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A structural approach to the regolith : identification of structures, analysis of structural relationships and interpretations / *Une approche structurale appliquée aux couvertures pédologiques : identification des structures, analyse des relations structurales et interprétations*

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Résumé

Une approche structurale appliquée aux couvertures pédologiques : identification des structures, analyse des relations structurales et interprétations

L'article est scindé en deux parties. Dans la première partie, une approche de terrain adaptée à l'identification des structures (transitions entre matrices) d'une couverture pédologique et à l'analyse de leurs relations structurales est présentée. Dans la seconde partie, plusieurs exemples du milieu intertropical ont été sélectionnés pour illustrer cette approche.

Schématiquement, l'approche comprend deux étapes. La première étape consiste à collecter les données de terrain, à établir des analogies (d'un profil à un autre ou d'une toposéquence à une autre) et un inventaire des matrices et des structures qui leurs sont associées, à l'échelle de la couverture pédologique étudiée. La seconde étape est consacrée à l'étude des relations structurales, exprimées en termes de concordance et de discordance. Elle est entreprise sur des documents où ont été reportées les différentes structures identifiées. Si les relations de concordance permettent le regroupement de matrices en systèmes pédologiques (ensemble de matrices), les relations de discordance sont utilisées pour circonscrire les systèmes à leur périphérie. Les relations de concordance montrent qu'il existe des règles générales dans la distribution, l'emboîtement des matrices et des structures qui leurs sont associées. Les relations de discordance nous autorisent à subdiviser chaque couverture pédologique en un nombre limité de systèmes pédologiques qui peuvent, eux-mêmes, être regroupés en domaines (ensembles de systèmes pédologiques). Cette subdivision qui respecte la structure d'ensemble de la couverture pédologique rend compte des caractéristiques propres à chaque système pédologique et de la manière dont ils sont articulés. Le raisonnement structural adopté permet également d'établir des filiations entre matrices et d'envisager, de ce fait, une chronologie relative dans la mise en place des matrices et des systèmes pédologiques.

La seconde partie de l'article est consacrée à l'application de l'approche structurale à trois couvertures pédologiques du milieu intertropical (Asie, Afrique et Amérique du Sud). A partir d'exemples, il est montré que le groupe¬ ment de matrices en systèmes pédologiques puis en domaines permet d'aboutir à une représentation synthétique et simplifiée des couvertures pédologiques qui facilite de ce fait leur comparaison. D'autre part, la caractérisation micro et ultra-microscopique des constituants de chaque matrice permet de révéler les principaux processus biogéochimiques ou physico-chimiques qui agissent au sein des systèmes pédologiques identifiés. Enfin, cet article tend à montrer qu'il existe un nombre limité de type de structures, de matrices et de systèmes pédologiques. Aussi, la grande diversité d'organisation des couvertures pédologiques peut être attribuée au simple fait qu'un même type de structure peut contenir différents types de matrices et qu'un même type de matrices peut être observé dans différents types de structures.

Abstract

This paper is divided into two parts. In the first part, a field method of identifying structures defined by matrix boundaries and studying their relative distribution at a specific landscape unit scale is described and in the second part different examples from the intertropical zone are given to illustrate the method. The method consists in two stages. By collecting field data and establishing analogies (from one profile to another or from one toposequence to another), the first stage involves an inventory of matrices and structures existing in the regolith. The second stage establishes structural relationships in terms of concordant and discordant relationships. Structures showing concordant relationships may have their matrices grouped into soil systems (matrix set), whereas discordant relationships are used to demarcate the soil systems. Concordant relationships suggest that general rules exist in the distribution and nesting of structures and matrices. Discordant relationships allow the division of each regolith into a limited number of soil systems which can further be grouped into domains (soil system set). This division relates to large structures of the regolith and gives an account of the characteristics specific to each soil system. By defining the way in which all the listed structures and matrices are linked, this method enables the establishment of a relative chronology for their formation. In the second part of the paper, examples of three regoliths from the intertropical zone (Asia, Africa and South America) are used and then into domains may give a schematic representation which enables easy comparison of regoliths. Furthermore, by studying components and characteristics of each matrix at micro-scale, it is possible to point out main soil processes acting in each soil system. From this paper, it emerges that, in the studied environments, there is a limited number of structures, matrices and soil system types. However, as the same type of structure may contain different types of matrices and the same type of matrix may be observed in different types of structures, there is high diversity in the regolith.

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A STRUCTURAL APPROACH TO THE REGOLITH : IDENTIFICATION OF STRUCTURES, ANALYSIS OF STRUCTURAL RELATIONSHIPS AND INTERPRETATIONS

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SUMMARY — This paper is divided into two parts. In the first part, a field method of identifying structures defined by matrix boundaries and studying their relative distribution at a specific landscape unit scale is described and in the second part different examples from the intertropical zone are given to illustrate the method.

The method consists in two stages. By collecting field data and establishing analogies (from one profile to another or from one toposequence to another), the first stage involves an inventory of matrices and structures existing in the regolith. The second stage establishes structural relationships in terms of concordant and discordant relationships. Structures showing concordant relationships may have their matrices grouped into soil systems (matrix set), whereas discordant relationships are used to demarcate the soil systems. Concordant relationships suggest that general rules exist in the distribution and nesting of structures and matrices. Discordant relationships allow the division of each regolith into a limited number of soil systems which can further be grouped into domains (soil system set). This division relates to large structures of the regolith and gives an account of the characteristics specific to each soil system. By defining the way in which all the listed structures and matrices are linked, this method enables the establishment of a relative chronology for their formation.

In the second part of the paper, examples of three regoliths from the intertropical zone (Asia, Africa and South America) are used to illustrate this structural approach. It is shown that the grouping of matrices first into soil systems and then into domains may give a schematic representation which enables easy comparison of regoliths. Furthermore, by studying components and characteristics of each matrix at micro-scale, it is possible to point out main soil processes acting in each soil system.

From this paper, it emerges that, in the studied environments, there is a limited number of structures, matrices and soil system types. However, as the same type of structure may contain different types of matrices and the same type of matrix may be observed in different types of structures, there is high diversity in the regolith.

Regolith, Soil systems, Matrices, Structures, Structural relationships, Transitions between ferralitic, ferruginous and hydromorphic soils in the intertropical zone

Une approche structurale appliquée aux couvertures pédologiques : identification des structures, analyse des relations structurales et interprétations

RÉSUMÉ — L'article est scindé en deux parties. Dans la première partie, une approche de terrain adaptée à l'identification des structures (transitions entre matrices) d'une couverture pédologique et à l'analyse de leurs relations structurales est présentée. Dans la seconde partie, plusieurs exemples du milieu intertropical ont été selectionnés pour illustrer cette approche.

Schématiquement, l'approche comprend deux étapes. La première étape consiste à collecter les données de terrain, à établir des analogies (d'un profil à un autre ou d'une toposéquence à une autre) et un inventaire des matrices et des structures qui leurs sont associées, à l'échelle de la couverture pédologique étudiée. La seconde étape est consacrée à l'étude des relations structurales, exprimées en termes de concordance et de discordance. Elle est entreprise sur

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des documents où ont été reportées les différentes structures identifiées. Si les relations de concordance permettent le regroupement de matrices en systèmes pédologiques (ensemble de matrices), les relations de discordance sont utilisées pour circonscrire les systèmes à leur périphérie. Les relations de concordance montrent qu'il existe des règles générales dans la distribution, l'emboîtement des matrices et des structures qui leurs sont associées. Les relations de discordance nous autorisent à subdiviser chaque couverture pédologique en un nombre limité de systèmes pédologiques qui peuvent, eux-mêmes, être regroupés en domaines (ensembles de systèmes pédologiques). Cette subdivision qui respecte la structure d'ensemble de la couverture pédologique rend compte des caractéristiques propres à chaque système pédologique et de la manière dont ils sont articulés. Le raisonnement structural adopté permet également d'établir des filiations entre matrices et d'envisager, de ce fait, une chronologie relative dans la mise en place des matrices et des systèmes pédologiques.

La seconde partie de l'article est consacrée à l'application de l'approche structurale à trois couvertures pédologiques du milieu intertropical (Asie, Afrique et Amérique du Sud). A partir d'exemples, il est montré que le groupement de matrices en systèmes pédologiques puis en domaines permet d'aboutir à une représentation synthétique et simplifiée des couvertures pédologiques qui facilite de ce fait leur comparaison. D'autre part, la caractérisation micro- et ultra-microscopique des constituants de chaque matrice permet de révéler les principaux processus biogéochimiques ou physico-chimiques qui agissent au sein des systèmes pédologiques identifiés.

Enfin, cet article tend à montrer qu'il existe un nombre limité de type de structures, de matrices et de systèmes pédologiques. Aussi, la grande diversité d'organisation des couvertures pédologiques peut être attribuée au simple fait qu'un même type de structure peut contenir différents types de matrices et qu'un même type de matrices peut être observé dans différents types de structures.

