Revista Brasileira de Ciência do Solo

Division - Soil in Space and Time | Commission - Soil Genesis and Morphology

Cemented Horizons and Hardpans in the Coastal Tablelands of Northeastern Brazil

João Bosco Vasconcellos Gomes[(1)*], José Coelho Araújo Filho[(2)], Pablo Vidal-Torrado[(3)], Miguel Cooper[(3)], Elen Alvarenga da Silva[(4)] and Nilton Curi[(4)]

[(1)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Florestas, Colombo, Paraná, Brasil.
[(2)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Solos - UEP Recife, Recife, Pernambuco, Brasil.
[(3)] Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Departamento de Ciência do Solo, Piracicaba, São Paulo, Brasil.
[(4)] Universidade Federal de Lavras, Departamento de Ciência do Solo, Lavras, Minas Gerais, Brasil.

ABSTRACT: Horizons with varying degrees of cementation are a common feature of the soils from the coastal tablelands of Northeastern Brazil. In most cases, these horizons are represented by the following subsurface horizons: fragipan, duripan, ortstein, and placic. The aims of this study were to analyze differences regarding the development and the degree of expression of cementation in soils from the coastal tablelands of Northeastern Brazil: *Planossolo Háplico* (p-SX), *Espodossolo Humilúvico* (p-EK), *Espodossolo Ferrihumilúvico* (p-ESK), and *Argissolo Acinzentado* (p-PAC) pedons. The pedons studied displayed features related to drainage impediments. The cemented horizons from p-SX and p-EK had the same designation (Btgm), displaying a duric character that coincided with gleization features and are under podzolized horizons. In the p-ESK, the podzolization process is of such magnitude that it leads to the cementation of its own spodic horizons, which were both of the ortstein type (Bhsx and Bsm). In the p-PAC cementation is observed in two placic horizons and in the Btx/Bt horizon, as well as in the upper parts of the Bt/Btx horizon. Analysis of the micrographies from the cemented horizons showed predominance of a low porosity matrix. Such porosity is relatively greater in the horizons of "x" subscript than in the horizons with duric character. The Fe segregation lines were notable in the cemented horizons from p-EK and p-PAC, which corroborates the presence of placic horizons in such pedons. The preponderance of kaolinite in the clay fraction was widely verified in all the cemented horizons analyzed. Water immersion tests were the criteria adopted to define the duric character of the Btgm horizons from p-SX and p-EK, and in the Bsm horizon from the p-ESK. These tests were also used to confirm field morphology. In most cases, the maximum values of Fe, Al, and Si, determined by different extractions, occurred in positions overlaying the cemented horizons, whether they were spodic or not. The extracts of the aqueous solution displayed a noticeable accumulation of Si in the cemented horizons, except in the p-PAC. The presence of argillans in all cemented horizons allows them to be defined as illuvial, with the exception of the placic horizons, regardless of the presence of podzolization processes. The cemented horizons were preponderantly apedal, with a matrix of little porosity. The Fe, Al, and Si contents extracted by acid ammonium oxalate were effective at highlighting the influence of compounds with a low degree of crystallinity in the morphology of cemented horizons.

Keywords: fragipan, duric character, podzolization.

*** Corresponding author:**
E-mail: joao.bv.gomes@embrapa.br

Received: November 24, 2015

Approved: July 12, 2016

How to cite: Gomes JBV, Araújo Filho JC, Vidal-Torrado P, Cooper M, Silva EA, Curi N. Cemented Horizons and Hardpans in the Coastal Tablelands of Northeastern Brazil. Rev Bras Cienc Solo. 2017;41:e0150453.

INTRODUCTION

Horizons with varying degrees of cementation are a common feature of soils from the coastal tablelands of Northeastern Brazil (Araújo Filho, 2003). In most cases, these horizons are represented by the following subsurface horizons: fragipan, duripan (duric character), ortstein (cemented spodic horizon), and placic (Soil Survey Staff, 1999; Santos et al., 2013). Moreover, detailed soil maps (1:100,000 or greater) have shown that the geographic expression of such horizons in the coastal tableland soils is greater than that represented on more generalized maps of the region (Araújo Filho et al., 1999; Araújo Filho, 2003; Curi and Ker, 2004). The cemented horizons usually occur in *Argissolos Amarelos* (Udults and Ustults), *Argissolos Acinzentados* (Udults and Ustults), and *Espodossolos* (Spodosols), but they are also found in *Neossolos Quartzarênicos* (Quartzipsamments), *Planossolos Háplicos* (Quartzipsamments), and other soil classes from the Brazilian System of Soil Classification (Santos et al., 2013). The ortstein is a cemented spodic horizon, which is typically influenced by organometallic complexes. The placic horizon is a thin pan of black to dark-red color, cemented by Fe (or Fe and Mn) and organic matter. This horizon may or may not be associated with the spodic horizon (Soil Survey Staff, 1999; Santos et al., 2013).

Whether the presence of cementing agents is necessary for a horizon to be diagnosed as a fragipan is still disputed (Aide and Marshaus, 2002; Weisenborn and Schaetzl, 2005), or not very relevant (Certini et al., 2007). The development of fragipans by the compression of particles has been explained by different theories, which are not mutually exclusive: past periglacial conditions (Bryant, 1989; Payton, 1992) and water-driven collapse deposits (Assallay et al., 1998), including the effect of earthquakes in the liquefaction of waterlogged deposits (Green et al., 2005). Several studies, along with Soil Taxonomy (Soil Survey Staff, 1999), report the relevance of low-crystallinity materials, such as Si, Fe, and Al compounds, regarding expression of two of the most singular properties of a fragic material: breakability under moist conditions, due to sudden rupture of aggregates under pressure (the air is vigorously expelled as the pores are saturated with water); and the soil aggregate slaking after a relatively short time period of water immersion (Norfleet and Karathanasis, 1996; Duncan and Franzmeier, 1999).

Unlike the concept of the fragipan, which does not require the presence of a quantity of Si that characterizes it as a cementing agent, the duripan is necessarily cemented by a silification process (Norton, 1994; Schaetzl and Anderson, 2013). Such a process predominantly occurs in the small pores and in the grain-to-grain contacts, without a total filling of the spaces between grains (Chadwick et al., 1987).

In the coastal tablelands, cemented horizons occur in sandy loam, sandy clay loam, and loamy sand textured soils (their occurrence is uncommon in soils with a texture which approximates sandy clay). They occur in spodic and textural B horizons located in the extensive plateaus with flat relief, mainly when associated with closed depressions (Filizola et al., 2001). The associated climate is humid tropical. However, the occurrence of cemented horizons tends to increase in dry summer conditions, on latitudes north of the city of Salvador, BA (Ribeiro, 1998).

In order to contribute to understanding the processes that regulate the cementation of pedogenetic horizons in the coastal tablelands of Northeastern Brazil, the aim of this study was to analyze the different development conditions of such horizons, and to evaluate the degree of cementation in these soil materials, which were sampled in four pedons. Expression of the degree of cementation was verified according to field morphology and through immersion of parts of the cemented materials in water, as well as in acid and basic solutions. The soil horizons were characterized through morphological, physical, micromorphological, mineralogical, and chemical properties in order to understand the genesis of these cementations.

MATERIALS AND METHODS

Four pedons from the coastal tablelands were selected: sand/sandy-clay-loam *Planossolo Háplico Distrófico espessarênico*, *dúrico*, *espódico* (p-SX); sand/sandy-clay-loam *Espodossolo Humilúvico Órtico dúrico* (p-EK); sandy-loam/sandy-clay-loam *Argissolo Acinzentado Distrocoeso fragipânico* (p-PAC); and sand/sandy-loam *Espodossolo Ferrihumilúvico Órtico dúrico*, *fragipânico* (p-ESK), representing different conditions of expression of the cementation processes (Figure 1).

Tertiary sediments from the Barreiras Formation compose the parent material of all the pedons analyzed. The sites sampled were located from the shoulders to the summits of the landscape, under flat relief, with 0-1 % slope. The soil drainage ranges from moderate to imperfect.

These sediments are mineralogically homogeneous in the clay fraction (extremely kaolinitic, very little oxidic), yet highly variable in particle size (Resende et al., 2011). The areas of Coruripe, Umbaúba, and Acajutiba (p-EK, p-PAC, and p-SX) have a humid tropical climate with dry summers, whereas Nova Viçosa (p-ESK) has a humid tropical climate with no dry season, i.e., the lowest average monthly rainfall is above 60 mm. The coastal tablelands comprise an area of approximately 52,811 km^2 within three

