Iron bands, fragipans and duripans in the northeastern plateaus of Brazil — properties and genesis

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Boulet, R., Fritsch, E., Filizola, H. F., de Araujo Filho, J. C., Leprun, J. C., Barretto, F., Balan, E. and Tessier, D. 1998. **Iron bands, fragipans and duripans in the northeastern plateaus of Brazil — properties and genesis.** Can. J. Soil Sci. **78**: 519–530. Iron bands, fragipans and duripans are common in yellow low-activity clay soils developed from the *Barreiras* Group in coastal plateaus of northeastern Brazil. Such indurated horizons are found in depressions of the plateaus where sugar cane growth is greatly reduced. Little research has being done on the nature of their bonding agents and their genesis. Research carried out in arid zones has frequently attributed duripan consistency to amorphous silica; however, duripans in northeast Brazil occur under higher rainfall (1500–2000 mm). The objective of this work was to study the nature and distribution of soil features in a plateau to better understand the processes associated with soil hardening. Two transects, across a small and a large depression, were investigated using field soil characterisation, micromorphological techniques, and mineralogical and geochemical analyses.

The formation of the indurated horizons studied is due to two sequential processes: development of aquic conditions and incipient podzolization. Such processes have affected the upper part of a thin (<0.6 m in small depressions) or thick (>0.6 m in large depressions) compact clay horizon, showing horizontal plans likely inherited from the sediment. Onset of aquatic conditions formed the first fragipans overlying iron bands. Later, aquic conditions are combined with incipient podzolization to produce bleached loose horizons overlying duripans and iron bands. As the bonding agents in the duripans are organo-metallic complexes, these duripans appear to be very different from those described in arid environments.

Key words: Low activity clay Ultisols, *Barreiras* Group, iron bands, fragipans and duripans, organo-metallic complexes.

Boulet, R., Fritsch, E., Filizola, H. F., de Araujo Filho, J. C., Leprun, J. C., Barretto, F., Balan, E. et Tessier, D. 1998. **Bandes ferrugineuses, fragipans et duripans dans les plateaux du nord-est du Brésil — propiétes et genèse.** Can. J. Soil Sci. **78**: 519–530. Bandes ferrugineuses, fragipans et duripans sont fréquents dans les sols à argiles 1/1 développés sur la formation *Barreiras* des plateaux côtiers du nord-est du Brésil. Ces horizons indurés sont situés dans les dépressions des plateaux, zones où la croissance de la canne à sucre est fortement réduite. Très peu de travaux traitent de la nature de leur ciment et de leur processus de formation. Les travaux entrepris dans les zones arides attribuent fréquemment la cohésion des duripans à de la silice amorphe; néanmoins, les duripans du nord-est du Brésil sont présents dans des zones plus pluvieuses (1500–2000 mm). Ce travail a pour objectif l'étude de la nature et de la distribution spatiale des organisations pédologiques d'un plateau en vue d'une meilleure compréhension des processus d'induration. Deux transects recoupant une petite et une grande dépression ont été retenus pour des observations macro- et micro-morphologiques et pour des investigations minéralogiques et géochimiques.

La formation de ces horizons indurés est attribuée au développement séquentiel de deux processus : hydromorphie et début de podzolisation. De tels processus ont affecté la partie supérieure d'un horizon compact argileux peu épais (<0.6 m dans les petites dépressions) ou plus épais (>0.6 m dans les grandes dépressions), montrant des plans horizontaux probablement hérités de la stratification du sédiment. L'hydromorphie ménagée a formé en premier des fragipans surmontant des bandes ferrugineuses. Ultérieurement, le développement de cette hydromorphie et les prémices de podzolisation ont abouti à la formation d'horizons meubles blanchis, de duripans et de bandes ferrugineuses. Dans la mesure où les ciments des duripans sont constitués de complexes organo-métalliques, ces formations indurées apparaissent ainsi très différentes de celles décrites dans des environnements plus arides.

