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Soil features at toposequence scale for identifying structures, water flows and processes either past or present

Organisations pédologiques aux échelles topo-séquentielles en vue d'une identification des structures, des écoulements et des processus passés ou actuels

FRITSCH Emmanuel 1&2, FITZPATRICK Rob William 3, MELFI Adolpho José 1, HERBILLON Adrien Jules 1&2 & BOULET René 1&2

1 NUPEGEL, USP, Caixa Postal 11348, 05422-970, São Paulo, SP, Brazil
2 ORSTOM (RED, UR2/GP23), USP-IG, C.P. 11348, 05422-970 São Paulo, SP, Brazil
3 CSIRO, Division of Soils, Private Bag Nº 2, Glen Osmond, 5064, South Australia

The paper presents a method for mapping and interpreting soil features at toposequence scale using either trenches of sufficient length and depth and/or close spaced profile pits along a transect. Three examples of soil toposequences of the lateritic environment are presented to illustrate the method. Since the succession of soil features and soil types down the slopes are found to be similar to those established from toposequences and soil map studies, each cross section displayed in the paper can be considered as representative of a given landscape.

For each toposequence, soil features are graphically mapped on cross section. Such a mapping does not require *a priori* grouping. The grouping of soil features in larger soil compartments is done later on using the geometrical relationships that they display at toposequence scale. Finally, the boundaries of these soil features and/or soil compartments define the main structures of the soil-landscape and each boundary structure is then characterized by its size and shape.

Soil features and boundary structures are also used for interpreting ancient and/or modern water flows and processes. Water duration either past or present can be related mainly to soil colour and pattern (e.g. mottles) whereas water movement is inferred from the shape of boundary structures. In the same way, the nature and the distribution of the features at toposequence scale enable to highlight the main processes and to propose the ways in which they are thought to have come into existence. However, such a method is not adequate to indicate whether these processes are still occurring nowadays or have occurred at some time in the past.

Keywords : Soil toposequences, soil features and structures, water flows and processes, lateritic environment.
Mots clés : toposéquence de sol, organisation et structures pédologiques, écoulements d'eau, environnement latéritique

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ABSTRACT

Three examples of soil toposequences of the lateritic environment are presented in this paper (i) to show how soil features can be used for identifying the main structures of the soil-landscape, (ii) to suggest a method for interpreting ancient and/or modern soil-water processes from both soil features and structures, and (iii) to present the ways in which the processes are thought to have come into existence. Soil features are purposely placed first in the paper title to emphasize that most efforts to understand the genesis of lateritic soil features must begin with their morphology and the study of their spatial distribution in the landscape.

INTRODUCTION

The subject most often considered in pedological studies is the vertical organization of the soil, which is taken from a pedon (Boulaine, 19). Soil features are described in soil horizons and the latter are commonly analysed for identifying diagnostic properties. The nature and the vertical distribution of these diagnostic horizons and properties are later used to classify the soils (e.g. Soil Survey Staff, 1992). Such a method of soils characterization has proved to be performant for interpreting processes and assessing water movement at specific places in the landscape. However in this method, the soil features are automatically grouped in a rigid fashion, thus making lateral linking between profile horizons along toposequences difficult (Fritsch and Fitzpatrick, 1994). Soil toposequence studies do not require prior grouping of soil features. The main soil features of the landscape are mapped on cross sections. The grouping of soil features into soil layers or soil systems is done later one at toposequence scale using spatial relationships (Fritsch *et al*, 1992). The concepts of horizon boundary and pedon are therefore replace by the concept of feature boundary and soil system. The concept of feature or matrix boundary has been applied for long at micro-scale using thin sections (Brewer and Sleeman, 1988). In this paper, it is also applied at toposequence scale.