Couvertures pédologiques, Systèmes pédologiques, Matrices, Structures, Relations structurales, Transitions entre sols ferrallitiques, ferrugineux et hydromorphes en milieu intertropical

I - INTRODUCTION

The subject most often considered in pedological studies is the vertical organization of the soil, which is taken from a pedon (SOIL SURVEY STAFF, 1975). On that scale, the classification of a soil is most often determined by both the identification of horizons and the way in which they are vertically superposed. However, in order to obtain an understanding of the spatial distribution of soils in the landscape, it is necessary not only to identify these horizons, but also to recognize their boundaries (both lateral and vertical) and their relative distribution on macro-scale. The aim of the study is no longer the pedon but the whole regolith (*sensu* BATES and JACKSON, 1987), which may be confined to a specific landscape unit : an interfluve or a small catchment for instance. The advantage of working on a specific landscape unit scale has long been appreciated. Indeed, the concepts of soil catenas (MILNE, 1934), soil associations (Bodengesellschaft) (SCHLICHTING, 1970), and soil combinations (FRIDLAND, 1974) have already proved to be fruitful. Similarly, the morphological approach of pedology developed by TRICART (1974) and KILLIAN (1974) relies heavily on the relationships between soil distributions and landscape units.

The approach of studying the soil and its components in a three dimensional landscape unit gives added interest to toposequential studies (transects positioned on the steepest axes from a high to a low point). This approach was introduced in Africa by two pedologists from ORSTOM (BOCQUIER, 1971 ; BOULET, 1974). They explained the formation of the soils both by the characterization of their components and by the study, on different scales, of their distribution and spatial relationships.

For the past twenty years, French pedologists have applied this approach to several regoliths both in the intertropical (e.g. BOULET, 1978 ; FRITSCH, 1984 ; LUCAS, 1989) and in the temperate (e.g. CURMI, 1979) zones. Some studies have associated a detailed characterization of the regolith with the study of its hydrological functioning (e.g. BOULET *et al.*, 1979 ; GUEHL, 1984) or with the capacity of the physical environment to produce plants (e.g. BOULET *et al.*, 1984b).

Tab. 1 – ***Components and structures at different organization levels in pedology and in geology.*** Composants et structures à différents niveaux d'organisation en pédologie et en géologie

	Pedology Primary (PM) and secondary (SM) minerals			Geology Primary minerals (PM)		
Scale	Organization levels	Components	Structures	Organization levels	Components	Structures
micro-	mineral	atoms	crystal structures (e.g. networks,) crystalline systems)	mineral	atoms	crystal structures (e.g. networks, crystalline systems)
	plasma	set of minerals (SM)	plasmic structures (e.g. plasma orientation)		set of crystals	mineral structures (e.g. macles, zonations)
scale macro-	matrix	set of minerals (SM and PM)	physical structures (or aggregates : e.g. blocky) boundary structures (e.g. glossic, pocket)	rocks	set of minerals (PM)	rock structures (e.g. granular)
scale	system	set of matrices	boundary structures (e.g. bassin, tongue)	formation	set of rocks	tectonic structures (e.g. layer, eruptive massifs)

In 1977, several authors (Millot *et al.*, 1977 ; Boulet *et al.*, 1977 ; Bocquier *et al.*, 1977 ; Chauvel *et al.*, 1977 ; Nahon and Millot, 1977) demonstrated the decisive role of soil formation processes (including transfer of matter, mineralogical and structural transformations) on the three dimensional organization of the regolith. Furthermore, these authors also demonstrated how these processes control landscape evolution.

These studies all indicate the obvious advantage of approaching the characterization of soils at different organization levels (from micro- to macro-scale, table 1). However, studies involving micro-scale organizations (mineral, plasma, matrix *sensu* Muller, 1987) is only likely to reveal the elementary mechanisms and processes which occur and interact in every regolith. In contrast, studies involving macro-scale organizations (matrix, system) enable the localization of structures as defined below, in which the elementary mechanisms and processes may occur.

The objectives of this paper are : (i) to describe a field method for identifying various macro-structural volumes in regolith, (ii) to illustrate the significance of their relative distribution to each other and (iii) to present three examples from intertropical zones in Asia, Africa and South America to illustrate how this method can be used as a framework for soil-landscape process studies. We also stress how grouping of matrices into soil systems allows for a more simplified form of representing soil-landscapes so as to emphasise particular soil processes.

II – METHOD

1. Definition of structures

In the present paper, the term "structure" does not have exactly the same meaning as that commonly used in field pedology (see e.g. soil survey staff, 1951). We use the term "structure" to simply demarcate any particular volume of components in the regolith which are homogeneous (i.e. in nature and type of relative arrangement ; Foucault and Raoult, 1988). This concept of structure is very similar to the so-called "boundary structures" defined by Brewer and Sleeman (1988) and each particular structure (or volume) can be characterized by size and shape.

In the regolith, the type of components to be considered depends on the scale of observation or organization. At each organization level as shown in table 1 (i.e. from micro- to macro-scale), it is possible to assign one main type of component and structure. Thus for each organization level, a particular type of component can be linked to the type of structure as follows : crystal structure, plasmic structure, physical structure (*sensu* BREWER and SLEEMAN, 1988) of a matrix (or aggregates) and boundary structure of a matrix or of a soil system. This is somewhat analogous to what has already been established in geology (table 1).

This paper will deal only with macro-scale observations and stress the importance of identifying the transition between either two matrices or two systems (matrix set) to reveal boundary structures. Because they are related to organizational levels of higher orders (matrix, system), these boundary structures are largest on the scale of a landscape unit. 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 preferably in trenches of sufficient length and depth or from close spaced profile holes along a transect.

At soil-landscape scale, the boundaries demarcated can be represented by at least three main types of transition between matrices (or systems) as shown between matrices X and Y in figure 1. The first transition type, between matrix X and Y, is very gradual (fig. 1 A). Several intermediate stages may be distinguished. The most typical example in the intertropical zone corresponds to a toposequence in which very gradual (vertically from bottom to top and laterally from the upper to lower parts of the slopes) transition from red to yellow matrices is observed. If the vertical gradient is in meters, the lateral gradient is often in hectometers. At this level, a problem arises concerning the choice of value limits for positioning the boundaries. This choice is arbitrary and depends on the observer. The value limits drawn will thus mark the boundaries of different stages in a gradient that is gradual and continuous.

The second transition type, between matrix X and Y, is abrupt (fig. 1 B). Contrary to the former case, the location of the transition is so obvious that different observers will always position the boundary in the same place. The most typical case corresponds to the extension boundary of the horizons of the podzols (E, Bh, Bs).

Finally, in the third transition type, the transition between matrices remains abrupt but they interpenetrate each other. For example, in going from left to right in figure 1 C : (i) centimeter-size mottles of Y matrix appear in matrix X, (ii) Y mottles increase in size and number, coalesce and isolate the X matrix in the form of mottles and (iii) the remnant X mottles decrease in size and number, and disappear. In intertropical zones, this type of transition is usually related to increasing reductomorphic processes. In cross section, the precise demarcation of the transition between these two types of matrices would involve a somewhat detailed but unnecessarily complicated study. However, a more simplified representation of the gradient discussed above is therefore used. Such a representation will give an account of the relative proportion of matrix Y in relation to matrix X. The percentage of matrix X can be estimated or quantified and value limits (or envelope curves) arbitrarily selected as in the first type of transition (fig. 1 A). For example, in figure 1 C, the following three envelope curves have been demarcated :

(i) the appearance of matrix Y mottles in matrix X ;
(ii) the matrix Y mottles coalesce, giving rise to remnants of matrix X as mottles ;
(iii) the disappearance of remnant X matrix mottles.

These transitions between matrices may be established on the basis of a differentiation which may concern a single characteristic only (e.g. colour or particle size distribution) or a group of characteristics which may vary simultaneously and are correlated with each other (e.g. colour and aggregation stage). This proposed method of firstly demarcating single characteristics rejects initial grouping of several characteristics which would limit or compromise the correct recognition of the structural relationships.

The transitions between matrices can be represented in cross sections (toposequences or parts of toposequences), maps or block diagrams. In these representations, the demarcated boundaries define the main structures at the landscape unit scale. Among these structures, the two dimensional representations (cross sections or maps) correspond to curves and the three dimensional representations (block diagrams) cor-