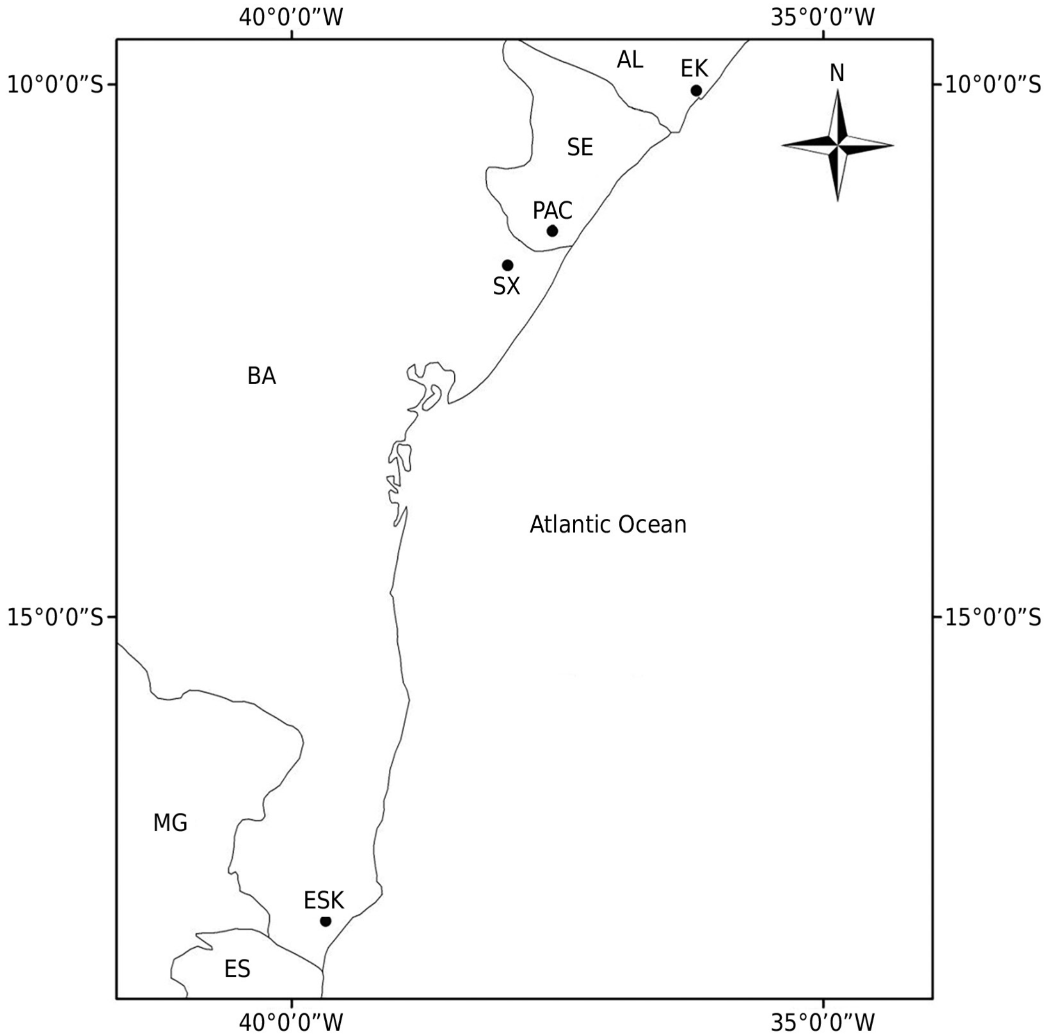

Figure 1. Location of the pedons sampled in the municipalities of Coruripe (AL), Umbaúba (SE), Acajutiba (north of BA), and Nova Viçosa (south of BA). Pedons: SX = sand/sandy clay loam *Planossolo Háplico Distrófico espessarênico*, *dúrico*, *espódico*; EK = sand/sandy clay loam *Espodossolo Humilúvico Órtico dúrico*; ESK = sand/sandy loam *Espodossolo Ferrihumilúvico Órtico dúrico*, *fragipânico*; and PAC = sandy loam/sandy clay loam *Argissolo Acinzentado Distrocoeso fragipânico*.

states (Alagoas, Sergipe, and Bahia) where the pedons were described and sampled (Silva et al., 1993). The Coruripe site (p-EK) is the only area studied under primary forest (Silva et al., 1993). The Acajutiba (p-SX) and Nova Viçosa (p-ESK) areas are under areas planted to eucalyptus, whereas the Umbaúba area (p-PAC) is located in an area planted to 'Pera' orange.

Soil description, sampling and analysis

Pits were dug for morphological description, sampling the horizons of each pedon, and soil classification, which was complemented by laboratory analysis (Santos et al., 2013). Undisturbed soil samples were collected in the horizons selected for micromorphological analysis. Duplicates of disturbed soil samples were also collected, and one sample was kept under refrigeration for extraction of the soil solution. Soil clods were collected from the cemented horizons for immersion tests. In such horizons, as well as in other horizons with hard to extremely hard soil consistency, in which Kopecky ring samples of known volume could not be collected, soil clod samples were also gathered for analysis of bulk density (BD). The disturbed and unrefrigerated soil samples were air-dried, crushed, and sieved (2 mm mesh), in order to obtain Air-Dried Fine Earth (ADFE). Clay samples were separated from the ADFE by sedimentation after chemical dispersion (1 mol L^{-1} NaOH) and were used for X ray diffraction studies (35 kV, 25 mA, and CoKα radiation). Bulk density was determined using the volumetric ring method or the clod method, depending on the sample type (Archer and Smith, 1972). Particle size distribution was determined according to the pipette method (Gee and Bauder, 1986) using a NaOH solution as a chemical dispersant; pH was measured in water and KCl; organic C was determined according to the Walkley and Black method (Walkley, 1946). Ca, Mg, and Al were determined through KCl extraction (McLean et al., 1958); K and Na, through HCl extraction (Mehlich, 1953); H+Al, through a calcium acetate extraction at pH 7 (Shaw, 1959); and P, through extraction by Mehlich-1 (Mehlich, 1953). Iron and Al contents were determined by atomic absorption, using the ADFE after sieving through a 100 mesh, according to the following extraction processes: dithionite-citrate-bicarbonate (Mehra and Jackson, 1960; Jackson, 1974); acid ammonium oxalate (according to the Tamn method); and sodium pyrophosphate, the last two adapted from Wang (1978). Silica was determined in acid ammonium oxalate (Wang, 1978) through plasma spectrometry produced by inductive coupling (ICP-AES). Thin sections were prepared from the undisturbed samples for micromorphological characterization (Murphy et al., 1977; Ringrose-Voase, 1991; Castro et al., 2003). Images were acquired using a Sony® digital camera (DFW-X700 model) coupled to a Zeis® polarizing petrographic microscope. Interpretations followed the terminology defined by Brewer (1976), Bullock et al. (1985), and Lima et al. (1985).

The aqueous solution was extracted from the refrigerated samples through shaking, centrifugation, and extract filtering (soil: water ratio of 1:0.5) (Rhoades, 1982). The extract was used for determining dissolved organic C in a carbon analyzer, and Fe and Al were determined by atomic absorption. For Si analysis, 5 mL of the aqueous extract was mixed with 0.5 mL of 7.5 % sulphomolybdic acid solution (7.5 g of ammonium molybdate + 10 mL of 9 mol L^{-1} sulfuric acid completed to 100 mL with distilled water. After a 10 min resting period, 1 mL of a 20 % tartaric acid solution was added, and after a 5 min resting period, 5 mL of 0.3 % ascorbic acid was added. After 1 h, Si was read in a 600 nm wavelength spectrophotometer.

Immersion test of cemented materials in water and in acid and base solutions

Fragments of seven cemented horizons of 0.05 to 0.1 m in size were immersed in water (8 h) and in solutions of HCl (1, 3, and 6 mol L^{-1}; evaluations at 4, 6, 7, and 8 days) and NaOH (1 and 4 mol L^{-1}; evaluations at 4, 6, 7, and 8 days) and were evaluated according to Araújo Filho (2003).

RESULTS AND DISCUSSION

Soil morphology and physical properties

All the pedons studied had features which relate to drainage impediments. They are located on predominantly flat relief, with some degree of concavity. Features associated with redoximorphic conditions are present, expressed in pale colors, mottlings, and bands of Fe oxide segregation (Table 1, Figure 2). The cemented and/or hardened horizons (apparently cemented) are located in the lower parts of the sequa, coinciding with illuvial horizons.

Of the four soils studied, three had features indicating podzolization in the upper portion of the sequum, with spodic horizons or spodic character beneath the eluvial horizons (Silva et al., 2013). The podzolization process is intense in p-EK and p-ESK and only incipient in the p-SX (not enough to classify it as a Spodosol). The p-PAC presented argilluviation as the main pedogenesis process. The p-SX, p-EK, and p-ESK, which exhibited podzolization, had, below the A horizon, an eluvial E horizon of relatively paler colors in relation to its neighboring horizons, single-grained structure, loose or very friable consistency, and clay contents always below 100 g kg^{-1} (Tables 1 and 2, and Figure 2).

The cemented horizons of p-SX and p-EK (identified as Btgm) displayed both duric character and gleying features. These features occurred beneath the horizons with podzolization in each pedon, acting as an impervious layer at the subsurface and favoring the occurrence of podzolization, which is also favored by other conditions, such as flat relief, concave topography, and sandy-quartzous parent material (Oliveira et al., 2010; Silva et al., 2013). The p-ESK also had flat relief conditions and sandy-quartzous material from p-SX and p-EK, showing, in its lower portion, a C horizon with massive structure and particle size distribution that suggests a lithological discontinuity in relation to the Bsm horizon (Table 2). The podzolization process in p-ESK is of such magnitude that it resulted in cementation of the spodic horizons, both characterized as ortsteins (Bhsx and Bsm), but with a different magnitude of cementation.

The Btgm horizon of the p-EK had thin, cemented, red-colored (10R), and discontinuous plates of a placic horizon within it, which distinguishes it from the Btgm horizon of p-SX, which had only mottles (Table 1).

The p-PAC, a Grayish Argisol, was developed from sediments with quite different clay contents in relation to the other pedons studied (Table 2), and it did not have an eluvial horizon. Cementation occurs in two placic horizons and in the Btx/Bt horizon and is also present in parts of the Bt/Btx horizon. The structure of the non-cemented B horizons (BA1, BA2, Bt, and parts of the Bt/Btx) is typical of Argisols from the coastal tablelands (Ferreira et al., 1999), which are weak, of medium to small size class, subangular, and blocky.