Lateritic soil-landscapes generally occur in the intertropical zone and cover about 20% of the continents (Tardy, 1993). The lateritic soils comprising the whole regolith (i.e. indurated and/or loose layers from the bed rock up to the soil surface) are commonly thick and strongly weathered. Broadly speaking, the formation of such soil-landscapes can be attributed to two categories of opposite chemical processes. The fist one, called here the laterisation processes (see e.g. Kellogg, 1936; Millot 1970; Schellmann, 1981; Tardy, 1993) is characterized by depletion of bases and silica followed by the residual accumulation of the most stable secondary minerals (predominantly kaolinite with variable amounts of aluminium and iron oxides). Such processes, thought still active nowadays in the most humid tropical areas, are known to have been initiated a very long time ago (since the Tertiary and possibly at specific places since the Cretaceous). In the upper part of the lateritic soil-landscapes, they are at the origin of the development of various types of well-drained low activity soils (e.g. Ferralsols, but also Acrisols, Nitosols and Lixisols according to FAO, 1988). The second category of processes is transforming pre-existing lateritic materials into weakly or strongly hydromorphic soils and are therefore believe to be more recent. These soil change processes (Fanning and Fanning, 1989) generally occur in downslope positions and are linked to the fluctuation of perched and ground water aquifers. They lead firstly to the mobilisation and redistribution of iron oxides. Kaolinite also may be mobilized either as particles or possibly by dissolution favouring the residual accumulation of sandy materials enriched in quartz (Fritsch *et al*, 1992).

This paper presents three examples of toposequences studies carried out in the lateritic environment. One of its objectives are to show how soil features may be used at toposequence scale for demarcating the main structures of the soil-landscapes. The relative distribution of these features within such structures are further interpreted in terms of water flows and soil processes.

SOIL FEATURES FOR IDENTIFYING BOUNDARY STRUCTURES AND SOIL SYSTEMS AT TOPOSEQUENCE SCALE

The term ‘structure’ is used here to demarcate any particular volume which is homogeneous in term of nature of components and type of arrangement (Foucault and Raoult 1988). Thus the types of structures to be considered depend on the scale of observation. From crystal to toposequence scale, it is possible to differentiate the following types of structure (Fritsch *et al*, 1992): crystal structure (set of atoms), plasmic structure (set of oriented secondary minerals), boundary structure of soil features (set of primary and secondary minerals), physical soil structure (set of aggregates) and boundary structure of soil systems (set of soil features). This paper will only deal with boundary structures (*sensu* Brewer and Sleeman, 1988) of soil features or soil systems which can be characterized by size and shape. Due to their large size, they are often not completely observed at the profile scale and, consequently, have been overlooked by pedologists. It is, therefore, necessary to demarcate all boundary structures at toposequence scale using either trenches of sufficient length and depth and/or from close spaced profile holes along a transect.

Boundary structures may be inherited from lithology (e.g. plans of stratification, diaclase and fracture) or acquired during pedogenesis. Boundary structures acquired by pedogenesis are either parallel to the soil surface or demarcating more irregular-shaped volumes (Fig. 1). The latter may be grouped in two categories depending on whether they have a finite boundary (closed volumes) or a non finite boundary (open volumes) on a landscape unit scale (Fritsch *et al*, 1992). Closed volumes may occur in upslope positions, particularly on the plateaus and are commonly related to pocket-, basin- or bowl-like structures (Figs. 1[A] and 1[C]). They may start from the soil surface (Fig. 1[A]) or be internal (Fig. 1[C]). Open volumes generally occur in footslope positions and are often related to tongue-like structures (Figs. 1[B] and 1[D]). As for closed volumes, they may start from the soil surface (Fig. 1[B]) or be internal (Fig. 1[D]). More complex and irregular-shaped volumes may also be observed at landscape scale (Figs. 1[E], 1[F], 1[G] and 1[H]). They most often result from the expansion of former closed or open volumes which have coalesced.

The grouping of soil features into soil systems is done at toposequence scale using geometrical relationships between boundary structures (Fritsch *et al.,* 1992). Concordant structures never intersect. They may be nested into each other both in closed or open volumes. The nesting (see the bowl-like structure in figure 2[B]) indicates that soil change processes have occurred in such a way that the outer features are less transformed than the inner features. It is therefore possible to establish a chronological order of soil features formation within such structures and to group these features into larger soil compartments or soil systems. Discordant structures do intersect and generally occur at the periphery of the soil systems. Discordant relationships also enable to establish a chronological order of soil system formation (Fritsch *et al.* 1992). Accordingly, such grouping of soil features into a limited number of soil systems respect the main structures of the soil landscape. It also permit to display the soil landscape in a more simplified form and to present the ways in which the soil features are thought to have come into existence. This differentiation of the soil-landscape into a limited number of soil systems (set of soil features) is the basis of an approach known as the *structural analysis of the soil-landscape* (Boulet *et al.,* 1982).