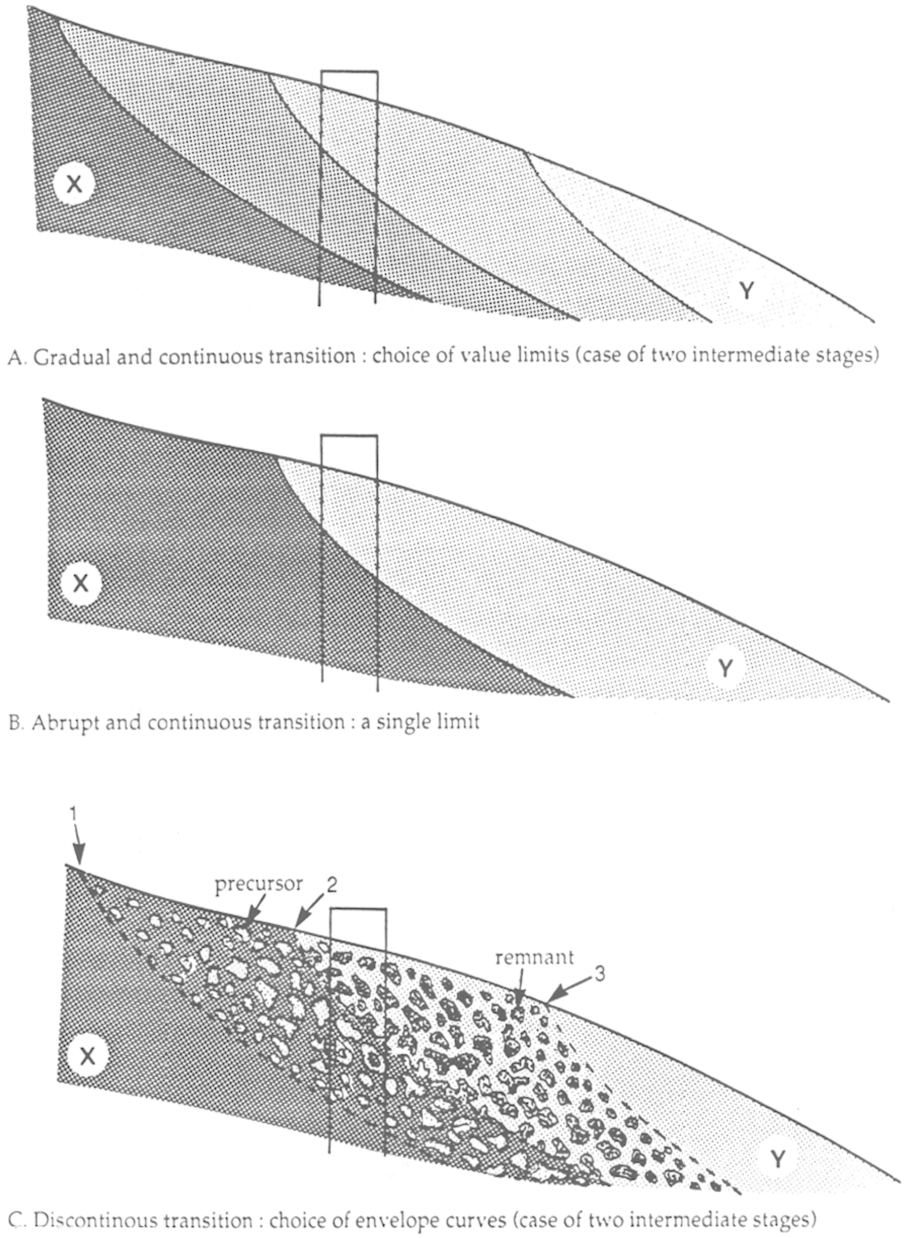


Fig.1 – ***Major types of transition between two matrices (X, Y) at a toposequence scale where rectangle represents a soil profile : three different transitions for a same structure type.*** Principaux types de transition entre deux matrices (X, Y) à l'échelle d'une toposéquence (le rectangle représentant un profil) : trois sortes de transition pour un même type de structure

respond to volumes. In the two dimensional representations, they may be associated with the concept of the isovalue curve (e.g. TURENNE, 1977) or the isodifferentiation curve (BOULET *et al.*, 1982).

2. Types of boundary structures

Boundary structures of regolith may be grouped in two major families depending on whether they have been inherited from lithology or acquired during pedogenesis. On these grounds, the regolith includes the following : rock substratum, saprolite and solum. Schematically, the passage from rock to saprolite takes place showing the appearance of the saprolitic texture (juxtaposition of large secondary minerals ;

MULLER, 1987) and maintaining the lithological structures of the bed rock. In contrast, the passage from the saprolite to the solum marks the disappearance of both the lithological structures and saprolitic textures. This is coupled with the appearance of soil textures (strongly and closely associated and finely-devided secondary minerals ; MULLER, 1987) and physical soil structures (matrices fragmented into aggregates). The transitions between rock, saprolite and solum are often more complex because they frequently interpenetrate each other. Thus, saprolite matrices may appear in certain fissures of the fresh rock and inversely fresh rock fragments may be found in the saprolite and solum. Likewise, soil differentiation may occur in the saprolite and inversely saprolite fragments may remain in the solum, whilst gradually being transformed. These interpenetrations suggest differential rock weathering and pedogenetic processes due to lithological heterogeneities (e.g. FRITSCH *et al.*, 1990 a).

a) Structures inherited from lithology

The substratum (rock) heterogeneities are the origin of inherited lithological (or saprolitic) structures in the regolith. The more distinct the substratum heterogeneities (cases of facies or rock changes) are in the regolith, the greater the inheritance. These inheritances are frequent in soils developed on sedimentary or metamorphic rocks.

The structures inherited from lithology are fairly diversified (e.g. chevron, discontinuous blocks and lithorelic nodule alignments). A comprehensive inventory is not made here but two examples of these structures are given. Figure 2 shows two different structure types : a chevron structure demonstrating the saprolite–soil transition, and a discontinuous subhorizontal block and nodule alignment structure. In close vicinity to the saprolite, the nodules are aligned in structural concordance with the dip of the rock. Due to chemical erosion and creeping which is greater nearer the soil surface, these alignments change direction in accordance to the slope and thus reflect the *in situ* formation of a "stone line".

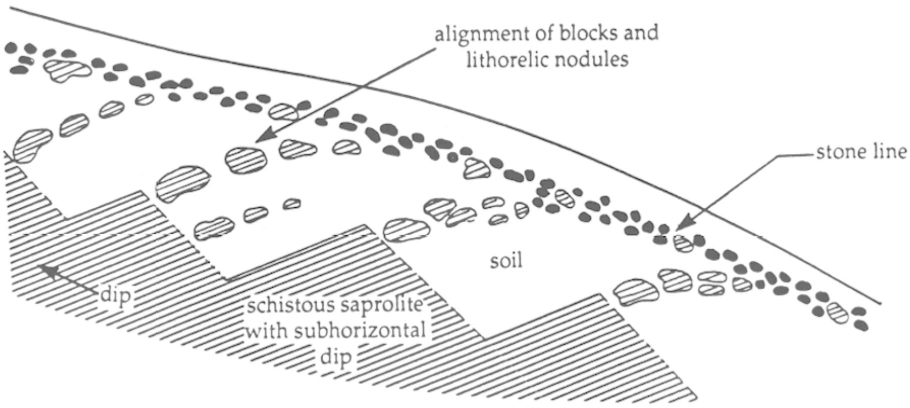


Fig.2 – *Example of inherited lithological structures in an interfluve (Kattinkar, India) : chevron structure (saprolite–soil transition), sub-horizontal and discontinuous block and lithorelic nodule alignments.* Exemple de structures lithologiques héritées dans un interfluve (Kattinkar, Inde) : structure en chevrons (transition saprolite–sol), alignements sub-horizontaux et discontinus de blocs et nodules lithorelictuels

b) Structures linked with pedogenesis

There are two main types of pedological structures on the landscape unit scale (fig. 3). These have either a non finite boundary (open volumes) or a finite boundary (closed volumes).