Mots clés: Ultisols à argiles 1/1, formation *Barreiras*, bandes ferrugineuses, fragipans et duripans, complexes organo-métalliques

Fragipans and duripans greatly reduce the infiltration of water and penetration of roots, making soils difficult to manage. They are frequent in the semi-arid and arid regions of the world (FAO-UNESCO 1975). Fragipans are commonly sandy clay subsurface horizons and often display redoximorphic features (Soil Survey Staff 1992). They have a hard consistency when dry, but slake when placed in water. In contrast, duripans are frequently sandy, have a higher consistency, and the dry fragments do not slake in water, even during prolongated immersion (Soil Survey Staff 1992). The consistency of duripans is commonly due to amorphous silica, which coats and bonds quartz grains together (Chartres and Fitzgerald 1990; Balbir-Singh and Gilkes 1993). Bonding agents are less abundant in fragipans

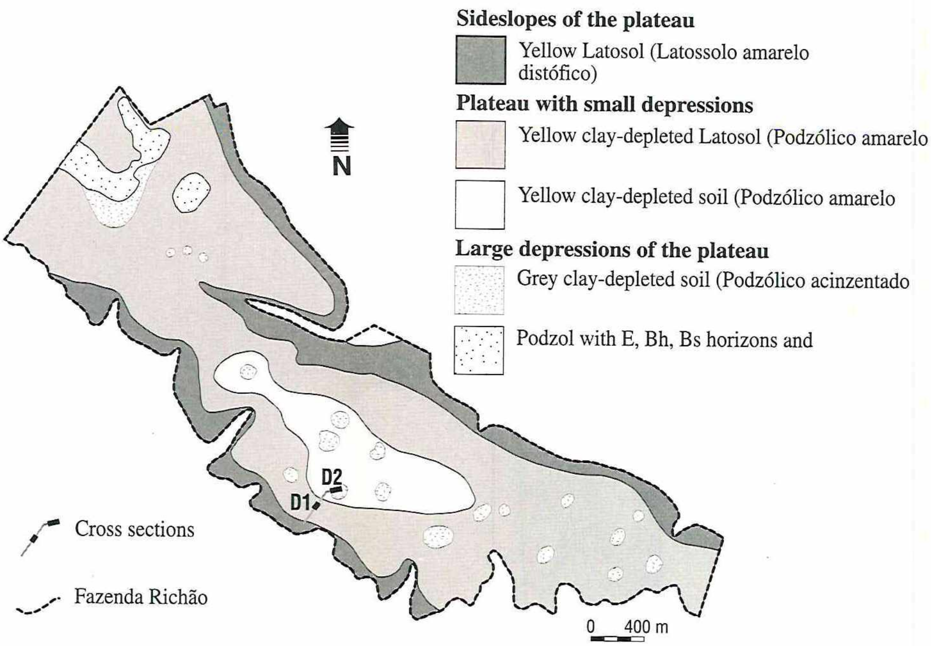

Fig. 2. Soil map of the Riachão Plateau (from Silva and Coelho 1989) and locations of cross sections D1 and D2.

similar to the second. However, the large depressions with fragipans and duripans also contain genuine Podzols in their centres. According to this soil distribution pattern, a small and a large depression of the second type of *Tabuleiros* were selected in the Richão's plateau (Fig. 2) as sites which best illustrate the formation of iron bands, fragipans and duripans in yellow low activity clay soils.

Field and Laboratory Investigations

A trench, 15 m long and 2 m deep, (cross section D1) was dug in the small depression (0.3 m deep) and an another 25 m long and 2 m deep upslope and 3 m deep downslope (cross section D2) was dug in the larger depression (1.5 m deep). Soil horizons and features were described in the trenches, graphically demarcated and numerated using tracing paper stuck on Polaroid photographs. Cross sections D1 and D2 were cleaned with knifes and photographed. The colour photos were later digitised and mounted together using a computer (Figs. 3[IA] for D1 and 3[IIA] for D2). Field observations and computing procedures (Rinder et al. 1994) were used for mapping the soil features in vertical cross section (Fig. 3[IB] and Fig. 3[IIB]). In the trenches, the main soil features were sampled vertically at five profile key sites and at specific places between the profiles in April 1996. Soil samples were air dried and sieved to 2 mm prior to physical, chemical and mineralogical investigations. Undisturbed soil materials were also collected for thin sections and ultra thin cuts.