The clay content of the cemented horizons ranged from 90 to 260 g kg^{-1} (Table 2). Variations in the clay content of these horizons have also been recorded in other studies of coastal tableland soils (Figure 3). However, silt content ranged from 10 to 160 g kg^{-1} (Table 2). Some of the results found in other studies (Figure 3) showed silt contents that were quite higher, reaching values above 60 %. Considering the pre-weathered parent material of the coastal tableland soils, it is likely that the high values of silt content found in other studies are related to problems of adequate soil dispersion. In the cemented horizons, in addition to the variation in clay contents, the textural gradient also varied greatly between the horizon immediately above and the cemented horizon (Table 2), reaching a maximum in the p-SX (textural gradient between EBh and Btgm of 3.7).

The cemented horizons, mainly those with a duric character, had higher values of BD than the overlying horizons (Table 2), corroborating the findings from other studies with soils of the coastal tablelands (Filizola et al., 2001; Araújo Filho, 2003; Moreau et al., 2006) and with fragipans formed in glacial deposits (Habecker et al., 1990; Weisenborn and

Table 1. Morphological properties of the horizons from the studied pedons

Horizon	Depth	Predominant colors (moist)	Mottlings (moist color)[3]	Predominant structure[4]	Secondary structure[4]	Consistency (moist)
	m					
SX profile – *Planossolo Háplico Distrófico espessarênico, dúrico, espódico*; moderately well to somewhat poorly drained, sand/sandy clay loam						
Ap	0.00 - 0.18 (0.15)	10YR 5/3	-	single grain	-	loose
EA1	0.18 (0.15) - 0.60	10YR 6/3	f, medium, faint, 10YR 7/3	single grain	-	loose
EA2	0;60 - 0.98 (1.15)	10YR5/3	f, medium, faint, 10YR 7/3	single grain	-	very friable
E	0.98 (1.15) - 1.49 (1.6)	2.5Y 6/2	-	single grain	-	very friable
EBh	1.49 (1.6) - 1.75 (1.85)	10YR 4/2	-	massive	-	very friable
Btgm	1.75 (1.85) - 2+	10YR 7/2	c, m-c, faint, 10YR 5/4 and 7.5YR 5/4	massive	-	extremely firm
EK profile – *Espodossolo Humilúvico Órtico dúrico*; somewhat poorly drained, sand/sandy clay loam						
O	-0.05 - 0.00	10YR 3/1	-	-	-	-
A	0.00 - 0.08	10YR 4/1	-	single grain	w-m f-m g	loose
E	0.08 - 0.5	10YR 4/3	-	single grain	-	loose
BhE	0.5 - 0.6 (0.7)	10YR 3/3.5	-	single grain	w f-m sb	very friable
Bh1	0.6 (0.7) - 0.85	10YR 3/2.5	-	single grain	w f-m sb	very friable
Bh2	0.85 - 0.95 (1.1)	10YR 3/2	-	single grain	w f-m sb	very friable
Btgm	0.95 (1.1) - 1.4+	10YR 7/3	-	massive	-	extremely firm
Placic[1]	~1.2	10R 3/2. 10R 4/6	-	massive	-	very firm
ESK profile – *Espodossolo Ferrihumilúvico Órtico dúrico, fragipânico*; moderately well to somewhat poorly drained, sand/sandy loam						
Ap	0.0 - 0.2	10YR 3/2	-	single grain	-	loose
E	0.2 - 0.48	10YR 6/2	-	single grain	-	loose
Bh	0.48 - 0.54 (0.6)	10YR 3/3	-	single grain	w f-m sb	very friable
Bhsx	0.54 (0.6) - 0.8 (0.95)	7.5YR 3/2	-	massive	-	very firm
Bsm	0.8 (0.95) - 1.25	2.5Y 7/6. 2.5YR ¾	-	massive	weak fine-very fine platy	extremely firm
2C	1.25 - 1.8+	10YR 7/6	c, coarse, prominent, 2.5YR 4/6	massive	-	extremely firm
PAC profile – Argissolo Acinzentado Distrocoeso fragipânico; moderately well to somewhat poorly drained, sandy loam/sandy clay loam						
Ap	0.00 - 0.13	10YR 3/2	-	m f-vf g	single grain	very friable
BA1[2]	0.13 - 0.36	10YR 4/2.5	c, f-m, distinct, 10YR 7/3	weak medium block subangular	-	friable
BA2[2]	0.36 - 0.49	10YR 4/3	f, f-m, distinct, 10YR 7/3	w m-c sb	-	friable
Bt	0.49 - 0.65 (1.05)	10YR 4.5/3	-	w m-c sb	-	very friable
Btx/Bt	0.66 (1.06) - 1.16 (1.46)	2.5Y 7.2	c, m-c, prominent, 2.5YR 4/5	massive	-	very firm/firm
Bt/Btx	1.16 (1.46) - 2.00+	10YR 6/6. 10YR 5/3	c, m-c, prominent, 10R 3/4	w m-c sb	massive	very friable/very firm
Placic[1]	0.66 (1) and 1.16 (1.46)	10R 3/2. 10R 4/6	-	massive	-	extremely firm

[1] Placic: occurs in an irregular and wavy form, with 1.0-15 mm thickness. They are very discontinuous in the EK profile (see figure 2). [2] BA1 and BA2 horizons of the PAC profile have a cohesive character of intermediate expression. [3] Mottling (quantity, size, contrast, and color): few = f; common = c; fine-medium = f-m; medium-coarse = m-c. [4] Structure (grade. size, and type): weak = w; moderate = m; very fine = vf; fine = f; medium = m; coarse = c; granular = g; subangular block = sb.

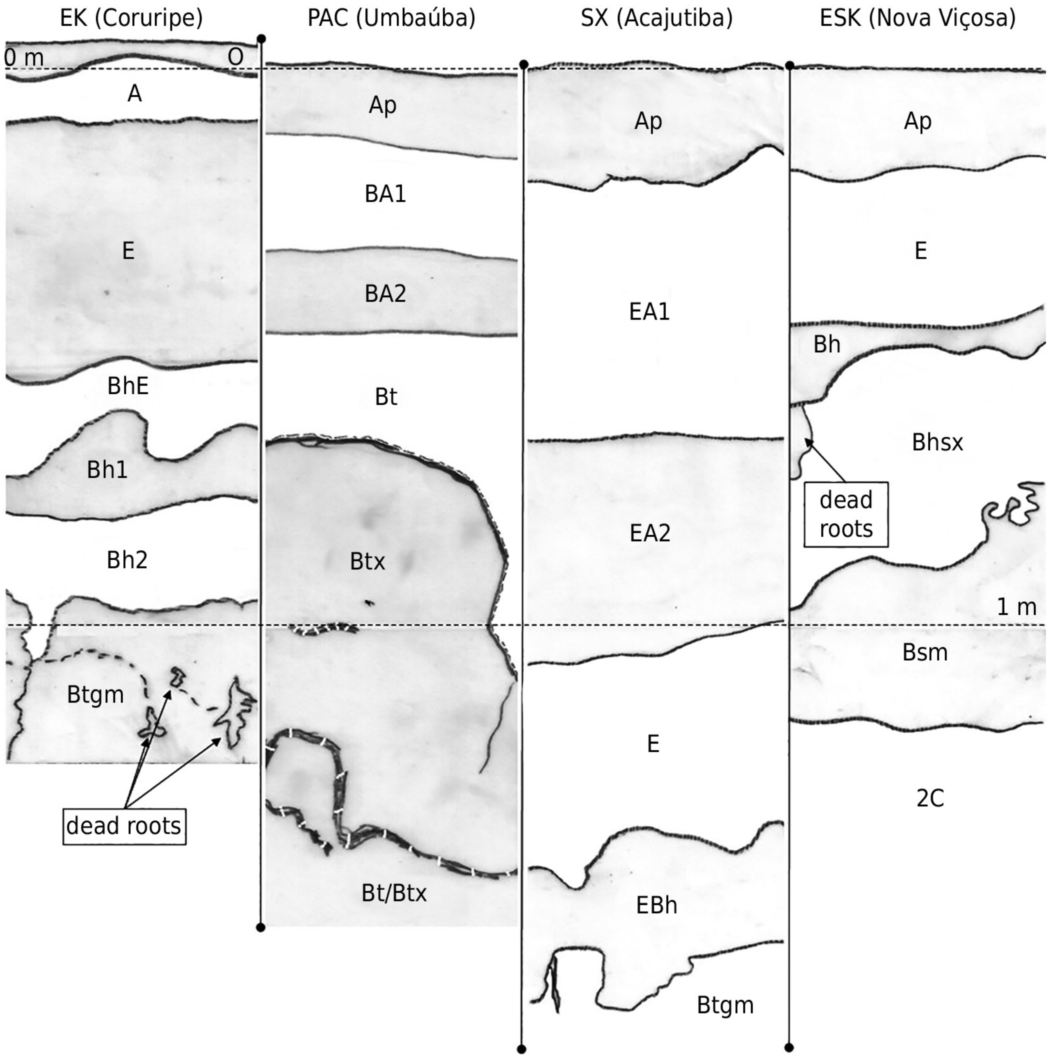

Figure 2. Sketch of the horizon sequence in the soil profiles studied (EK = sand/sandy clay loam *Espodossolo Humilúvico Órtico dúrico*; PAC = sandy loam/sandy clay loam *Argissolo Acinzentado Distrocoeso fragipânico*; SX = sand/sandy clay loam *Planossolo Háplico Distrófico espessarênico, dúrico, espódico*; and ESK = sand/sandy loam *Espodossolo Ferrihumilúvico Órtico dúrico, fragipânico*). Dotted lines represent the material of the placic horizons. Horizons with subscript “x” and “m” represent apparent cementation (fragipan or ortstein) and extreme cementation (duric character, or, concomitantly, an ortstein), respectively.