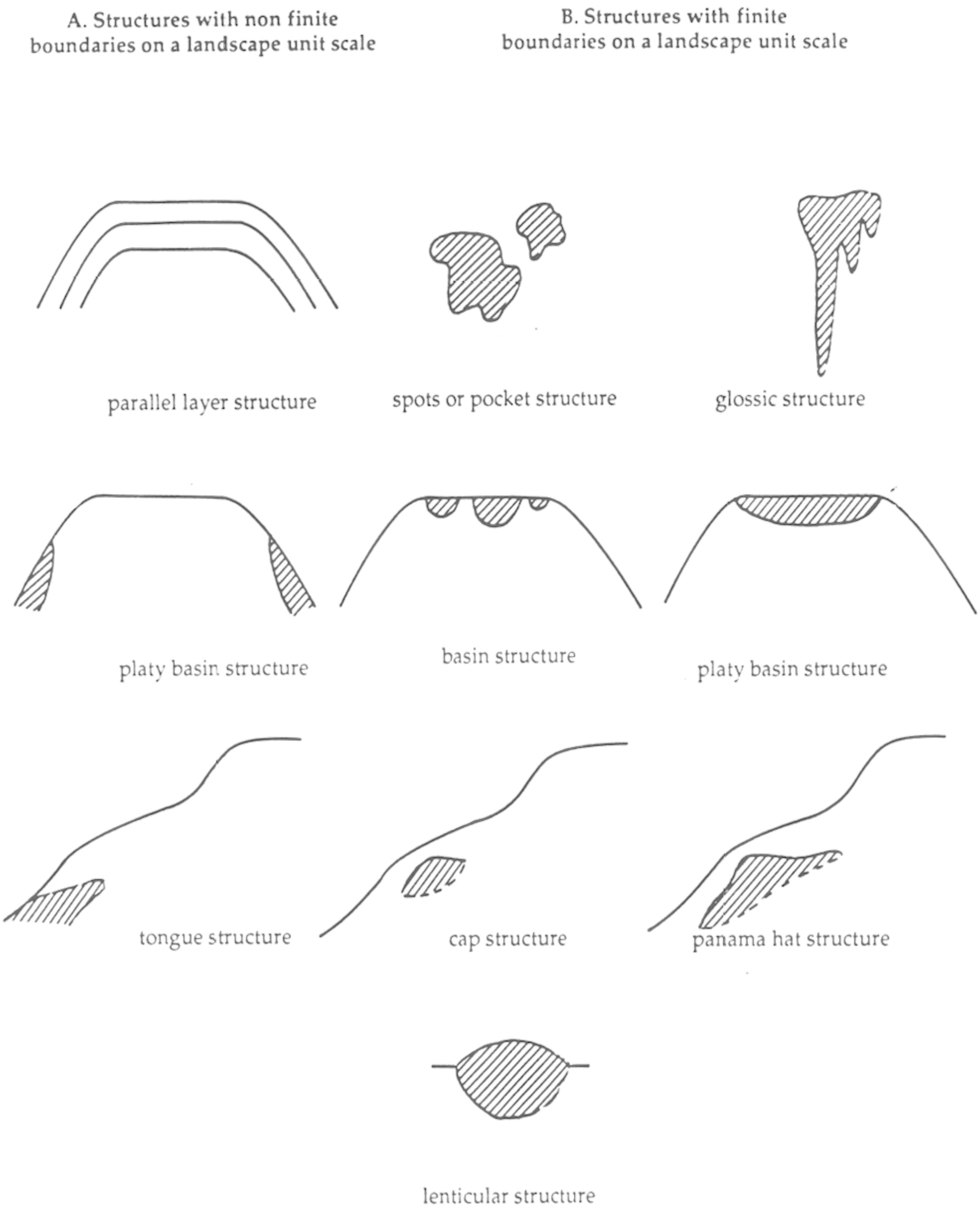


Fig.3 – *Examples of pedological structures at meter scale for pocket, glossic, lenticular structures and, at a toposequence scale, for the other structures.* Exemples de structures pédologiques à l'échelle du mètre pour la structure en tache, en glosse ou en lentille, et à celle de la toposéquence pour les autres structures

The first case (open volumes) (fig. 3 A) concerns structures in parallel layers, certain platy basin structures and tongue structures. The former are roughly parallel to the topographical surface. The two others have a radial distribution with respect to the drainage axes (e.g. rivers).

In the second case (closed volumes) (fig. 3 B), three large structure types may be observed as follows according to the relative size of their vertical and lateral extension :

(i) virtually equivalent vertical and lateral extension : pocket, basin, cap, lenticular (internal basin with cap) structures ;

(ii) dominant vertical extension : glossic structures ;

(iii) dominant lateral extension : platy basin and panama hat structures.

Research carried out to date shows, on the matrix scale, a very limited number of such boundary structures. However, very different components may be found in identical boundary structures. For example, several lenticular structures have been observed in an interfluve from India (PETERSCHMITT, 1991). On the midslope (fig. 4 A), the structure contains a yellow matrix and downslope (fig. 4 B) white matrices overlie ochre and brown-black matrices. Similarly, in the second example (fig. 4 B), a lenticular structure is nested in a larger other one and contents of each of them are slightly different.

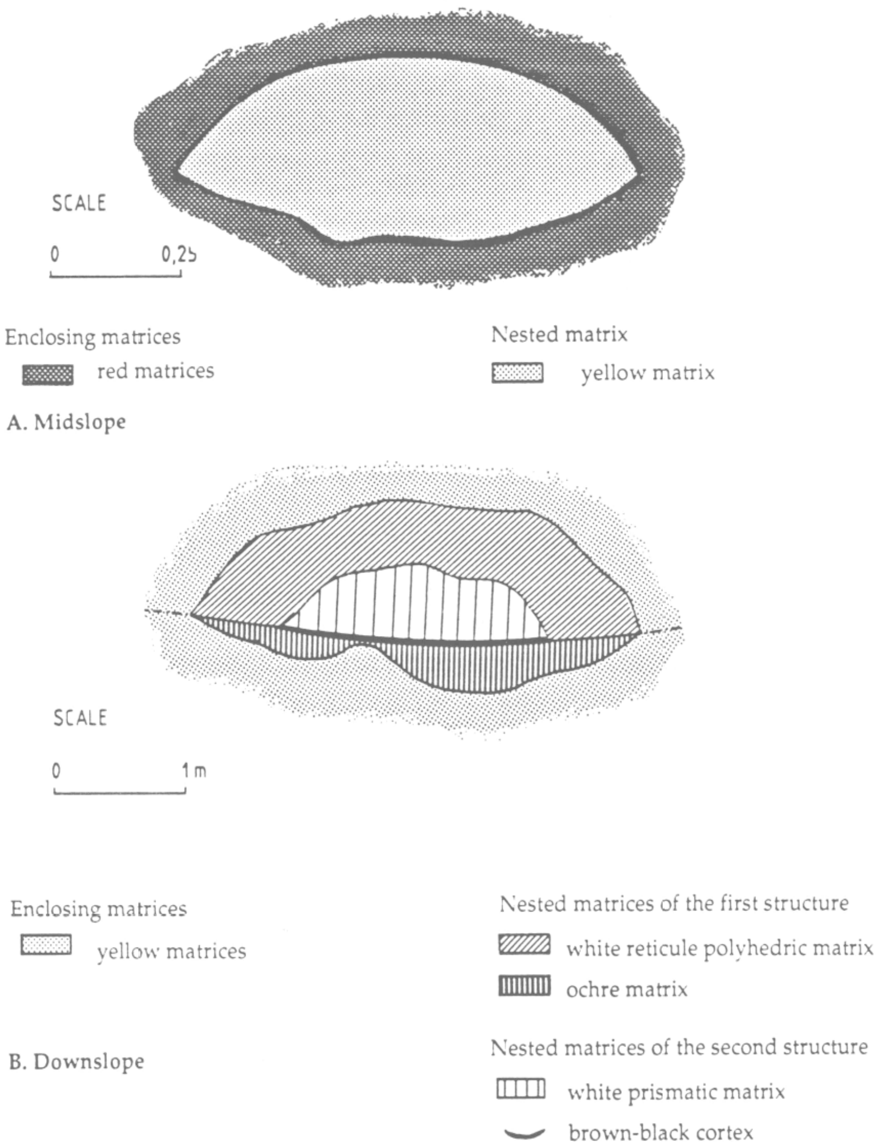


Fig.4 – *Example of a same type of structure (lenticular structure) with different types of matrices in an interfluve (Kattinkar, India).* Exemple d'un même type de structure (en lentille biconvexe) contenant différents types de matrices dans un interfluve (Kattinkar, Inde)

3. Structural relationships

Figure 5 A displays the set of boundary structures (transition between matrices) recognized in a toposequence from Ivory Coast (FRITSCH *et al.*, 1990 a). On the basis of this representation, certain boundary