Particle size analysis consisted of H_2O_2 oxidation, soil dispersion with $Na_4P_2O_7$, sand fraction sieving and clay + silt pipetting. pH was measured both in water and M KCL (soil: H_2O 1:2.5). Carbon content was measured on a Carmograph LOCO CR412 and nitrogen content determined by micro-Kjedahl volumetric method. Chemical analysis were performed in Canada (Actlabs LTD) using ICP. The oxalate technique proposed by MacKeague and Day (1966) was performed on eight samples. Samples were treated with 0.2 M NH_4O_x at pH 3 in the dark. The solutions were separated from the residues by centrifugation and the amounts of Si, Al and Fe were measured by atomic adsorption spectrophotometry.

The mineralogy of samples was characterised using powder **X-ray diffraction (XRD)** with a Philips diffractometer and PW3020 vertical goniometer (40 kV, 30 mA, Cu-Kα radiation, scanning rate of 1°2θ/3mm). The **mean coherent domain (MCD)** of kaolinite was calculated on the 001 peak using the Windfit program. Kaolinite contents were assessed from total Al_2O_3 contents of chemical analysis after subtraction of the Al associated with iron oxides (as 15% of Al substitution in goethite). Optical microscopy, **scanning electron microscopy (SEM)** using energy **dispersive X-ray spectroscopy (EDX)** were also used.

RESULTS

Morphological Features of Soils in Small and Large Depressions

The soil features of cross sections D1 and D2 were grouped in two categories (Fig. 3) according to colour which may be used to assess the soil moisture regime (Vepraskas 1992; Fritsch and Fitzpatrick 1994; Peterschmitt et al. 1996). Lateritic features occur on the edges of the depressions and are associated with redoximorphic features in the depressions.

I. LATERITIC FEATURES. On the edges of depressions D1 and D2 (left parts of Fig. 3[I] and 3[II]), yellow soils were split into four superimposed horizons (Ap, A, AB and B1) according to colour, texture and structure. At about 2 m depth, the B1 horizon is reddish yellow (7.5YR6/5), rich in clay (up to 70%), very crumbly, porous, and made of microaggregates (50–150 µm) which are locally grouped in subangular blocky aggregates (1–2 cm). Upwards, this horizon is more yellowish (10YR6/8) and the blocky aggregates are bigger (1–5 cm). The overlying AB horizon is light yellowish brown (10YR6/5), sandy clay and massive. Under an optical microscope, clay cutans are scarce and the progressive compaction of the microaggregates between the B1 and AB horizons is related to deterioration in soil structure. The A horizon is pale brown (10YR4/3), sandy clay loam and massive. The upper Ap horizon is dark greyish brown (10YR4/2), sandy clay loam containing zones where very coarse blocky aggregates (3–15 cm) are numerous and others where small blocky aggregates predominate (1–5 cm). Due to soil structure degradation and waterlogging, depression D1 was ploughed at deeper depth as indicated by plough pan and mixing the Ap and A horizon materials (right part of Fig. 3[I]).

At about 1 m depth, the upper horizon boundary of B1 is undulating and generally associated with a thin (1 cm) discontinuous dark reddish brown (2.5YR3/3) weakly indurated iron band which often displays cutans under the microscope. Numerous yellow (10YR6.5/6) volumes of different sizes (0.01 up to 1 m on the edge of depression D1) are generally present just below the iron band. The yellow volumes are massive and more coherent than the surrounding brownish yellow (10YR6/8) B1 horizon. Both iron bands and yellow volumes may occur further down at different depth. They are generally smaller and less coherent.

The iron bands and the yellow volumes in the upper part of the B1 horizon coalesce and demarcate an almost continuous compact B2 horizon of about 0.6 m thickness in the small depressions (right part of Fig. 3[I]). This horizon displays several very clear horizontal plans in its upper part which might be remnants of *Barreiras* stratification. The lower limit of the horizon appears very irregular and diffuse. According to macro- and micro-observations, this horizon is crossed by numerous tubular pores (2–5 cm) filled with brownish yellow microaggregates more or less compacted which are likely of termitic origin. The pores often show a preferential vertical or horizontal orientation, the latter highlighting the horizontal plans of the compact horizon. At several places the compact horizon is also cut by vertical channels of 0.05–0.30 m diameter, filled with porous yellowish brown clay material. Such channels contain remnants of the compact horizon and numerous fine roots. In one place, a 20-cm-thick root of the original forest was extracted from a vertical channel.