Schaetzl, 2005). The horizons with duric character had the highest values of BD. In the p-PAC, BD values in the BA1 and BA2 horizons (of 1.69 and 1.67 Mg m^{-3}, respectively) were greater than in the horizons with fragic materials (Btx and Bt/Btx, of 1.56 and 1.49 Mg m^{-3} respectively). These higher BD values in the horizons with cohesive character, as in the BA1 and BA2 horizons of the p-PAC, are typical of soils from the coastal tablelands, regardless of the presence of cemented horizons (Jacomine, 2001; Araújo Filho, 2003).

Micromorphological properties

The skeleton of all the cemented horizons is dominated by quartz grains. Analysis of the micrographs from these horizons showed the predominance of a low porosity matrix, in accordance with the BD values (Table 2). Porosity is relatively greater in the horizons with the “x” subscript (the Btx/Bt horizon from p-PAC and the Bhsx horizon from p-ESK) than in the horizons with a duric character (the Btgm horizon from p-SX and p-EK).

The horizons with a duric character had several micromorphological features in common: porphyric distribution, with some portions more open and others more closed; predominance

Table 2. Soil texture and bulk density of the horizons from the studied pedons

Profile	Horizon	Coarse sand	Fine sand	Silt	Clay	Texture class	Bulk density
		g kg^{-1}					Mg m^{-3}
SX	Ap	510	420	40	30	sand	-
	EA1	540	390	20	50	sand	-
	EA2	530	360	50	60	sand	-
	E	550	340	60	50	sand	-
	EBh	500	410	20	70	sand	1.84
	Btgm	330	260	150	260	sandy clay loam	1.95
EK	A	680	260	10	50	sand	-
	E	600	270	40	90	loamy sand	1.66
	BhE	640	180	40	140	sandy loam	1.48
	Bh1	540	240	60	160	sandy loam	1.39
	Bh2	480	290	50	180	sandy loam	1.42
	Btgm	510	240	50	210	sandy clay loam	1.84
ESK	Ap	560	310	60	70	loamy sand	1.53
	E	600	320	30	50	sand	1.66
	Bh	550	330	30	90	loamy sand	1.47
	Bhsx	500	320	50	130	sandy loam	1.60
	Bsm	490	310	110	90	loamy sand	1.81
	2C	380	250	130	240	sandy clay loam	1.70
PAC	Ap	480	210	160	150	sandy loam	1.54
	BA1	470	230	70	230	sandy clay loam	1.69
	BA2	360	250	80	310	sandy clay loam	1.67
	Bt	330	260	40	370	sandy clay	1.41
	Btx/Bt	360	320	120	200	sandy clay loam	1.56
	Bt/Btx	330	280	160	230	sandy clay loam	1.49

of massive microstructure (apedal features); segregation of Fe oxides; planes pores; and argilluviation features, as seen in the microlamination of the clay coatings (Figures 4a, 4b, and 4c).

The two horizons with milder cementation ("x" subscript) differed from each other in texture and in the major pedogenetic process type, podzolization in the Bhsh horizon from p-ESK, and argilluviation in the Btx/Bt horizon from p-PAC. The fragipan from p-PAC (Btx/Bt horizon) had both harder and softer portions. In its hardest parts, it had porphyric distribution with simple spaces and distinct lines of Fe oxide segregation, with portions coinciding with limits of voids (Figure 5a). The ortstein from p-ESK (Bhsx horizon) had enaulic distribution with chitonic portions and skeleton (which predominates over the matrix) with strong organic matter coatings (Figures 5b and 5c), in addition to a partial filling of the inter-grain space with microaggregates of fine material rich in organic matter. The fragipans from p-ESK and p-PAC have features common to the fragipans of the northern hemisphere: both have a well-distributed fabric, without pore interruptions; coated pores without fillings are common in the Btx/Bt horizon from p-PAC; and in the Bhsx horizon from p-ESK, bridges between grains are common (Miller et al., 1993; James et al., 1995; Weisenborn and Schaetzl, 2005).

No features indicating silica were found in the micrographs. Observation of micromorphological evidence for silica cementation, even in duripans, can be impeded by the close relationship of silica with ferriargillans and clays of these horizons (Torrent et al., 1980). However, this evidence is commonly described in micrographs and in electron microscopy images of horizons with duripans or with some degree of silica cementation (Chadwick et al., 1987;

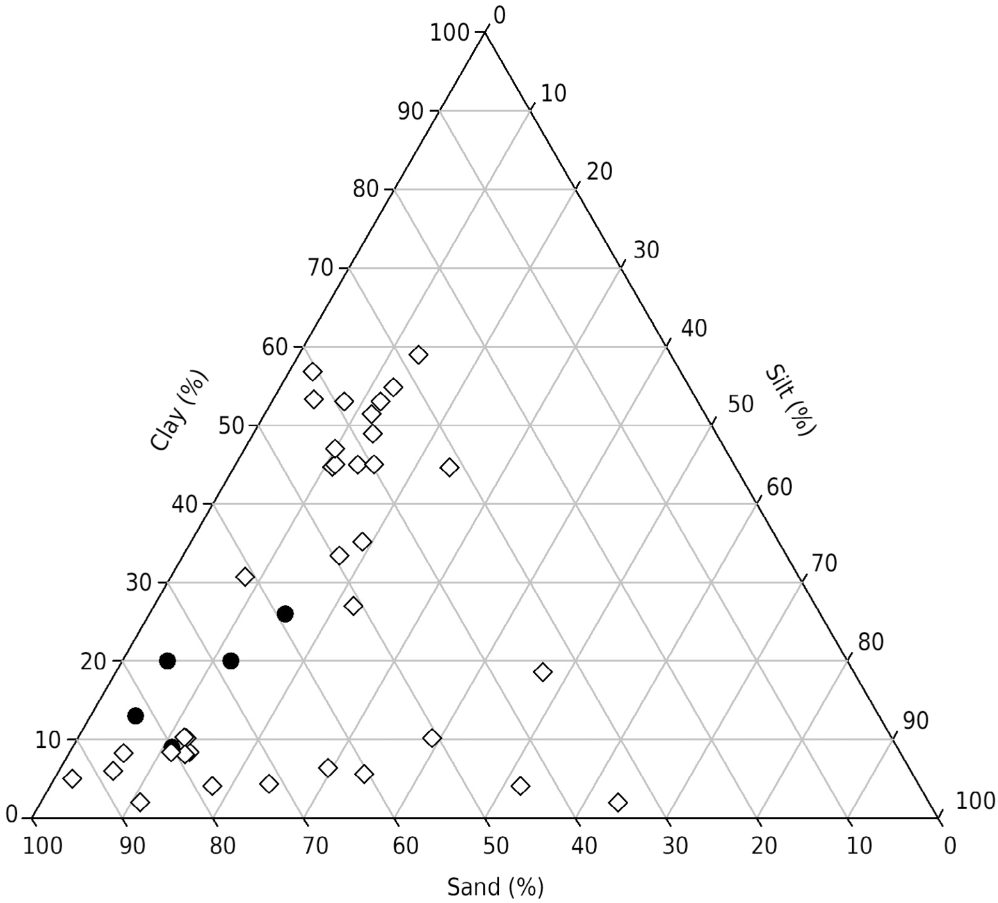

Figure 3. Texture ternary graph of the cemented horizons from this study (•) and from other studies (◇), all in soils of the coastal tablelands (Filizola et al., 2001; Araújo Filho, 2003; Moreau et al., 2006).

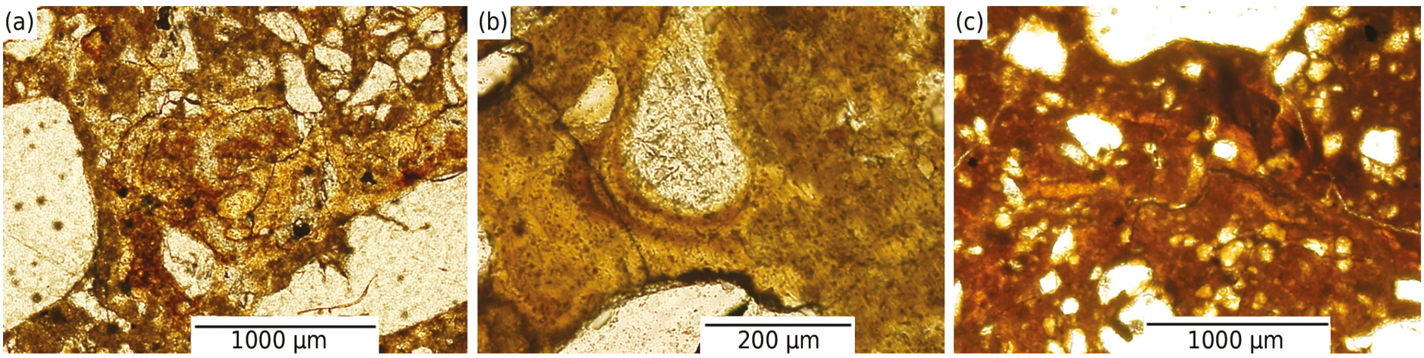

Figure 4. Micrographs (under planar polarized light) of selected micromorphological features from Btgm cemented horizons. (a) EK profile: predominance of single-spaced porphyric distribution, with closed porphyric parts (right side, above); low porosity (planes pores); and matrix with segregation of Fe oxides (central part of the photo). (b) EK profile: pore with oriented clay (argilluviation process). (c) SX profile: single-spaced porphyric distribution; segregation of Fe oxides in several parts of the thin section; low porosity (planes pores).