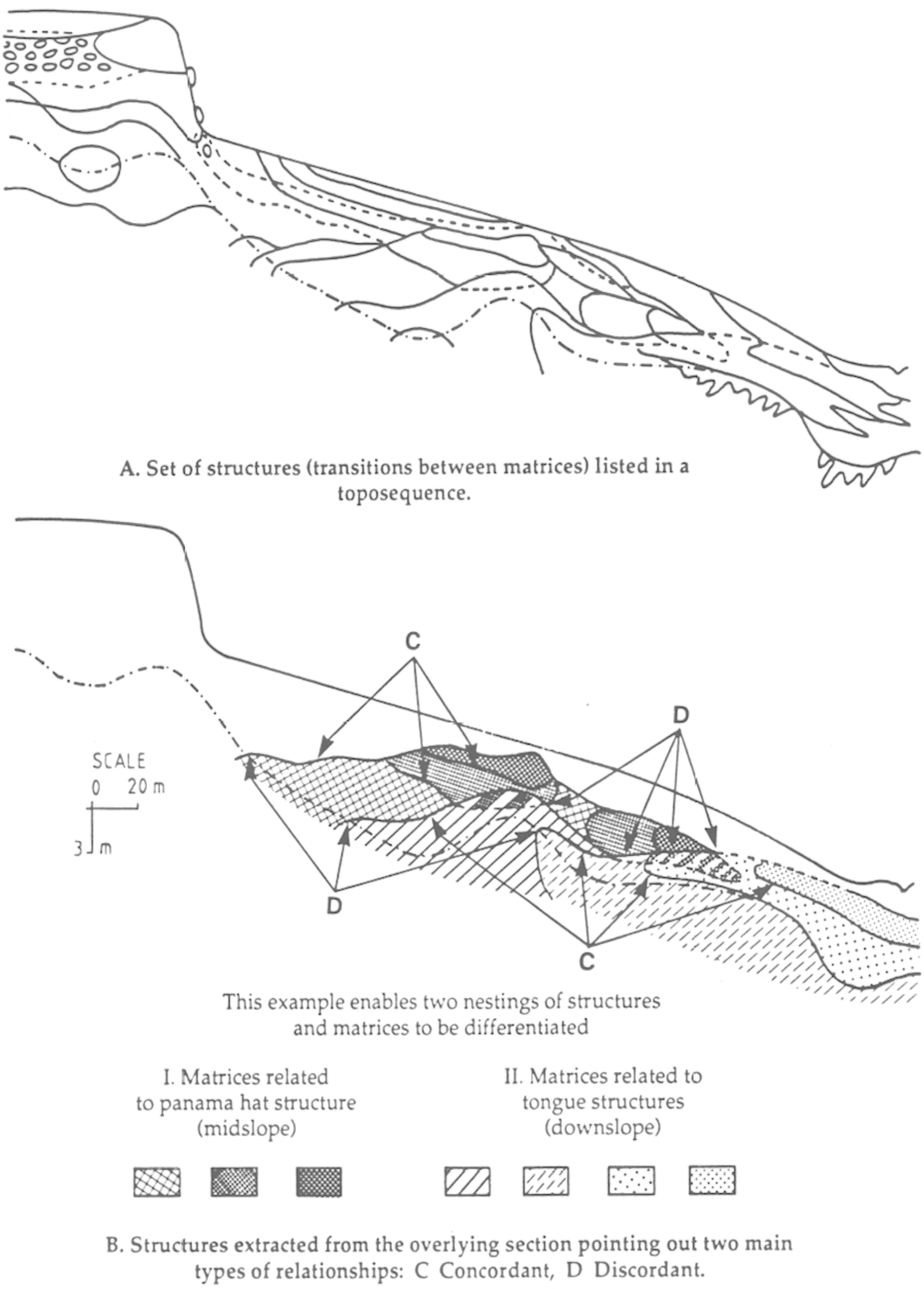


Fig.5 – *Inventory of structures and example of structural relationships on a toposequence scale (Booro Borotou, Ivory Coast). With respect to the scale of the sketches, the vertical scale of soil structural volumes is enlarged by factor of two.* Inventaire des structures et exemple de raisonnement structural établi à l'échelle d'une toposéquence (Booro Borotou, Côte d'Ivoire). Par rapport aux échelles topographiques, celle verticale des volumes pédologiques est multipliée par un facteur deux

structures have been retained (fig. 5 B) to point out the two major types of structural relationships identified which are : concordant and discordant (respectively C and D on figure 5 B). Concordant structures never intersect. They are either superposed (in the case of parallel layer structures), or nested into each other (in the case of other boundary structures). In this second case, the structures are often reproduced on increasingly smaller scales. Thus in figure 5 B, nesting of panama hat structures in the medial part of the slope and a nesting of tongue structures in the lower part of the slope have been noted.

Discordant structures need to be considered with more care and two general cases may be observed. The specific characteristics of each of the three matrix types (X, Y, Z) are sufficient to distinguish them (fig. 6). In both cases, the envelope of the matrix Z intersects at the transition between X and Y. In the first case, all the Z characteristics are different from those of the other two matices (juxtaposition of matrices). In the second case, matrix Z is identified by a single characteristic which is absent in both X and Y matrices (e.g. a different colour). This characteristic, however, does not completely mask the transition between X and Y. In other words, this new characteristic (specific to Z) is superimposed on a previous differenciating characteristic. The interpretations given to these two types of discordance may differ slightly. In the first case, there may have been distinct formational phases without establishing relative chronology, whereas in the second case, the superimposition indicates that the new Z characteristic is formed later compared to the differentiation between X and Y.

A. Discordant with juxtaposition : Z intersects the transition between X and Y (abrupt discontinuity)

B. Discordant by superimposition : Z is superimposed on X and Y (interpenetration)

Fig.6 – *Schematic representation showing the two types of discordant relationships between matrices (X,Y,Z).* Représentation schématique montrant les deux types de discordance structurale entre matrices (X,Y,Z)

4. Interpretations deduced from structural relationships

a) *Grouping of matrices into sub-systems, systems and domains*

As a whole, the concordant and discordant structural relationships enable certain structures and the matrices they contain to be grouped within large sets termed soil systems. Thus, based on structural criteria, any soil system is defined as being an ordinate succession of matrices superposed or nested into one another. Structures are concordant when related to a soil system but are discordant at the transition between soil systems (FRITSCH *et al.*, 1986 a).

Although the concordant and discordant relationships are sufficient to demarcate the boundaries of soil systems, chemical and mineralogical data are necessary to define and characterize each of them. Moreover, chemical and mineralogical characterization of the matrices of a soil system make it possible to conclude that the soil system results from a predominance of one or several soil processes (e.g. more or less selective leaching, eluviation, illuviation) which may surperimpose and obliterate the resulting effect of previous soil processes (e.g. ferralitization, fersialitization).

Based on chemical and mineralogical criteria, certain soil systems can be subdivided in two or more sub-systems, each being characterized by predominance of only one (e.g. more or less selective leaching) or two (e.g. eluviation–illuviation, podzolization) soil processes.

In contrast, at a landscape scale, certain adjacent systems may be grouped into domains. This grouping of soil systems is based on the predominance of one or several types of soil formation processes (e.g. ferralitic domain, ferruginous and hydromorphic domain, podzolic and hydromorphic domain).

b) Chronology of matrix formation

The relative distribution and the mineralogical relationships between matrices enable the establishment of affiliated linkages within the soil systems and chronological relationships between matrices and soil systems.

Within each system, the concordant structures enable affiliated linkages and chronological relationships between matrices to be established. From this point of view, two major soil system types can be distinguished. In cases of parallel layer structures, each matrix may originate from the transformation of the directly underlying layer. The progress of such a possible transformation takes place from top to bottom according to direction of solute percolation through the regolith (gravitational flow). Similarly in cases of nested structures (e.g. pockets and tongues), the succession of matrices from outside to inside will undergo different major stages of transformation which normally progresses radially. Although each matrix may have some characteristics which are inherited from previous matrices of the regolith, their nesting testifies that they are the core of transformations. Hence, in nested matrices of a soil system (e.g. tongues as shown in figure 7), each successive external matrix is considered to be less transformed than the corresponding internal matrix.

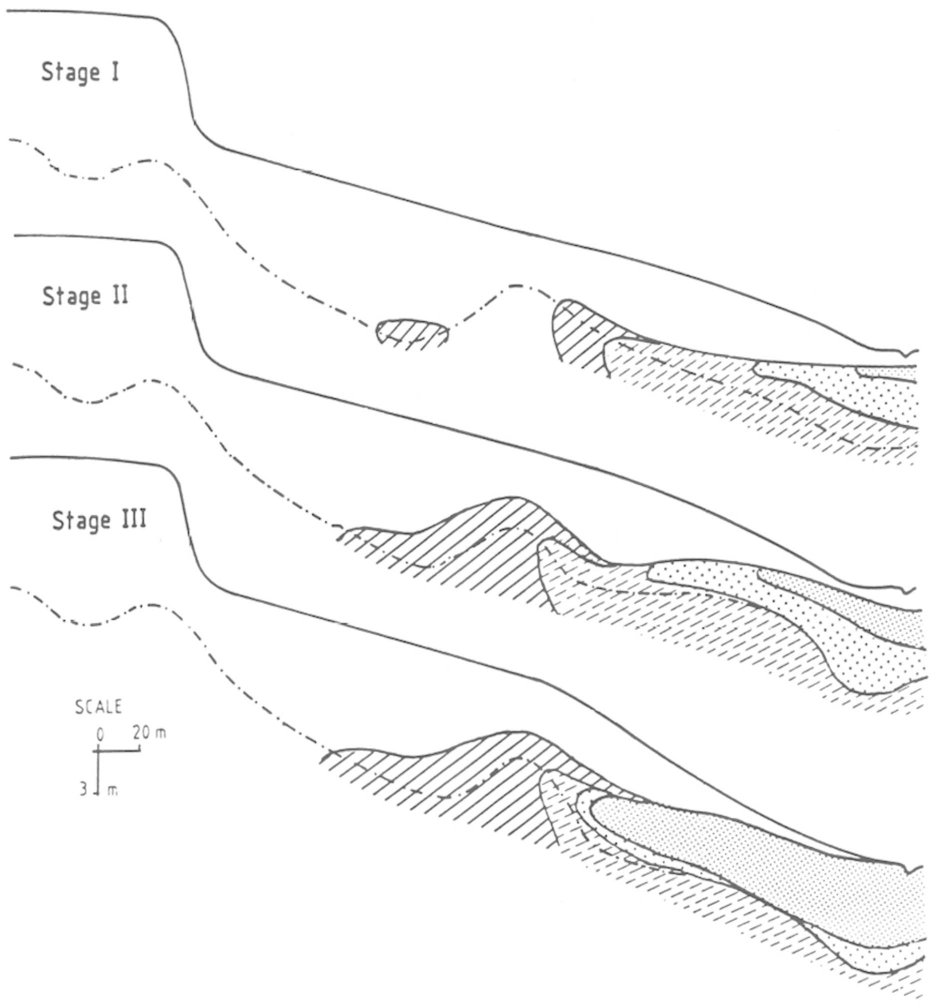


Fig.7 – *Expansion of an hydromorphic soil system upslope (Booro Borotou, Ivory Coast). Scales and shading as for figure 5 B.* Expansion vers l'amont d'un système hydromorphe (Booro Borotou, Côte d'Ivoire). Echelles et trames identiques à celles de la figure 5 B

At transitions between soil systems, discordant structural relationships enable chronological relationships to be established. These relationships may only be considered in cases of a superimposition of new characteristics on a previous soil system (see fig. 6 B).

c) *Soil system evolution*

At landscape scale (e.g. interfluve) or regional scale (sets of interfluves on the same type of substratum for a given climate), multitoposequences studies display almost identical matrices, structures and related distributions. From one toposequence to another, the only significant variations refer to the relative extension of a matrix or a soil system to each other on the slope. The latter frequently occurs in relation to slope shape.