II. REDOXIMORPHIC FEATURES IN THE SMALL DEPRESSION: IRON BANDS AND FRAGIPANS. In the small depression, the continuous iron bands may cap the upper limit of the compact yellow B2 horizon (Fig. 3[I]) or more commonly appear further down in this horizon at one or two levels. In the latter case, iron bands have either a pale (2.5YR5/2) or a dark reddish brown (2.5YR3/4) colour. Pale reddish brown iron bands are thick (2–5 cm) and consist of multiple thin iron-rich sheets with diffuse boundaries. Dark reddish brown iron bands are thinner (<2 cm) and occur as a single pan with an abrupt upper transition and a diffuse lower transition. These iron bands are often located in the horizontal plans of the compact horizon but locally dip downwards and have a pronounced wavy or even convolute form. Therefore, they are similar to the so-called placic horizon (Soil Survey Staff 1992). The compact horizon which overlies these iron bands presents a lighter yellow colour with reddish brown iron stains in tubular pores and has a hard consistency typical of fragipans. From top to bottom, the succession of fragipans and iron bands may be as follows: (1) pale yellow (2.5Y7/5) sandy clay fragipan, (2) first iron band either pale or dark reddish brown, (3) yellow (2.5Y7/6) sandy clay fragipan and (4) second pale or dark reddish brown iron band. The upper pale yellow fragipan may be capped by a thin pale reddish yellow iron band which likely marks the position of a former dark reddish brown iron band. Fragipans and iron bands demarcate two platey bowl-like structures in depression D1 (Fig. 3[I]). The first bowl-like structure at the border of the depression is 15 cm deep and 4 m wide; whereas, the second one appears larger in the centre of the depression (30 cm deep and 9 m wide).

III. REDOXIMORPHIC FEATURES IN THE LARGE DEPRESSION: IRON BANDS, FRAGIPANS, DURIPANS AND GREY HORIZONS. Figure 3[II] shows that the compact soil layer including the B2 horizon, the fragipans and the duripans is thicker in depression D2 than in depression D1 (0.8 m at the border of depression D2 and more than 2 m in its centre). At the border of depression D2, vertical soil differentiation is similar to those described in the centre of depression D1; fragipans and iron bands occur in particular in the upper part of the compact B2 horizon. Toward the centre of depression D2, the following changes are noticed: (1) the compact B2 horizon disappears due to increasing thickness of the overlying fragipans, (2) simultaneously the upper part of the fragipans transforms into pale yellow (2.5YR7/4) and white (2.5YR8/1) sandy clay or clay duripans, separated by a continuous pale or dark reddish brown iron band, (4) over the white duripan the lateritic horizons disappear due to the development of a light grey (10YR7/2) sandy clay AB horizon, a pale grey (10YR5/1.5) sandy clay loam A horizon and a dark grey (10YR4/1) sandy clay loam Ap horizon, (5) the duripans become thicker and may expand downwards below the pale or dark reddish brown iron bands, and (6) the upper part of the white duripan show figures of dismantling and is transformation into coarse and irregular shaped nodules.

As for fragipans in depression D1, duripans of depression D2 often display horizontal plans. They are crossed by numerous tubular pores filled with light grey microaggregates and cut by vertical channels (former root channels). They also contain reddish brown stains in tubular pores and present pale reddish yellow iron bands which likely mark the position of former dark reddish brown iron bands.