SOIL FEATURES AND STRUCTURES FOR INDENTIFYING WATER FLOWS

Soil colour is probably the most relevant type of feature to assess the soil moisture regime in the landscape (Vespraskas, 1992; Fritsch and Fitzpatrick, 1994; Peterschmitt *et al.,* 1996). Change of colour from red soils in well drained upslope positions through yellow to grey soils in poorly drained lower positions is the most striking soil pattern of the lateritic environment (Milne, 1934, Daniels *et al.*, 1975; Chauvel, 1977; Coventry *et al.*, 1983, Curi and Franzmeier, 1984). Changes of colour may be attributed to different causes. However, several studies have indicated that they can be associated with the depletion of the red (hematite) and yellow (goethite) pigments of the soils and related to selective dissolution of iron oxides which affect first hematite then goethite (Karim and Adams, 1984, Schwertmann, 1984; Jeanroy *et al*., 1991; Peterschmitt *et al.,* 1996). Progressive dissolution and depletion of iron oxides from red to grey soils is due to increasing periods of saturation and reduction (i.e. aquic conditions *sensu* Vepaskas, 1992), and activity of iron-reducing bacteria (Macedo and Bryant, 1989). Peterschmitt *et al.* (1996) have therefore suggested to link red features to well drained conditions, yellow features to the onset aquic conditions and white features to strongly waterlogged and reducing conditions, as well as to assign redox depletion features to yellow and white features. Dissolved iron may migrate downwards and concentrate at specific places to form redox concentration features (e.g. iron stains in macro-voids, iron-rich mottles isolated or anastomosed as in plinthitic horizons and thin iron pans). Redox depletion and redox concentration features are generally linked and grouped in redoximorphic features (Vepaskas, 1992).

Water duration and water movement may be deduced from both soil features and boundary structures. Two toposequences are presented to illustrate this approach. In both toposequences, lateritic soils are reddish yellow and rich in low activity clay (up to 70%). In the Manaus (Brazil) toposequence (Fig. 2), redoximorphic features in soil materials (Fig. 2[B]) occur in internal pocket- or bowl-like structures on the edge of a plateau (as already shown in figure 1[C]). In the Kattinkar (India) toposequence (Fig. 3), similar redoximorphic features (Fig. 3[C]) are observed in internal pocket-, tongue- and bowl-like structures in downslope positions (as already shown in figure 1[D] for tongue-like structures). Yellow features may occur alone in the pocket-like structures. They may also be present in the upper part of the bowl-like structures or tongue-like structures. Such distributions are consistent with the onset of aquic conditions. White features are internal to the bowl- and tongue-like structures and therefore indicating longer periods of water duration probably due to fluctuation of groundwater aquifers. Thin iron pans only occurs at the bottom of the bowl-like structures. Pocket- and bowl-like structures are closed volumes. Bowl-like structures containing white layers and thin iron pans are assigned to fluctuation of perched watertables. As redox depletion features (i.e. yellow and white layers) are overlying redox concentration features, iron pans lihely act as an hydrological barrier which promotes the development of aquic conditions in the overlying white and yellow soil layers. Water flows are vertical but the saturated zones expand upwards and laterally in reponse to rainfalls. These saturated zones are not linked to the hydrological network and most of the elements translocated by the perched water (e.g. iron) remain in their corresponding pocket- or bowl-like structures. In contrast, the tongue-like structures are linked to the hydrological network in downslope positions. The yellow zones appear commonly in the upper part and/or at the periphery of the tongue like structures; and the internal white zones in downslope positions is closely linked to the hydrological network. Vertical and lateral water flows promote at depth the recharge of the ground water aquifers, and the saturated zones expand upwards and upslope in reponse to rainfalls and soil structure boundaries. As redox depletion features are generally more abundant than redox concentration features (often iron-rich mottles and iron stains), the major part of the elements translocated by the groundwater aquifers (e.g. iron) is exported into the river systems. Consequently, it is assumed that the saturated zones reproduce similar boundary structures than those of their corresponding redoximorphic features and that both saturated zones and redoximorphic features may expand in the landscape, as shown in figures 1[E] to 1[H], in reponse to higher rainfall periods. However, the formation of redoximorphic features may be past or present. Thus it is worthwhile to calibrate redoximorphic features to periods of saturation and reduction (Vepaskas, 1992) in order to check whether aquic conditions are still occurring during the year or have occurred at some time in the past (Faulkner and Patrick 1992; Blavet, 1997; Fritsch *et al*., 1998).