Following selection of the most representative toposequences, it is possible to trace the genesis of the regolith by identifing the main stages of the expansion or contraction of soil systems (BOULET *et al.*, 1977). Selected toposequences are easier to interpret when each soil system is considered separately (FRITSCH *et al.*, 1986 b). Figure 7 shows three different stages in the development of a hydromorphic soil system with nested tongue structures observed in a catchment from the Ivory Coast. Hydromorphic soil formation is explained simply by the successive expansion of the various matrices as well as the soil system upslope. In addition, it should be noted that the most internal matrix within the soil system expands gradually in going from stage 1 to stage 2 but in stage 3 the expansion become so large that it compresses the outer matrices which disappear in places.

The expansion of one soil system will always take place to the detriment of one or more other soil systems. Thus, on a landscape unit scale, two main domains can be distinguished. The soil systems of the first domain are in a potentially contracting phase while those of the second domain are in a potentially expanding phase. On a landscape or regional scale, the contraction or expansion of a soil system (or a domain), in relation to each other, is the result of differential soil system (or domain) development. Some studies have shown that this differential soil system (or domain) development in the regolith can be controlled by both internal (lithologic) and external (climatic and tectonic) factors (e.g. BOULET, 1974 ; BOULET *et al.*, 1984 a and b ; FRITSCH *et al.*, 1990 a and b).

III – APPLICATION OF THE METHOD TO CERTAIN EXAMPLES

The examples given are taken from three structural studies carried out on three different continents (Asia : India, Africa : Ivory Coast and South America : French Guiana). This chapter is restricted first to the application of the structural approach to two different scales (matrix, system) and second to the demonstration that the grouping of matrices into systems makes its possible to establish the main lines of the organization of regolith.

1. Examples of structural relationships

From the definition given to soil systems it is apparent that concordant relationships are better observed within each soil system and that, in opposition, discordant relationships appear more distinctly on their peripheries. Indeed, the preferential development of a system in relation to another, on the one hand, reveals new nested structures and, on the other hand, gradually makes the structures of the enclosing system disappear. Thus, discordant relationships between the structures of these two systems will be increasingly indistinct the greater the distance from their transition zone. Consequently, in the following examples, concordant relationships have been established between matrices within a soil system and discordant relationships, more often than not, have been established between soil systems, in other words, between matrix sets.

a) *Concordant structures within soil systems*

Two pertinent examples showing concordant structures have been observed in downslope positions in landscapes of the intertropical zonc (fig. 8). They belong to hydromorphic soil systems in ferralitic environments. In the first example (PETERSCHMITT, 1991), a double lenticular structure, on a matrix scale, appear downslope. It contains four types of matrices in going from top to bottom in figure 8 A as follows : a white polyhedric matrix (1), a white prismatic matrix (2), a brown-black goethitic cortex (3) and a bright ochre goethitic matrix (4). With respect to the pale yellow coloured surrounding matrices, the former two comprise deferruginized levels and the latter two ferruginized ones. The external boundary of both 1 and 4 matrices demarcate the first larger lenticular structure and the external boundary of both 2 and 3 matrices demarcate the second smaller lenticular structure which is nested in the first. The matrices of the second lenticular structure correspond to a more advanced stage of transformation than those of the first one. The transformation consists primarily of deferruginization in the upper part and ferruginization (goethitization) in the lower part of each lenticular structure and develops radially in the pale yellow surrounding coloured matrices.

In the second example (FRITSCH *et al.* 1990 a), five tongue structures are nested (fig. 8 B). The first (and most external) envelope (1 on fig. 8) marks the appearance of white mottles in the surrounding organizations consisting either of soil matrices (red, ochre or mottled matrices, the latter grading towards induration) or of coloured saprolite matrices (lithochromic). The second envelope (2 on fig. 8) localizes the position where these white mottles become sufficiently large and numerous to coalesce (fig. 1 C). As in example one concerning the lenticular structures (fig. 8 A), these two tongues correspond to two different stages of deferruginization, at first prominent and sparse, then becoming more extensive. This characterizes a hydromorphic soil system which progresses upslope. With respect to the surrounding matrices, the last three tongue structures (3, 4, 5 on fig. 8) and the matrices they demarcate show a gradual loss of clay (grey or white sandy clay loam to sandy matrices) from the upper part and its accumulation in the lower part (macro illuviation cutans in sandy-clay soil matrice and in saprolite). They show two stages of clay eluviation in the upper part and clay illuviation in the lower part, thereby characterizing an eluvial–illuvial sub-system nested in a hydromorphic soil system.

b) *Discordant structures between soil systems*

As previously demonstrated (fig. 6), discordant structures either show a juxtaposition of matrices or are the result of a superimposition of new types of characteristics. These two possibilities will be considered separately below where two examples are given for each type of discordance.

Discordant with matrix juxtaposition

Example A (fig. 9 A) occurs frequently in intertropical zones and can be observed on a profile scale. A lithorelic nodule alignment set appears discordant on the vertical differentiation of the profile. It is very difficult to establish a relative chronology of formation between indurated and loose matrices. On the other hand, relationships are established between a subvertical and discontinuous structure inherited from the lithology, and a horizontal structure (in parallel layers) linked with pedogenesis. Some studies (e.g. MULLER *et al.*, 1981 ; FRITSCH, 1984) have shown that this discordance was the result of a double and parallel mode of formation (in going from bottom to top) between ferruginized saprolite mottles and loose soil matrices which in contrast deferruginize. This duel mode of formation is related to lithological heterogeneity.

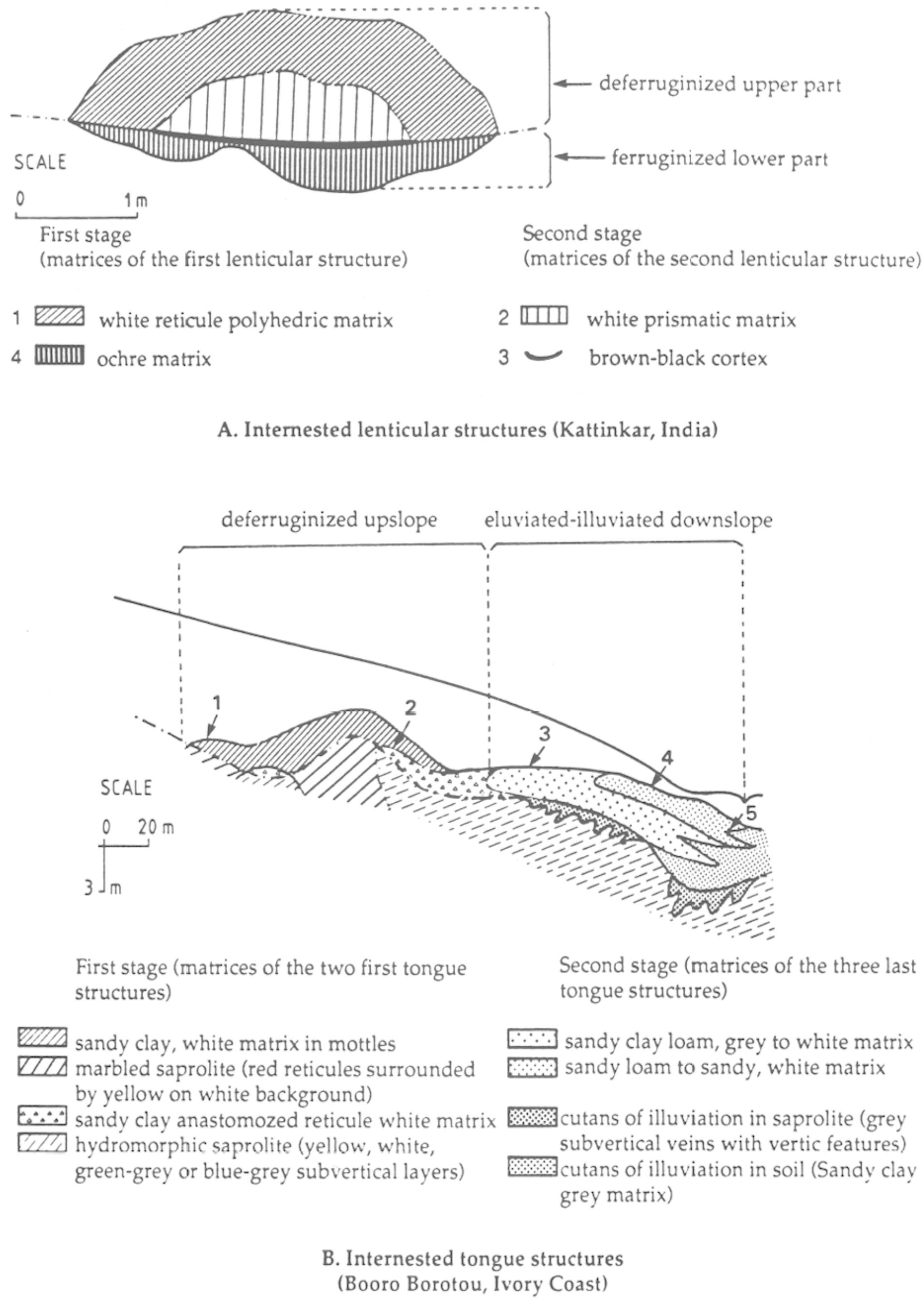
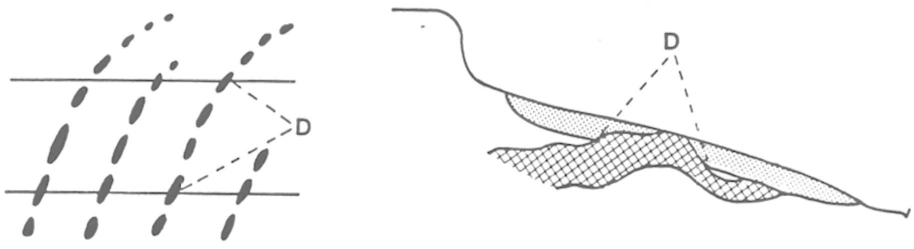


