an extraction solution of sulfuric acid (1:1). SiO_2 was extracted with 30%NaOH (EMBRAPA, 2011). Aluminum and iron contents were determined in the extracts by atomic absorption spectrophotometry, and the results were represented as oxides (Al_2O_3 and Fe_2O_3). Silica content was determined by colorimetry (Kilmer, 1965). The results were used to calculate a weathering index (the Ki index) based on the contents of SiO_2 and Al_2O_3 (Ki = $[SiO_2 / Al_2O_3]$ x1.7; see Demattê et al., 2004).

The mineralogical analysis was carried out in the diagnostic subsurface horizons (X-ray diffraction modeling and thermal analysis). The bulk mineralogy of the parent materials was analyzed by XRD as

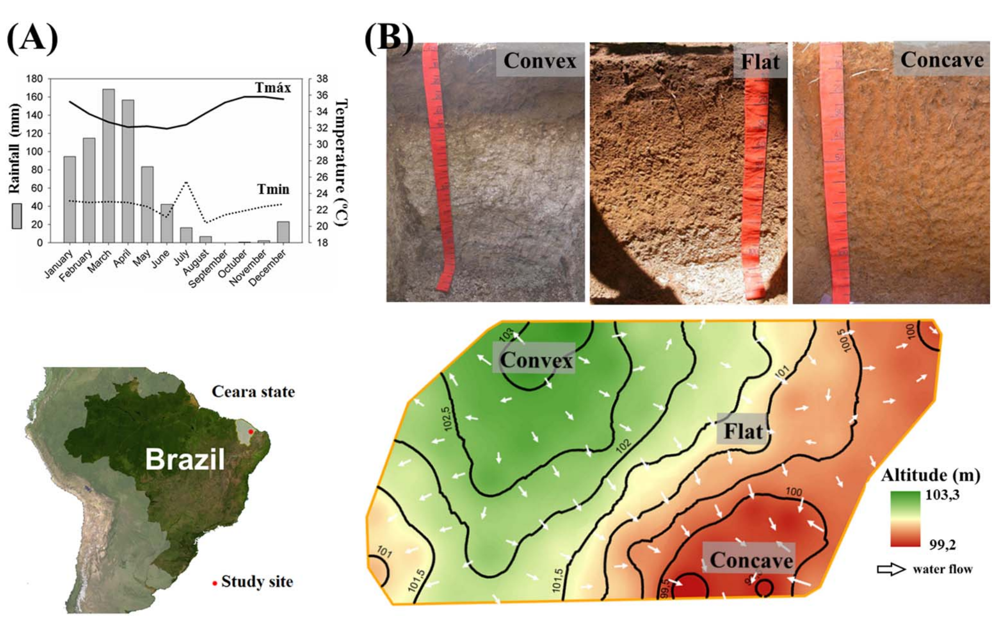

Fig. 1. (A) Brazil, Ceará State (NE), and climate conditions (mean temperature and rainfall) at the study site; (B) The digital elevation model and the three soil profiles representative of each surface (convex, flat and concave); arrows indicate the direction of preferential water fluxes at the land surface.