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Clay mineralogy and genesis of fragipan in soils from Southeast Brazil

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ABSTRACT

Fragipan horizon has a hard consistency when dry but is brittle when moist. Such a horizon restricts root growth and water infiltration due to the low volume of macropores and discontinuous voids. In Rio de Janeiro state in Brazil, neighboring soils were developed from different materials (sediments and granite/gneiss) and were subject to the same environmental conditions; one manifested fragipan characteristics in the subsurface and the other did not. The main objective of this study was to characterize and quantify clay minerals and relate their properties to the genesis of fragipan horizons. The fragipan in the studied soils show high bulk density (1.67 g cm^{-3}) and low average macroporosity (0.03 cm cm^{-3}), total porosity (0.42 cm cm^{-3}) and hydraulic conductivity (1.43 cm h^{-1}). Sequential and interrelated causes favored the formation of fragipan horizons: 1) face to face adjustment of kaolinite (Ka) filling of larger spaces occurring between sand grains, favored by low goethite contents and the absence of hematite and gibbsite; and 2) mineral binding and cementation of sand, silt and clay fractions by amorphous materials. Higher amounts of goethite and lower amounts of amorphous materials in the clay fraction were associated with horizons with higher total porosity.

1. Introduction

Cohesive behavior is a characteristic found in soils around the world (Chartres et al., 1990; Dexter, 2004; Ley et al., 1989; McKyes et al., 1994; Mullins et al., 1990; Prandel et al., 2014; Schjønning and Thomsen, 2013), but fragipan presents different cohesive features, as cementation is minimized by the presence of water (Embrapa, 2013; FAO, 2006; Soil Taxonomy, 1999). However, some cohesive horizons can be hard even under wet conditions as a result of iron oxide (laterite), calcium carbonate (petrocalcic horizons) and Si (duripan) accumulation (Franzmeier et al., 1996).

Young (1992) identified cohesive soils in the United Kingdom based on the following features: 1) a texture that is typically within the sandy clay to loamy sand range; 2) low organic matter content (typically below 20 g kg^{-1}); 3) weakly structured and prone to slumping when wetted; 4) hard setting upon drying with an apedal structure, consequently exhibiting high tensile and shear strength values; 5) low content of shrink-swell clays; and 6) friability only over a limited moisture range. The notion of apedality was restored by including the term 'structureless' into the definition: 'cohesive soils are soils that set to a hard, structureless mass during drying and are thereafter difficult or impossible to cultivate until the profile is rewetted' (Mullins et al., 1990).

The occurrence of cohesive horizons creates problems from a practical point of view, such as seedling emergence, blocking and resistance to root penetration, decreased productivity and greater effort for soil management (Daniells, 2012; Dexter, 2004; Greene et al., 2002; Mullins et al., 1987, 1990; Schjønning and Thomsen, 2013; Young, 1992). Bulk density of fragipan horizons can reach values as high as 1.7 Mg m^{-3} (Young, 1992), and root growth and distribution are restricted to the plow layer, owing to the high penetration resistance exhibited in this soil (greater than 6 MPa) (Young et al., 1991). Under field conditions fragipan soils can be too hard to cultivate, producing a cloddy structure in a slightly moist state when mechanically plowed (McKyes et al., 1994).

Some management techniques have been used to minimize the expression of the cohesive character in these soils: incorporation of maize residues (Mullins et al., 1987), deep tillage (Mead and Chan, 1992), an increased root system (permanent-pasture) (Chan, 1989), combined deep moldboard plowing and gypsum application (Hall et al., 1994), addition of ferrihydrite and Al oxides (Breuer and Schwertmann, 1999), treatment with anionic polymer (Chan and Sivapragasam, 1996) and no-till cropping (Ley et al., 1989).

For a complete understanding of fragipan soils, studies of effects on physical characteristics, crop management, and plant growth should be accompanied by the genetic causes of cohesion. In general, the causes of cohesion of fragipan horizons vary with local soil and climate conditions and are associated with both physical and chemical processes. In Australia, it was associated with cycles of wetting and drying

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(Chartres et al., 1990); in soils from Denmark and Switzerland, by packing of sand grains in sandy soils with low organic carbon (Schjønning and Thomsen, 2013); in Nigeria (Ley et al., 1989) and Western Australia (Harper and Gilkes, 1994), to the increase of clay due to illuviation joining coarse soil particles.

Some authors have concluded that the type of mineral in the clay fraction is more important than the amount of clay in promoting cohesion. The predominance of kaolinite in relation to the 2:1 expandable mineral hampers the development of structural cracks on drying and favors the formation of fragipan horizons (Mullins et al., 1987; Prandel et al., 2014). The juxtaposition of high crystallinity kaolinite was the cause of cohesion in kaolinitic soils formed from sediments in Brazil (Giarola et al., 2009). Mullins and Panayiotopoulos (1984) demonstrated that artificial mixtures of sand and as little as 2% kaolinite could exhibit cohesive behavior.

Other studies reported the importance of amorphous materials and fresh gels of elements, especially Si and Fe in the cohesion of subsurface layers (Brown and Mahler, 1988). Chartres and Norton (1994) pointed to silica and less crystalline Fe oxide (ferrihydrite) bonds on the clay surfaces as a determination factor of cohesion. This chemical effect was increased by the presence of very fine sand and silt particles and low soil biological activity. The crust formed by the precipitation of amorphous silica gels on mineral surfaces under reduced humidity promotes the reduction of porosity and hydraulic conductivity of soils (Daniells, 2012; Mckyes et al., 1994; Mullins et al., 1990). In fragipan soils of Australia, the strength was correlated positively with extractable Si and negatively with extractable Al by ammonium oxalate (Franzmeier et al., 1996).