Fig.8 – *Examples of concordant structures within hydromorphic soil systems in a ferralitic environment.*
Exemples de concordances structurales au sein de systèmes hydromorphes dans un environnement ferralitique

Example B (fig. 9 B) as presented by FRITSCH *et al.* (1990 a) was established at the soil system scale. In the mid-slope position a ferricrete soil system outcrops (panama hat structure grouping with a set of mottled matrices grading towards induration) and divides a superficial ferruginous soil system (platy basin structure grouping with a set of ochre to yellow matrices) in two parts. The transition between the two soil systems is very abrupt. Similarly, their matrices are abruptly different in their respective organization in that no chronology can be established. Importantly, it is impossible to know by structural relationships alone whether the superficial ferruginous soil system developed before or after the ferricrete soil system.



A. On a profile scale between a lithological subvertical nodule alignment and a pedological parallel layer structure
D = Discordant

B. On a soil system scale between a panama hat structure and a platy basin structure (Booro Borotou, Ivory Coast)
D = Discordant

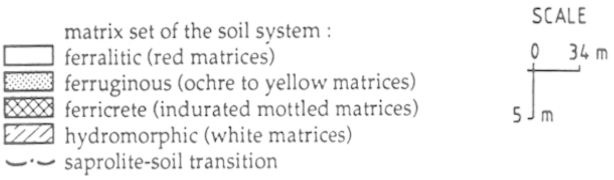
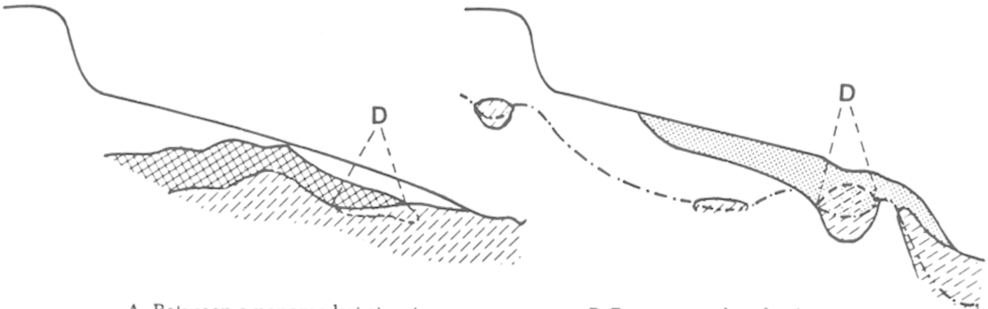


Fig.9 – *Examples of discordant structures with matrix juxtaposition.* Exemples de discordances structurales avec juxtaposition de matrices



A. Between a panama hat structure (ferricrete system) and a tongue structure (hydromorphic system)
D = Discordant

B. Between a platy basin structure (ferruginous system) and a pocket structure (hydromorphic system)
D = Discordant

Fig.10 – *Examples of discordant structures by superimposition on the periphery of soil systems (Booro Borotou, Ivory Coast). With respect to the scale of the sketches, the vertical scale of soil structural volumes is enlarged by a factor of two.* Exemples de discordances structurales avec superimposition à la périphérie de systèmes pédologiques (Booro Borotou, Côte d'Ivoire). Par rapport aux échelles topographiques, celle verticale des volumes pédologiques est multipliée par un facteur deux

Discordant between soil systems by superimposition

Example A (fig. 10 A) as presented by FRITSCH *et al.* (1990 a) was established at the soil system scale. Where the hydromorphic soil system intersects the ferricrete soil system, the latter breaks up into nodules and blocks of ferricrete. Example B (fig. 10 B), from the same landscape unit as shown in example A, represents a hydromorphic soil system which is superimposed locally in the superficial ferruginous soil system due to the occurrence of white reductomorphic mottles. In both examples, the superimposition of the hydromorphic soil system on other soil systems illustrates : (i) that the hydromorphic soil system can form in other soil systems at a later stage, (ii) that the hydromorphic soil system develops faster and at the expense of other soil systems. This hydromorphic soil system corresponds to the part of the regolith where mineralogical transformations and geochemical evolution are the most active at present (FRITSCH *et al.*, 1990 b).

2. Synthesis of the organization of three regoliths

In the three selected examples (fig. 11), previous studies devoted to the detailed characterization of three regoliths have enabled the soil processes which develop within the structures identified in the field to be determined. Spatial expansion and development trend with time of the processes identified are defined by the analysis of these structures and of their relationship.

The Indian example (PETERSCHMITT, 1991) is specific to the forests and savanna hills on the back slopes of the Western Ghats (South-West India) (fig. 11 A). It is the simplest of the three examples given with each soil system corresponding to a domain. It comprises a ferralitic domain (or soil system) at the hilltop, and a ferruginous and hydromorphic domain (or soil system) in the medial and lower positions of the landscape unit. Locally, the ferruginous and hydromorphic soil system appears at the midslope position (pocket or lenticular structures) and increases in extent downslope (tongue structure). Pockets (or lens) are larger and more numerous the closer they are to the tongue structure. They may, therefore, be considered as precursors of soil chemical processes which increase considerably downslope. In this ferruginous and hydromorphic soil system two sub-systems can be perceived : a ferruginous sub-system (yellow matrices) into which, at the foot slope position, a pseudogley sub-system (white matrices) is nested. In certain places at the foot slope position, this pseudogley sub-system includes double lenticular structures mentioned previously (fig. 4 B or 8 A).

The Ivory Coast example (FRITSCH *et al.*, 1990 a) is characteristic of the plateau landscape in the West African forest–savanna transition zone. It consists of two domains and four main soil systems (fig. 11 B).

The ferralitic domain occupies the high positions in the landscape unit and includes two soil systems : a ferricrete soil system and a ferralitic one (loose red clayey matrices). The ferricrete soil system "shields" the landscape at two levels : on the plateau and at midslope positions. In general, it "caps" the upper part of the saprolite which, in these topographical positions, appears to be nearer the soil surface. The ferralitic soil system is always adjacent to the ferricrete soil system.

The ferruginous and hydromorphic domain occupies the low lying positions in the landscape unit. It consists of two soil systems : a superficial ferruginous soil system and a hydromorphic soil system. The ferruginous soil system has a platy basin structure which rarely exceeds the upper metre of the regolith. Although it generally occurs along foot slope positions, it may also appear between the edge of the plateau and the mid-slope nickpoint but occurs less frequently in the center of certain plateaux that are temporarily flooded (not represented in the figure). In the upper part, this soil system consists of ochre to yellow sandy clay matrices in which slightly coloured sandy clay loam to sandy matrices are nested downslope. This lateral gradient marks the following two stages of a subtractive and selective mode of formation (FRITSCH *et al.*, 1989) : (i) deferruginisation with selective dissolution of hematite (yellowing of the matrices), then of goethite (bleaching of matrices) and (ii) loss of clay, mainly kaolinite (eluviation and, or impoverishment).