Mineralogy and Chemistry of Soil Features in Small and Large Depressions

1. LATERITIC FEATURES. According to XRD patterns and chemical data, the lateritic features (Ap, AB, B1 and B2

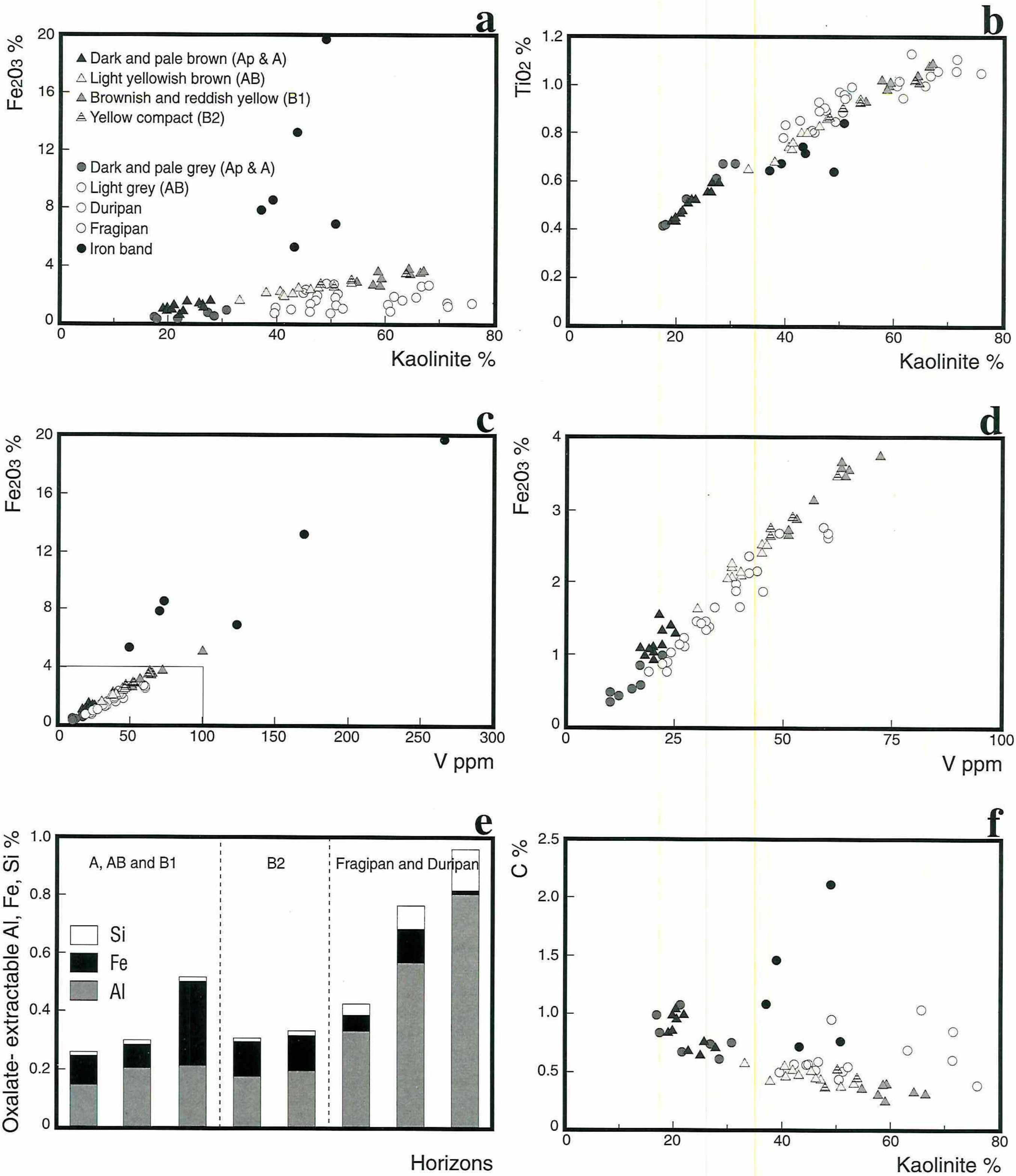

Fig. 5. Chemical data of the hydromorphic soil features (A and AB horizons, duripans, fragipans and iron bands) and comparison with data of the lateritic zone: (a) iron oxide content versus kaolinite content, (b) titanium oxide content versus kaolinite content, (c) iron oxide content versus vanadium content, (d) enlargement of (c), (e) oxalate-extractable Si, Fe and Al in different horizons and (f) total carbon content versus kaolinite content.