This apparent divergence of information about crystalline and amorphous materials justifies the need for further investigation of the genesis of cohesive soils, especially under varying geological and soil conditions. The main objective of this work was to study the clay fraction and its properties (quantity, chemical composition and crystallography) related to the genesis of fragipan horizons in two landscape positions.

2. Material and methods

2.1. Study area and soil sampling

The study area is located in Itaboraí county, state of Rio de Janeiro, Brazil (Fig. 1). Regional climate is tropical, with a dry season in winter (one to three dry months) and a rainy season in summer from November to April. Average air temperature in the coldest month is above 18 °C and annual rainfall ranges from 1000 to 1500 mm (Ramos et al., 2013).

Regional basin stratigraphy is formed by Macacu Formation sediments from Eocene/Oligocene period overlapping granite/gneiss layers of St. Fidelis Formation of the Proterozoic age (Ramos et al., 2013). The thickness of the sediments package is approximately 200 m.

Two toposequences were studied (Table 1): toposequence 1 (fragipan soils) — Macacu Formation sediments; toposequence 2 (non-fragipan soils) — St Fidelis Formation (area without overlapping Macacu sediments). Non-fragipan soils were used as reference for discriminating soil attributes in the expression of cohesive character. Due to the small distance between toposequences (1 km), it can be assumed that the studied soils were subject to similar environmental conditions.

The morphology of soil profiles was described according to FAO (2006). Disturbed and undisturbed samples were collected from all horizons of soil profiles. Disturbed samples were air dried and sieved through a 2 mm mesh for soil physical and chemical characterization (Embrapa, 1997): pH in 0.01 mol L^{-1} $CaCl_2$ (soil/solution ratio 1: 2.5), non-exchangeable potential acidity (H) extracted with 0.5 mol L^{-1} pH 7 Ca acetate, exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} extracted with 1 mol L^{-1} KCl, exchangeable K^+ in 0.05 mol L^{-1} H_2SO_4 and 0.025 mol L^{-1} HCl, organic carbon (OC) extraction with H_2SO_4 and potassium dichromate. Soil texture was determined using the pipette method.

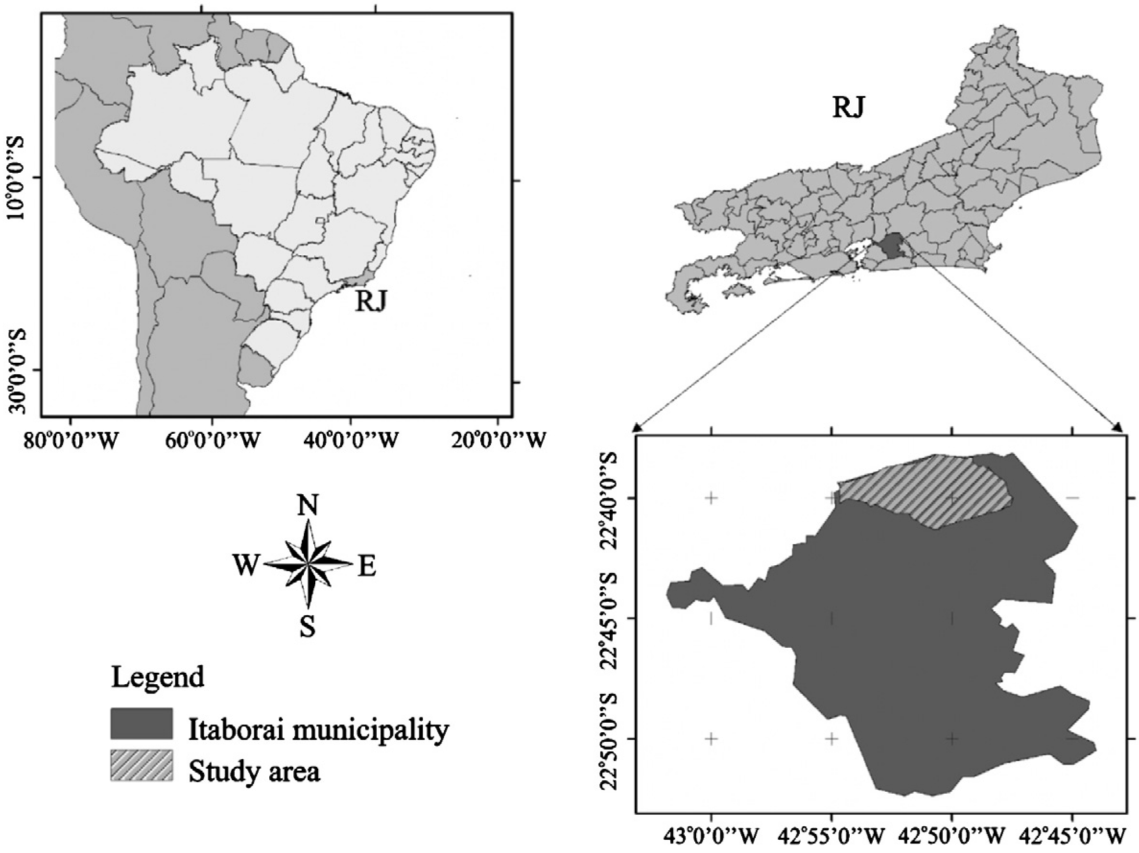

Fig. 1. Location of the study area.