Boettinger and Southard, 1990; Creutzberg et al., 1990; Hollingsworth and Fitzpatrick, 1994; Moody and Graham, 1997; Gutiérrez-Castorena and Effland, 2010).

Iron segregation bands were conspicuous in the cemented horizons from p-EK and p-PAC (Figures 4a and 5a), corroborating the diagnosis of the placic horizons in these pedons (Figure 2 and Table 1). Fe segregation features were found in a lower degree in the micrograph of the Btgm horizon from p-SX (Figure 4c), confirming the mottling identified in the morphological description made in the field (Table 1).

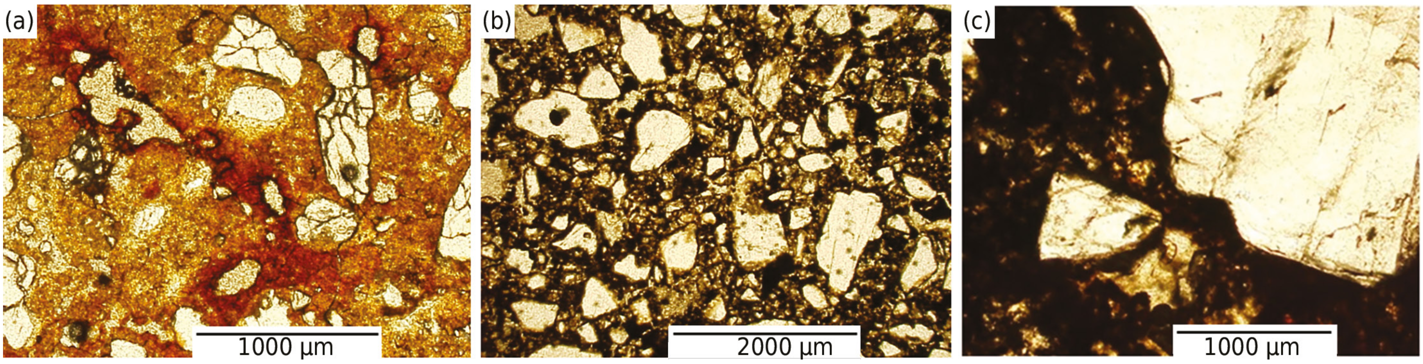

Figure 5. Micrographs (under planar polarized light) of selected micromorphological features from cemented horizons with "x" subscript (fragipan and ortstein). (a) PAC profile, Btx/Bt horizon (cemented part) - single-spaced porphyric distribution; vughs pores; and Fe oxides segregation line, including the border of pores. (b) ESK profile, Bhsx horizon - enaulic distribution with chitonic parts; quartz grains with continuous dark coating (organic matter). (c) ESK profile, Bhsx horizon - strong filling of the space between grains with microaggregates of fine material rich in organic matter.

Clay mineralogy

Except in the placic horizons from p-PAC, the clay fraction mineralogy of the cemented horizons studied was widely dominated by kaolinite, in agreement with data from the literature on coastal tableland soils (Moreau et al., 2006; Gomes et al., 2008, 2012) and also for the cemented horizons which occur there (Filizola et al., 2001; Araújo Filho, 2003; Moreau et al., 2006). Both placic horizons from p-PAC had a more complex assemblage, with detection of quartz, kaolinite, goethite, hematite, and ilmenite (Figure 6). In the cemented horizons (except for the placic horizons from p-PAC), a background could be noted in the clay fraction diffractograms, which can be associated with the presence of minerals with a low degree of crystallinity (Klug and Alexander, 1974) and, consequently, with the contents of Fe, Al, and Si extracted by acid ammonium oxalate (Table 3).

Immersion tests of cemented materials in water and in acid and basic solutions

Immersion tests in water were the criterion used to define the duric character in the Btgm horizons from p-SX and p-EK and in the Bsm horizon from p-ESK, and they served to confirm the field soil morphology description (Table 4).

In the acid solution immersion, the greatest resistance to slaking occurred in the fragments of the Btgm horizon from p-EK and in the Bsm horizon from p-ESK. The fragments of the Btgm horizon from p-EK were the only ones in which the slaking did not occur completely after 8 days of immersion in 4 mol L^{-1} NaOH solution.

From the immersion tests, the cemented horizons studied exhibited the following descending order regarding their degree of cementation: Btgm - p-EK > Bsm - p-ESK> Btgm - p-SX > deeper placic - p-PAC = shallower placic - p-PAC = Btx/Bt - p-PAC > Bhsx - p-ESK. These results are similar to those observed by Araújo Filho (2003) in the immersion tests of cemented materials of soils from the coastal tablelands of Alagoas.

pH and contents of Fe, Al, and Si in different extractions and in aqueous solution

The variations of pH were small, between 4.7 and 5.9 for all the horizons and between 4.7 and 5.5 for the cemented horizons (Table 3); pH values were relatively lower in the cemented horizons in relation to the overlying horizons, which differs from the data reported for soils with fragipan in glacial deposits by Miller et al. (1993) and Weisenborn and Schaetzl (2005).

Most often, maximum values of Fe, Al, and Si in the different extractions occurred in the cemented horizons, whether spodic or not. This trend is very clear in p-SX, p-ESK, and p-PAC and quite subtle in p-EK (Table 3). In the aqueous solution extracts, only the values of Si (Sih) showed a noticeable accumulation in the cemented horizons, excluding the fragipan horizon from p-PAC.

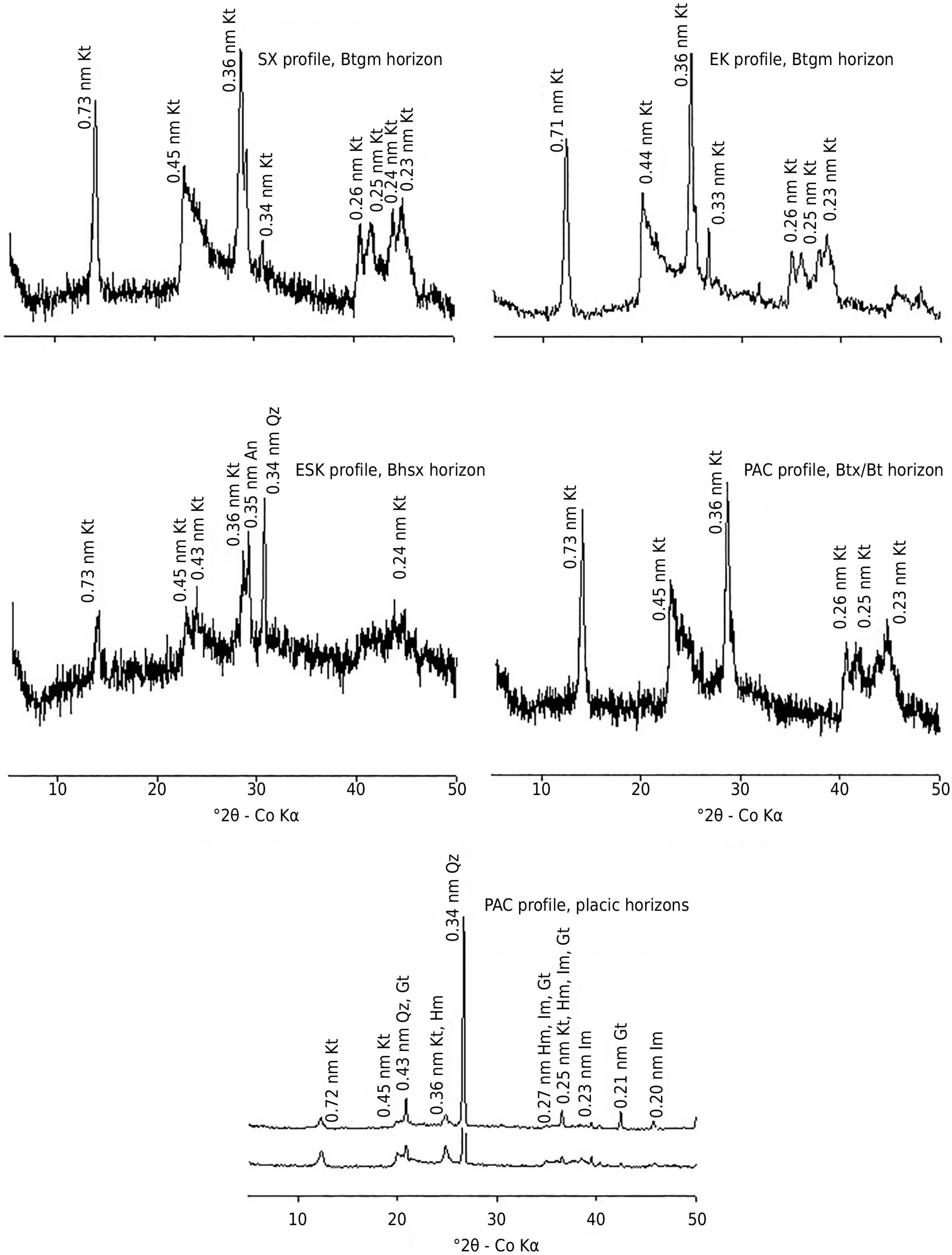

Figure 6. X rays diffractograms of clay samples saturated with Na^+ from the cemented horizons of the soil profiles studied. An: anatase, Gt: goethite, Hm: hematite, Kt: kaolinite, Qz: quartz, Im: ilmenite.