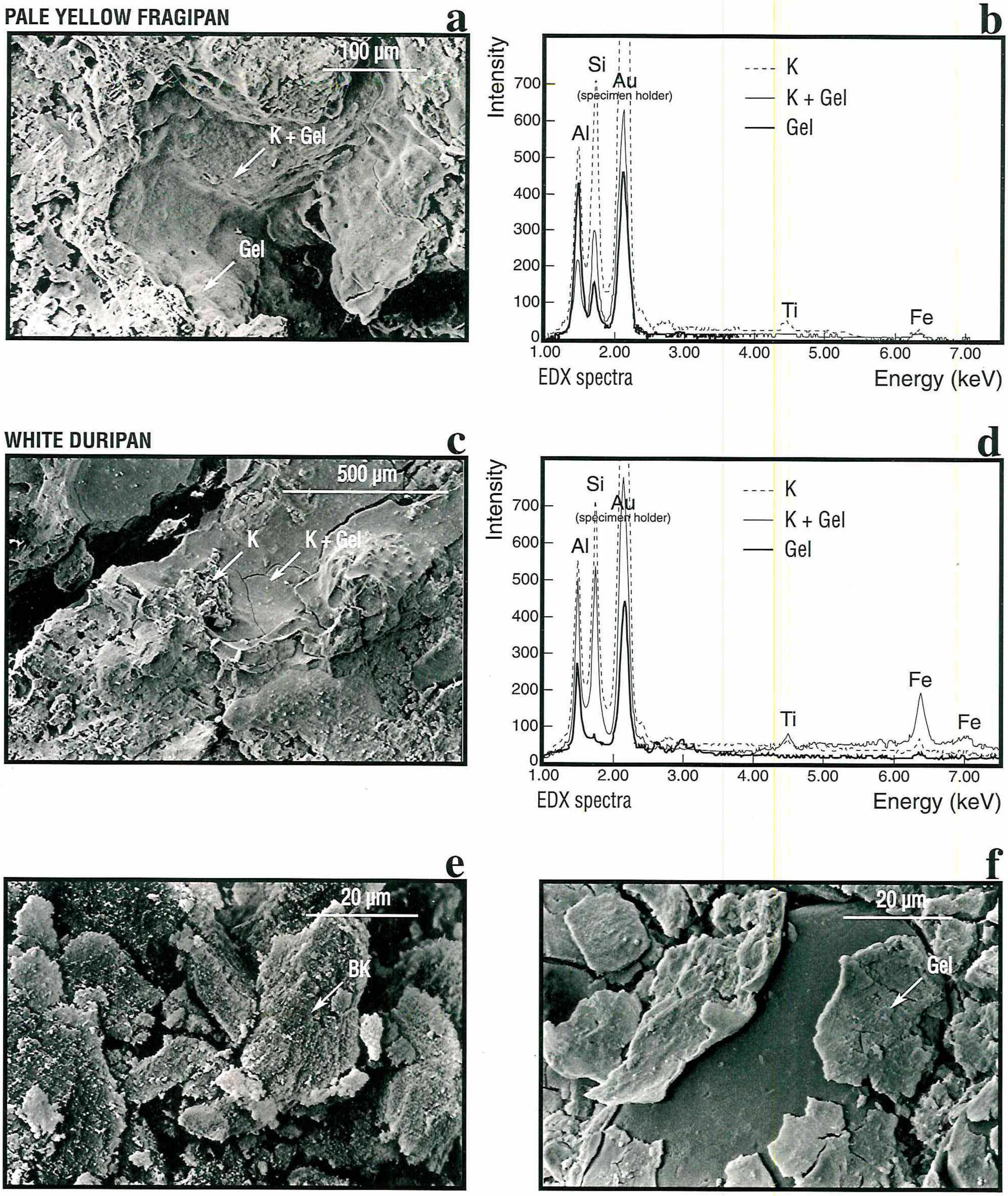

Fig. 6. (a) SEM of pale yellow fragipan showing kaolinitic matrix (K) coated with an amorphous phase (Gel) on the wall of a macropore, (b) corresponding EDX spectra, (c) SEM of white duripan showing an amorphous phase (Gel) cracked on the wall of a pore, (d) corresponding EDX spectra, (e) detail of (c) the clay matrix is composed of small platelets (1 µm) of kaolinite locally grouped within larger booklet-like shape polycrystal (20 µm) (BK), (f) amorphous phase (Gel) mixed with platelets of kaolinite are coating and binding quartz grains together (cracks were formed on drying).