SOIL FEATURES FOR IDENTIFYING SOIL PROCESSES

Soil features are used to identify either major soil processes (e.g. podzolization) or ‘narrow’ processes or mechanisms such as dissolution or precipitation of specific minerals or organo-mineral compounds as outlined for example by Fanning and Fanning (1989). The grouping of soil features into soil systems and their relative distribution within each soil system enable to identify the places where these processes are the most likely to act in the landscape.

A toposequence study carried out in South Australia is presented (Fritsch and Fitzpatrick, 1994) to illustrate how soil features (Fig. 4[B]) were grouped into soil systems (Fig. 4[A]), and how both soil features and soil systems were used for interpreting water flows (Fig. 4[C]), as well as for revealing the major soil processes (Fig. 4[D]). This toposequence is typical of the red-yellow and grey duplex soils (Palexeralf-Natraqualf) of the Mount Lofty Ranges which is undergoing severe land degradation problems in downslope positions (e.g. waterlogging, dry land salinity, erosion and water pollution). The toposequence was split into three superimposed soil systems : a pale brown/grey topsoil system, a red subsoil system and a yellow/white subsoil system. This distinction was based mainly on soil colour and texture, as well as on the relative distribution of these systems in the landscape. The red clay subsoil system or lateritic domain is an unsaturated layer. Vertical flows keeps this layer freely drained (see arrows in figure 4[C]). The pale brown/grey sandy loam topsoil system and the yellow/white clay subsoil system display redoximorphic features and were therefore grouped in a hydromorphic domain. They are separated by the red subsoil system in upslope positions and directly superposed in downslope position reproducing therefore the general structures of figure 1[H]. They were associated with fluctuation of a perched and a ground watertable, lateral throughflow and water mixing due to rising ground water up to the surface in downslope positions (the ground water is under pressure, see arrows in figure 4[C]). Formation of the lateritic domain was assign to three laterisation processes : saprolitization, ferralitization and glebulization. In the hydromorphic domain eight processes were differentiated : redoximorphism, clay eluviation and clay illuviation, salinization and sodification, sulfuricization and sulfidization, and erosion (cut and infill or soil deposition). The spatial distribution of these processes in the hydromorphic domain (Fig. 4[D]) and their relation with the actual waterflows (Fitzpatrick *et al.*, 1996, Fritsch *et al.*, 1998) enable us to deduced how such processes are supposed to have come into existence (Fritsch and Fitzpatrick, 1994).

CONCLUSION

Toposequence studies carried out in the lateritic environment all indicate that the soil-landscape may be dissociated in two distinct geochemical domains. The fist one is the domain of true soil laterisation characterized by the residual accumulation of the most stable secondary minerals previously formed under strong weathering conditions. The second one is the domain which is or has been affected by aquic conditions favouring therefore the removal of the secondary minerals of the lateritic domain and/or the development of various different soil processes depending on climatic conditions. For instance, podzolization may take place on completely ‘de-laterised’ sandy materials in humid conditions whereas salinization may occur in more arid one.

From all these toposequences studies, it clearly appear that as soon as the distribution of the soil features in the landscape has been logically displayed, an opportunity exist for several types of interpretations in terms of water flows and soil processes either past or present. Finally, the relationships established between soil features, water flows and soil processes at toposequence scale enable to deduce a chronology of soil formation and/or soil change processes and therefore to construct conceptual models. These models not only explain the history of the soil-landscape but also permit to predict future modes of soil-landscape evolution under changing environmental conditions (Fritsch and Fitzpatrick, 1994).

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