Table 3. Chemical analyses of the genetic horizons from the soil profiles

Horizon	pH(H_2O)	OC	DOC	Fe_d (1)	Al_d	Fe_o (2)	Al_o	Si_o	Fe_p (3)	Al_p	Fe_h (4)	Al_h	Si_h
		g kg^{-1}	mg kg^{-1}	g kg^{-1}							mg kg^{-1}		
SX profile													
Ap	5.2	10.4	15.4	0.06	0.18	0.05	0.31	0.29	0.06	0.25	0.03	0.28	0.00
EA1	5.6	3.5	4.7	0.04	0.40	0.05	1.03	0.76	0.04	0.72	0.01	0.72	0.00
EA2	5.4	5.2	5.2	0.08	2.29	0.08	7.81	3.47	0.07	2.42	0.00	0.00	0.00
E	5.6	2.9	2.4	0.02	0.84	0.04	2.38	0.95	0.04	1.33	0.00	0.00	0.00
EBh	5.3	5.2	2.6	0.00	2.11	0.04	7.31	2.19	0.03	2.42	0.01	0.00	0.15
Btgm	5.0	3.5	3.0	0.00	3.84	0.03	10.86	5.07	0.02	3.25	0.00	0.00	0.40
EK profile													
A	5.1	9.3	20.6	0.17	0.40	0.10	0.58	0.03	0.08	0.56	0.24	1.49	0.10
E	5.3	4.6	9.0	0.31	0.61	0.26	0.92	0.16	0.16	0.47	0.08	1.01	0.10
BhE	5.4	12.8	10.5	0.65	5.21	0.92	6.16	0.18	1.28	5.06	0.04	0.95	0.10
Bh1	5.5	19.1	10.4	0.43	10.04	0.70	16.75	0.34	0.30	10.81	0.03	0.47	0.05
Bh2	5.3	15.1	7.1	0.30	8.85	0.52	15.36	0.54	0.22	16.16	0.01	0.02	0.05
Btgm	5.2	4.6	4.4	0.74	3.55	0.87	13.96	0.58	1.04	2.59	0.01	0.00	0.80
ESK profile													
Ap	4.7	7.0	26.6	0.06	0.35	0.05	1.72	2.79	0.04	0.73	0.07	0.94	0.10
E	5.0	5.2	13.4	0.01	0.08	0.01	0.10	0.22	0.02	0.13	0.09	0.47	0.00
Bh	4.8	11.6	20.3	0.15	1.20	0.14	2.05	1.43	0.13	1.14	0.01	0.53	0.05
Bhsx	4.7	25.5	8.9	5.32	20.91	3.79	24.99	10.40	7.33	7.18	0.01	0.30	0.35
Bsm	5.1	12.8	6.6	15.97	21.42	9.31	40.24	44.85	9.12	11.83	0.01	0.35	0.51
2C	4.8	0.6	3.2	13.05	2.98	0.62	4.64	1.40	1.97	1.09	0.01	0.00	0.10
PAC profile													
Ap	5.5	11.6	10.8	1.26	0.53	0.59	0.77	0.19	1.00	0.36	0.13	1.26	0.00
BA1	5.9	6.4	10.9	1.65	0.72	0.77	0.99	0.02	1.67	0.50	0.02	2.30	0.00
BA2	5.8	5.8	17.8	3.21	1.34	0.86	1.65	0.03	2.49	0.84	0.02	5.15	0.00
Bt	5.4	3.5	4.6	3.31	1.35	1.82	1.69	0.03	2.27	0.76	0.02	0.84	0.00
Btx/Bt	5.5	8.7	4.8	4.86	8.98	3.58	31.94	1.74	5.52	4.24	0.02	0.34	0.00
Bt/Btx	5.4	4.6	5.5	7.68	5.62	2.31	12.15	0.60	3.94	2.23	0.02	0.49	0.15

DOC: dissolved organic carbon. (1) Fe_d and Al_d: Fe and Al extracted by Na citrate-dithionite-bicarbonate. (2) Fe_o, Al_o and Si_o: Fe, Al, and Si extracted by acid ammonium oxalate. (3) Fe_p and Al_p: Fe and Al extracted by Na-pyrophosphate. (4) Fe_h, Al_h and Si_h: Fe, Al, and Si in aqueous solution.

Table 4. Evaluation of crumbling of cemented materials in water and in acid and basic solutions

Profile	Horizon	Water after 8 h	HCl						NaOH			
			1 mol L^{-1}		3 mol L^{-1}		6 mol L^{-1}		1 mol L^{-1}		4 mol L^{-1}	
			4 days	8 days	4 days	8 days	4 days	8 days	4 days	8 days	4 days	8 days
			%									
SX	Btgm	absent	23	45	90	100	-	-	100	-	-	-
EK	Btgm	absent	4	13	7	30	10	40	10	60	40	80
ESK	Bhsx	strong	100	-	-	-	-	-	65	100	-	-
ESK	Bsm	absent	13	23	23	60	28	70	53	90	23	95
PAC	Btx/Bt	strong	20	40	100	-	-	-	60	100	-	-
PAC	More superficial placic	strong	55	80	100	-	-	-	65	100	-	-
PAC	Deeper placic	strong	30	80	100	-	-	-	45	100	-	-

It is important to notice that in p-SX, p-EK, and p-ESK, the spodic or transitional to spodic horizons, which are overlying the cemented horizons, are also accumulating Fe and Al, mainly associated with organic matter, which also occurs in the cemented and spodic horizons from p-ESK (Table 3). These results indicate the current condition of the podzolization process in those sites. Not only should the relative accumulation in the cemented horizon be considered, but also the absolute values from the extraction, especially in p-SX, p-EK, and p-ESK formed in sandy-quartzous sediments and with the simultaneous podzolization process. In any case, in the cemented Btgm horizon, p-EK has higher values for Fe and Si in relation to the overlying Bh1and Bh2 horizons, in addition to a significant absolute value of Al_o (13.96 g kg^{-1}), very close to the values from Bh1 and Bh2.

The absolute Al_o contents were high in all the cemented horizons, while the contents of Fe_o and Si_o were variable; for Fe_o, contents decreased in the following order: p-ESK > p-PAC > p-EK > p-SX; and for Si_o, they decreased in the following order: p-ESK > p-SX > p-PAC > p-EK. Therefore, the results observed reinforce the generalized importance of Al compounds with a low degree of crystallinity in the genesis of ortstein, fragipan, and duripan horizons in coastal tableland soils (Araújo Filho, 2003; Lima Neto et al., 2010; Corrêa et al., 2015). However, they also demonstrate that Fe and Si compounds with a low degree of crystallinity also take part in the process to a varied extent, an aspect which was also pointed out by Corrêa et al. (2015). Some hypothesis can explain the origin of Si acting in the genesis of these horizons: dissolution (by hydrolysis) of kaolinite, which is accelerated by the local redoximorphic conditions, being translocated downwards into the pedon (Duncan and Franzmeier, 1999); lateral transport, originating from soils (mainly Argissolos Amarelos and Latossolos Amarelos) that occur in the surroundings of the gentle depressions of the landscape (Moreau et al., 2006; Oliveira et al., 2010); and weathering of very small size quartz (Resende et al., 1988).

Processes of formation of cemented horizons

Three conditions favor or are even required for the development of pans and/or other cementations in soils from the Brazilian coastal tablelands, and they have already been discussed in previous studies (Boulet et al., 1998; Filizola et al., 2001; Moreau et al., 2006): flat or almost flat relief, with a tendency to form depressions; a water regime with seasonal periods of water excess in the pedon (redoximorphic conditions); and a sedimentary substrate with low clay contents (or the relief and the water regime conditions favor kaolinite hydrolysis). The well-defined dry period seems to increase the incidence or degree of the pans/cementations in these ecosystems. In the case of coastal tablelands under forest vegetation,(in which a shrub-like vegetation, known locally as "restinga", can also occur), the dry season often coincides with the summer and repeats one of the conditions stated by Franzmeier et al. (1989) as favorable to the formation process of fragipans in the mid-western United States. Podzolization can occur, favored by cementation in the lower parts of the pedons, or it can also be simultaneous, with the spodic horizon being cemented (Silva et al., 2012). The redoximorphic conditions cause strong dissolution and migration of Fe oxides, often forming iron bands. Soil development in sedimentary deposits with higher clay contents tends to decrease the effectiveness of the cementation process by compounds with a low degree of crystallinity in two ways: through the larger surface area of the sediment to be cemented and through the greater occurrence of expansion and contraction events (Smeck et al., 1989).

Opposing some studies about fragipans developed under periglacial conditions (Payton, 1992, 1993; Weisenborn and Schaetzl, 2005), the values of Fe, Al, and Si obtained in this study from different extractions increased in the fragipan (p-PAC) in relation to the horizon overlying it. Some micromorphologial features are common to these soil profiles, such as the constant presence of coated and unfilled pores, ferri-argillans, and matrix with intense Fe diffusion resulting from redoximorphic conditions, which form the placic horizons.