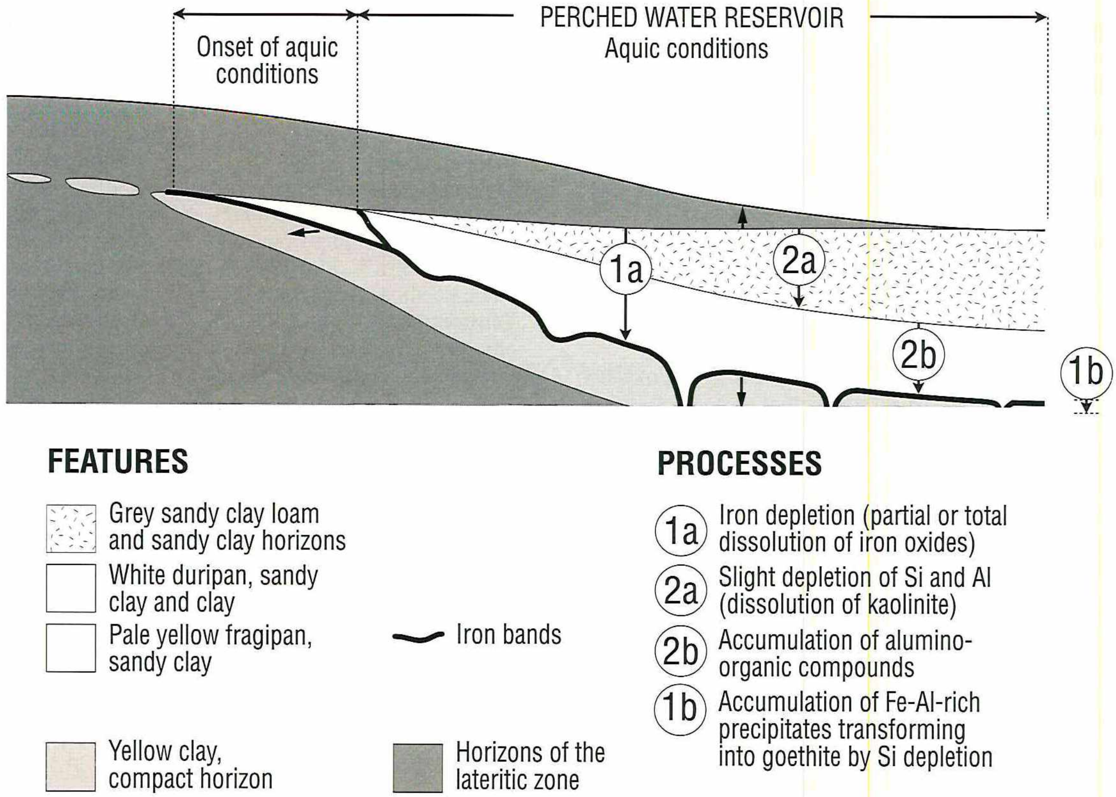

Fig. 8. Shematic cross section showing the two main processes (1 redoximorphism and 2 incipient podzolization) associated with the formation of fragipans, duripans and iron bands.

better understand the origin of this compact horizon. This horizon could be remnants of the *Barreiras* sediments (horizontal plans of stratification, remnants of booklets of kaolinite) which have, however, undergone strong mineralogical changes (kaolinite of low crystallinity) or be the result of in situ compaction of the upper B1 horizon. The geochemical evolution is related to the development of perched watertables which leak at different places, particularly in former forest root channels. The onset of aquic condition has formed fragipans and iron bands, whereas waterlogging has produced grey horizons, duripans and iron bands. Iron bands act as hydrological barriers that favour the development of aquic conditions in the overlying soil horizons.

CONCLUSION

Morphological features, geochemical and mineralogical data enabled us to reveal two main processes associated with the formation of iron bands, fragipans and duripans in the northeastern plateaus of Brazil. These two processes are attributed to redoximorphism and incipient podzolization. They are linked to the development of aquic conditions due to the occurrence of a pre-existing compact B horizon probably of a lower permeability. The processes initially expand downwards in the upper part of this B horizon to form fragipans associated with iron bands. Later, they expand both upwards and downwards to give rise to bleached loose horizons overlying duripans and several iron bands. From this study, it appears that these pans inherit parts of their physical properties from the compact B horizon in which they have developed. Accordingly, the pathways followed to form the indurated horizons in our study area are very different from those commonly reported for fragipans and duripans in more arid regions of the world. This explains why such horizons may be found in close association with genuine Podzols in higher rainfall areas.

ACKNOWLEDGEMENTS

The original research was funded by the project 94/2471-8 of the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and ORSTOM. We are grateful to the members of the Triumfo sugar cane factory for their technical assistance and encouragement.

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