The p-SX and p-EK exhibited a horizon with duric and gleyed characters. In these horizons, pale colors and argilluviation cutans predominated, and Fe diffusion zones were common (Figure 4). In the p-EK, as well as in the p-PAC, these Fe diffusion zones constituted Fe segregation lines, which are in fact pieces of the placic horizon. In the horizons with a duric character from both profiles, the cementing action of Al (formed with a low degree of crystallinity) and, to a lesser extent, of Si, was evident (Table 3). Horizons with some degree of podzolization occurred, overlaying the horizons with duric character.

In p-ESK, the massive structure (coherent) horizon 2C must have favored podzolization, and this process culminated in the formation of cemented spodic horizons (ortsteins). The deepest spodic horizon of this pedon still has a duric character. The values from different extractions of Fe, Al, and Si in these horizons indicate the occurrence of both the podzolization and cementation process (Table 3).

Practical Applications

The pans and the other forms of cementation in the four pedons studied were found below the cultivated soil layer (Table 1). Therefore, the soil limitations which can be associated with these features will generally be related to seasonal water excess. The extent of the limitation caused by water excess (oxygen deficiency) in the soil will depend on the degree of cementation, the depth of the cemented horizon, and the relief.

The p-EK site is located in a gentle depression, under forest vegetation, and with a seasonal water excess that is strong enough to restrict agricultural use in the area. The combination of a strong degree of cementation (duric character) with the small depth of the cemented horizon (0.95 m) and the flat and concave topography imposes a greater oxygen deficiency restriction (water excess) on the p-EK in comparison to the other soils studied, regardless of the fact that the primary vegetation found in the area is protected by law. In most cases, soils with a subsurface pan layer that are located on closed depressions, or on depressions associated with headwaters, are restricted from any agricultural activity, either by law or by suitability.

The p-SX and p-ESK are cultivated with eucalyptus. The presence of diffuse mottles in the EA1 and EA2 horizons of p-SX indicates a slight seasonal water excess during the rainy season. The aspect of the area planted to eucalyptus during the survey period and the greater depth of the Btgm cemented horizon (which starts at 1.75 m) indicate that limitations associated with water excess are only moderate in the area. Given that the soil texture is sandy up to the depth of the Btgm horizon, agricultural restriction of the p-SX is mostly linked to water deficiency in the soil. This restriction is attenuated by the water conservation environment provided by the system, due to flat relief and the presence of the cemented horizon, especially for forests (such as the areas planted to eucalyptus), which have a deep root system. In comparison to the p-SX, the p-ESK has the disadvantage of a shallower cemented horizon, located at a depth of 0.54 cm. Therefore, the latter pedon may induce antagonistic forms of plant stress due to water excess or water deficiency, depending on the annual rainfall distribution. During the period under study, the areas planted to eucalyptus in the p-ESK area displayed gaps and nonuniform development.

The p-PAC has two main differences in relation to the other soils studied: a clayier texture on the whole soil profile and a lighter degree of cementation (placic horizons and fragipan, both discontinuous). The area is located in an area planted to ‘Pera’ orange, and the plants are in the adult phase. Flat relief combined with the presence of subsurface obstructive layers generates an environment which tends to conserve soil moisture, particularly considering the clayier texture starting from the soil surface. The yield and the quality of the area planted to ‘Pera’ orange in the region are limited by intense water deficit during the summer, typical of the local climate. However, seasonal water excess also leads to plant anoxia, with the placic and fragipan (Btx) horizons beginning at a depth of 0.66 m.

CONCLUSIONS

The presence of argillans in all the cemented horizons, regardless of the presence of podzolization (in the case of the ortstein horizons), makes it possible to classify such horizons as illuvial.

The cemented horizons are predominantly apedal and have a slightly porous matrix.

Kaolinite dominates the mineralogy of the clay fraction of all the horizons of the soil profiles studied.

The extractions of metals and Si, predominantly by acid ammonium oxalate, were effective at highlighting the influence of low crystallinity compounds in the morphology of the cemented horizons, especially the Al compounds. Although highly variable in absolute terms, the values obtained by acid ammonium oxalate extraction and, partially, in the aqueous solution showed that Si tends to accumulate in the cemented horizons rather than in the overlying horizons. The Fe from the different extractions tends to accumulate in a distinct manner in the cemented soil horizons.

ACKNOWLEDGMENTS

The authors are thankful for financial support from the National Council for Scientific and Technological Development (CNPq), process number 472370/2006-5; and from Embrapa, Macroprogram 2 (02.05.1.16 and 02.12.01.036).

REFERENCES

Aide M, Marshaus A. Fragipan genesis in two Alfisols in east central Missouri. Soil Sci. 2002;167:453-64. doi:10.1097/00010694-200207000-00004

Araújo Filho JC. Horizontes cimentados em Argissolos e Espodossolos dos tabuleiros costeiros e em Neossolos Regolíticos e Planossolos da depressão sertaneja no Nordeste do Brasil [tese]. São Paulo: Universidade de São Paulo; 2003.

Araújo Filho JC, Lopes OF, Oliveira NMB, Nogueira LRQ, Barreto AC. Levantamento de reconhecimento de média intensidade dos solos da região dos tabuleiros costeiros e da baixada litorânea do estado de Sergipe. Rio de Janeiro/Aracaju: Embrapa Solos/Embrapa Tabuleiros Costeiros; 1999. (Boletim de Pesquisa, 4).

Archer JR, Smith PD. The relation between bulk density, available water capacity, and air capacity of soils. J Soil Sci. 1972;23:475-80. doi:10.1111/j.1365-2389.1972.tb01678.x

Assallay AM, Jefferson IF, Rogers CDF, Smalley IJ. Fragipan formation in loess soils: development of the Bryant hydroconsolidation hypothesis. Geoderma. 1998;83:1-16. doi:10.1016/S0016-7061(97)00135-3

Boettinger JL, Southard RJ. Micromorphology and mineralogy of a calcareous duripan formed in granitic residuum, Mojave Desert, California, USA. In: Douglas LA, editor. Soil micromorphology. Amsterdam: Elsevier; 1990. p.409-15.

Boulet R, Fritsch E, Filizola HF, Araújo Filho JC, Leprun JC, Barreto F, Balan E, Tessier D. Iron bands, fragipans and duripans in the northeastern plateaus of Brazil - properties and genesis. Can J Soil Sci. 1998;78:519-30.

Brewer R. Fabric and mineral analysis of soils. New York: R.E. Krieger; 1976.

Bryant RB. Physical processes of fragipan formation. In: Smeck NE, Ciolkosz EJ, editors. Fragipans: their occurrence, classification, and genesis. Madison: Soil Science Society of America; 1989. p.141-50. (SSSA Special Publication, 24).

Bullock P, Fedoroff N, Jonjerius A, Stoops G, Tursina T. Handbook for soil thin section description. Wolverhampton: Waine Research Publications; 1985.

Castro SS, Cooper M, Santos MC, Vidal-Torrado P. Micromorfologia do solo: bases e aplicações. Tópicos Cienc Solo. 2003;3:107-64.

Certini GC, Ugolini FC, Taina I, Bolla G, Corti G, Tescari G. Clues to the genesis of a discontinuously distributed fragipan in the northern Apennines, Italy. Geoderma. 2007;69:161-9. doi:10.1016/j.catena.2006.05.005

Chadwick OA, Hendricks DM, Nettleton WD. Silica in duric soils: I. A depositional model. Soil Sci Soc Am J. 1987;51:975-82. doi:10.2136/sssaj1987.03615995005100040028x

Corrêa MM, Ker JC, Araújo Filho JC, Camêlo DL. Formas de ferro, silício e, ou, alumínio na gênese de fragipãs e horizontes coesos dos tabuleiros costeiros. Rev Bras Cienc Solo. 2015;39:940-9. doi:10.1590/01000683rbcs20140679

Creutzberg D, Kauffmani JH, Bridges EM, Del Posso MG. Micromorphology of “Cangahua”: a cemented subsurface horizon in soils from Ecuador. Develop Soil Sci. 1990;19:367-72. doi:10.1016/S0166-2481(08)70349-0

Curi N, Ker JC. Levantamento pedológico de áreas da Aracruz Celulose S.A. nos estados da Bahia, Espírito Santo e Minas Gerais e sua interpretação para o cultivo de eucalipto e para o ambiente em geral. Lavras/Viçosa: UFLA/UFV; 2004.

Duncan MM, Franzmeier DP. Role of free silicon, aluminum, and iron in fragipan formation. Soil Sci Soc Am J. 1999;63:923-9. doi:10.2136/sssaj1999.634923x

Ferreira MM, Fernandes B, Curi N. Mineralogia da fração argila e estrutura de Latossolos da região Sudeste do Brasil. Rev Bras Cienc Solo. 1999;23:507-14. doi:10.1590/S0100-06831999000300003

Filizola HF, Lamotte M, Fritsch E, Boulet R, Araújo Filho JC, Silva FBR, Leprun JC. Os fragipãs e duripãs das depressões dos Tabuleiros Costeiros do Nordeste brasileiro: uma proposta de evolução. Rev Bras Cienc Solo. 2001;25:947-63. doi:10.1590/S0100-06832001000400018

Franzmeier DP, Norton LD, Steinhardt GC. Fragipan formation in loess of the midwestern United States. In: Smeck NE, Ciolkosz EJ, editors. Fragipans: their occurrence, classification, and genesis. Madison: Soil Science Society of America; 1989. p.69-97.

Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis. Physical and mineralogical methods. 2nd ed. Madison: American Society of Agronomy; 1986. Pt 1. p.383-411.

Gomes JBV, Bolfe EL, Curi N, Fontes HR, Barreto AC, Viana RD. Variabilidade espacial de atributos de solos em unidades de manejo em área piloto de produção integrada de coco. Rev Bras Cienc Solo. 2008;32:2471-82. doi:10.1590/S0100-06832008000600024

Gomes JBV, Araújo Filho JC, Curi N. Solos de tabuleiros costeiros sob florestas naturais e sob cultivo. Pesq Flor Bras. 2012;32:233-46. doi:10.4336/2012.pfb.32.71.233

Green RA, Obermeierb SF, Olson SM. Engineering geologic and geotechnical analysis of paleoseismic shaking using liquefaction effects: field examples. Eng Geol. 2005;76:263-93. doi:10.1016/j.enggeo.2004.07.026

Gutiérrez-Castorena MC, Effland WR. Pedogenic and biogenic siliceous features. In: Stoops G, Marcelino V, Mees F. editores. Interpretation of micromorphological features of soils and regoliths. Amsterdam: Elsevier; 2010. p.471-96.

Habecker MA, Mcsweeney K, Madison FW. Identification and genesis of fragipans in Ochrepts of North Central Wisconsin. Soil Sci Soc Am J. 1990;54:139-46. doi:10.2136/sssaj1990.03615995005400010022x

Hollingsworth DI, Fitzpatrick RW. Nature and origin of a duripan in a Durixeralf-Duraqualf toposequence: micromorphological aspects. In: Ringrose-Voase AJ, Humphreys GS, editors. Soil micromorphology: studies in management and genesis. In: Proceedings 9º International Working Meeting on Soil Micromorphology; 1992; Townsville. Amsterdan: Elsevier; 1994. p.835-44.

Jackson ML. Soil chemical analysis advanced course. 2nd ed. Madison: University of Wisconsin; 1974.

Jacomine PKT. Evolução do conhecimento sobre solos coesos no Brasil. In: Cintra LFD, Anjos JL, Ivo WMPM, editores. Workshop Coesão em solos dos tabuleiros costeiros. Aracaju: Embrapa Tabuleiros Costeiros; 2001. p.19-46.

James HR, Ransom MD, Miles RJ. Fragipan genesis in polygenetic soils on the Springfield Plateau of Missouri. Soil Sci Soc Am J. 1995;59:151-60. doi:10.2136/sssaj1995.03615995005900010024x

Lima Neto JA, Ribeiro MR, Corrêa MM, Souza JVS, Araújo Filho JC, Lima JFWF. Atributos químicos, mineralógicos e micromorfológicos de horizontes coesos de Latossolos e Argissolos dos tabuleiros costeiros do estado de Alagoas. Rev Bras Cienc Solo. 2010;34:473-86. doi:10.1590/S0100-06832010000200021

Klug HP, Alexander, LE. X-ray diffraction procedures. New York: John Wiley & Sons Ltd.; 1974.

Lima PC, Curi N, Lepsh IF. Terminologia de micromorfologia do solo. Bol Inf SBCS. 1985;10:33-43.

McLean EO, Hedleson MR, Bartlett RJ, Holowaychuk DR. Aluminum in soils: I. Extraction methods and magnitude clays in Ohio soils. Soil Sci Soc Am Proc. 1958;22:382-7. doi:10.2136/sssaj1958.03615995002200050005x

Mehlich A. Determination of P, Ca, Mg, K, Na and NH_4. Raleigh: North Carolina Soil Testing Division; 1953.

Mehra OP, Jackson ML. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. Clay Clay Miner. 1960;7:317-27. doi:10.1346/CCMN.1958.0070122.

Miller MB, Cooper TH, Rust RH. Differentiation of an eluvial fragipan from dense glacial till in Northern Minnesota. Soil Sci Soc Am J. 1993;57:787-96. doi:10.2136/sssaj1993.03615995005700030027x

Moody LE, Graham RC. Silica-cemented terrace edges, Central California coast. Soil Sci Soc Am J. 1997;61:1723-9. doi:10.2136/sssaj1997.03615995006100060025x

Moreau AMSS, Costa LM, Ker JC, Gomes FH. Gênese de horizonte coeso, fragipã e duripã em solos do tabuleiro costeiro do sul da Bahia. Rev Bras Cienc Solo. 2006;30:1021-30. doi:10.1590/S0100-06832006000600011

Murphy CP, Bullock P, Turner RH. The measurement and characterization of voids in soil thin sections by image analysis. Part I. Principles and techniques. J Soil Sci. 1977. 28:498-508. doi:10.1111/j.1365-2389.1977.tb02258.x

Norfleet ML, Karathanasis AD. Some physical and chemical factors contributing to fragipan strength in Kentucky soils. Geoderma. 1996;71:289-301. doi:10.1016/0016-7061(96)00016-X

Norton LD. Micromorphology of silica cementation in soils. In: Ringrose-Voase AJ, Humphreys GS, editors. Soil micromorphology: studies in management and genesis. Proceedings 9º International Working Meeting on Soil Micromorphology; 1992; Townsville. Amsterdan: Elsevier; 1994. p.811-24.

Oliveira AP, Ker JC, Silva IR, Fontes MPF, Oliveira AP, Neves ATG. Spodosols pedogenesis under Barreiras formation and sandbank environments in the south of Bahia. Rev Bras Cienc Solo. 2010;34:847-60. doi:10.1590/S0100-06832010000300026

Payton RW. Fragipan formation in argillic brown earths (Fragiudalfs) of the Milfield Plain, north-east England. I. Evidence for a periglacial stage of development. J Soil Sci. 1992;43:621-44. doi:10.1111/j.1365-2389.1992.tb00164.x

Payton RW. Fragipan formation in argillic brown earths (Fragiudalfs) of the Milfield Plain, north-east England. II. Post Devensian developmental processes and the origin of fragipan consistence. J Soil Sci. 1993;44:703-23. doi:10.1111/j.1365-2389.1993.tb02334.x

Resende M, Curi N, Santana DP. Pedologia e fertilidade do solo: interações e aplicações. Piracicaba: MEC/ESAL/Potafós; 1988.

Resende M, Curi N, Ker JC, Rezende SB. Mineralogia de solos brasileiros: interpretação e aplicações. Lavras: UFLA; 2011.

Rhoades JD. Soluble salts. In: Page AL, editor. Methods of soil analysis. 2nd ed. Madison: ASA/SSSA; 1982. v.1. p.167-79. (Agronomy Monograph, 9).

Ribeiro LP. Os Latossolos Amarelos do Recôncavo Baiano: gênese, evolução e degradação. Salvador: Seplantec-CADCT; 1998.

Ringrose-Voase AJ. Micromorphology and soil structure: description, quantification, application. Aust J Soil Res. 1991;29:777-813. doi:10.1071/SR9910777

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF. Sistema brasileiro de classificação de solos. 3a ed. Rio de Janeiro: Embrapa Solos; 2013.

Schaetzl R, Anderson S. Soils: genesis and geomorphology. Cambridge: Cambridge University Press; 2013.

Shaw WM. Determination of exchangeable hydrogen and lime requirement of soils. J Assoc Offic Agric Chem. 1959;34:437-52. doi:10.1080/00103628509367604

Silva EA, Gomes JBV, Araújo Filho JC, Vidal-Torrado P, Cooper M, Curi N. Morphology, mineralogy and micromorphology of soils associated to summit depressions of the Northeastern Brazilian coastal plains. Cienc Agrotec. 2012;36:507-17. doi:10.1590/S1413-70542012000500003

Silva EA, Gomes JBV, Araújo Filho JC, Silva CA, Carvalho SA, Curi N. Podzolização em solos de áreas de depressão de topo dos tabuleiros costeiros do Nordeste brasileiro. Rev Bras Cienc Solo. 2013;37:11-24. doi:10.1590/S0100-06832013000100002

Silva FBR, Riché GR, Tonneu JP, Souza Neto NC, Brito LT, Correia RC, Cavalcanti AC, Silva FHBB, Silva AB, Araújo Filho JC, Leite AP. Zoneamento agroecológico do Nordeste: diagnóstico do quadro natural e agrossocioeconômico. Petrolina: Embrapa-CPATSA/Embrapa-CNPS; 1993. v.2.

Smeck NE, Thompson ML, Norton LD, Shipitalo MJ. Weathering discontinuities: a key to fragipan formation. In: Smeck NE, Ciolkosz EJ, editors. Fragipans: their occurrence, classification, and genesis. Madison: Soil Science Society of America; 1989. p.99-112.

Soil Survey Staff. Soil survey manual. Washington, DC: USDA; 1999.

Torrent J, Nettleton WD, Borst G. Genesis of a Typic Durixeralf of Southern California. Soil Sci. Soc Am J. 1980;44:575-82. doi:10.2136/sssaj1980.03615995004400030029x

Walkley A. A critical examination of a rapid method for determination of organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci. 1946;63:251-63. doi:10.1097/00010694-194704000-00001

Wang C. Extractable Al, Fe and Mn (and Si if desired). In: Mckeague JA, editor. Manual on soil sampling and methods of analysis. 2nd ed. Ottawa: Canadian Society of Soil Science; 1978. p.98-108.

Weisenborn BN, Schaetzl RJ. Range of fragipan expression in some Michigan soils: I. Morphological, micromorphological, and pedogenic characterization. Soil Sci Soc Am J. 2005;69:168-77. doi:10.2136/sssaj2005.0168