The hydromorphic soil system increases in extent downslope (from the mid-slope nickpoint to the river) and shows a tongue structure (fig. 11 B). Like the ferruginous soil system, it is found locally, between summit and mid-slope nickpoint, but only at depth (pocket or lenticular structure, see fig. 10 B) in the saddles defined by the top of the saprolite. Downslope, it subdivides into a pseudogley and gley sub-system into which an eluvial–illuvial sub-system is nested (see also fig. 8 B). The latter is most developed in the flat ground and in lateral branches of the river in the catchment. By internal removal, the eluvial–illuvial sub-system appears to be the origin of the shaping of the lower parts of the landscape unit. Its nesting in a larger hydromorphic soil system enables its formation to be linked with the action of the groundwater (FRITSCH *et al.*, 1990 b). The eluvial part of this sub-system acts as a perched reservoir for groundwater where flow is fast (during filling or emptying). By plugging the pores, the illuvial part limits internal flow towards the river, and enables the

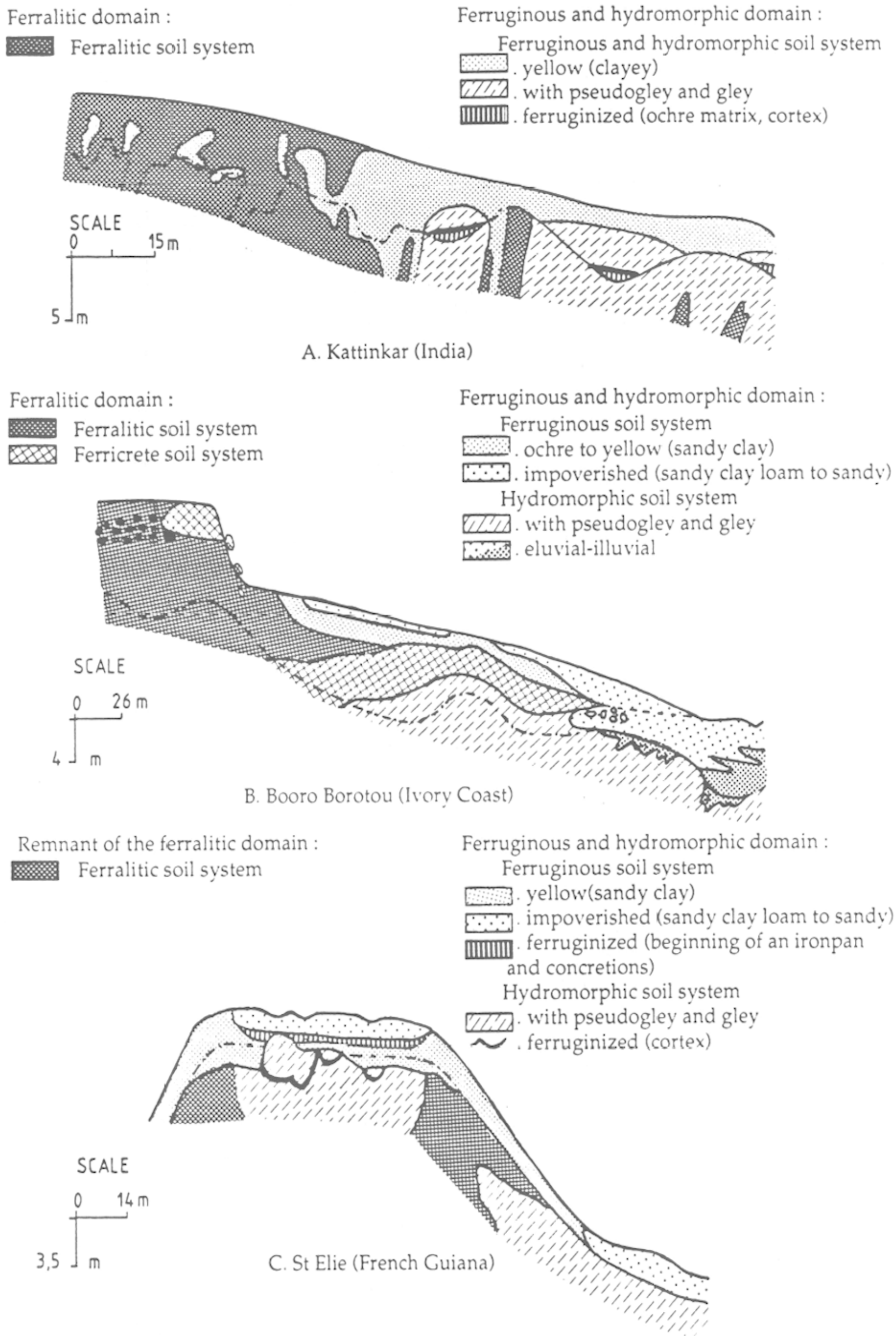


Fig.11 – ***Simplified form of representing three regoliths in domains and soil systems. With respect to the scale of the sketches, the vertical scale of soil structural volumes is enlarged by a factor of three in Kattinkar and of two in Booro Borotou and St Elie.*** **Représentation synthétique de trois couvertures pédologiques en domaines et systèmes pédologiques. Par rapport aux échelles topographiques, celle verticale des volumes pédologiques est multipliée par un facteur trois pour Kattinkar et deux pour Booro Borotou et St Elie**

filling and possible overflow of the groundwater. It should be noted that the illuviated part of the sub-system only appears upstream of certain rock outcrops situated in the riverbed.

The Guianese example (FRITSCH, 1984 ; FRITSCH *et al.*, 1986 a) is specific to certain tabular-topped hills in the Amazonian ferralitic forest environment. It shows the presence of two domains and three soil systems (fig. 11 C). In this example, the ferruginous soil system has overrun the whole upper part of the regolith and the hydromorphic soil system occurs at greater depth in two places : in the lower parts of the slopes and in the middle of the plateau. From this relative distribution, it is apparent that remnants of the ferralitic soil system (aureole and island-shaped) occupy the plateau edge.

Two platy basin structure sub-systems are nested in the yellow matrices (clay to sandy clay) of the ferruginous soil system. The first can be seen downslope and consists of sandy clay loam to sandy matrices showing clay losses (eluviation). The second can be seen in the plateau and consists of sandy clay loam matrices impoverished in clay (eluviation), overlying a yellow ochre ferruginized goethitic matrix. This diffuse accumulation of goethite with more locally concentrated zones (concretions and onset of incipient ironpan formation) gradually waterproofs the matrix and enables a perched water to be filled during the rainy season. This sub-system is thus subtractive for iron in its upper part and additive for iron in its lower part. Locally, the formation of incipient ironpan fragments (Bs) is proof of the onset of podzolization.

The hydromorphic soil system mainly develops in the saprolite of the schistous substratum, which it transforms first by deferruginization, then, by muscovite kaolinitization (formation of pseudogley and gley). This soil system always occurs downslope. In the plateau, it appears in the form of a basin which nests in lenticular structures of different sizes and sometimes coalesce. These lenticular structures are made up of a deferruginized and kaolinized (gley) upper part and a ferruginized lower part (narrow edged or brown-red cortex at the base of lenticular structures). In some parts of the hill, the lower hydromorphic soil system joins the upper one. The ferralitic system is thus cut off from its roots. It seems to "float" in a waterlogged environment, which is permanent in depth and temporary close to the surface. Knowledge of the regional soil environment (FRITSCH, 1978 ; BOULET *et al.* 1984 a) suggests that the hill studied corresponds to the final stage of the breakdown, by hydromorphy, of ferralitic regoliths formerly developed on schist.

From these three studies, it is apparent that the general tendancy is the breakdown and transformation of organizations related to the ferralitic domain whenever waterlogging conditions appear. The contraction of the ferralitic organizations in the landscape is coupled with the expansion of organizations related, in this case, to the ferruginous and hydromorphic domain. The first stage of this general transformation corresponds to the formation of yellow matrices retaining the same clay content as in the red surrounding matrices of the ferralitic domain. This "yellowing" process of initial red clay matrices is a prerequisite to any further processes such as clay eluviation (fig. 11 B and 11 C) or podzolization (fig. 11 C). In certain cases, the yellowing process precedes the bleaching process in the formation of pseudogleys (fig. 11 A) and is thus evidence of onset of hydromorphic conditions. On the other hand, the structures, in which the matrices of the ferruginous and hydromorphic domain are observed, reveal two kinds of spatial expansion. Thus, the structures, adjacent to the topographical surface, in the form of platy basin structures of different sizes, are the result of a superficial development (fig. 11 B and 11 C). In contrast, pocket and tongue structures are an indication of internal development (fig. 11 A) within the regolith. Whereas the former are often linked with decreasing water percolation, at the onset of saturation and lateral water flow (e.g. HUMBEL, 1978 ; BOULET *et al.*, 1979 ; GUEHL, 1984), the latter may be attributed to the presence of temporarily or permanently waterlogged zones (e.g. MONIZ and BUOL, 1982). Finally, the ultimate phase of development of these systems results in residual accumulation of quartz sands (eluvial part of the soil systems). Two cases may then be distinguished according to whether the residual quartz accumulation occurs in a semi-confined or open environment. The semi-confined case is differentiated from the open environment by the presence of an accumulation zone underneath or in the lower part of a leaching zone. This accumulation concerns either iron (fig. 11 A and 11 C), or clay (fig. 11 B). By plugging the pores, it waterproofs matrices and allows the formation of a perched water table. It can be observed both in the plateau positions (fig. 11 C) and in the low lying positions of the landscape unit (fig. 11 A and 11 B).

IV - CONCLUSION

This paper discusses structures defined by matrix boundaries and structural relationships. After introducing the method and a number of selected examples chosen from three different continents (Asia, Africa and South America), we have shown that structural studies based on concordant and discordant relationships enable regoliths to be divided into a small number of matrix sets or soil systems. Based on this division, the grouping of matrices into soil systems and domains enables the data gathered during the different stages of characterization of a regolith to be categorised. This division imprints the structure of this regolith and allows it to be represented schematically. From the schematic representation, it is possible, depending on the users, or the objectives, to supply part or all of the data gathered.

Furthermore, the paper shows that the structures and structural relationships are sufficient to demarcate soil systems, but that they are not suitable for characterizing them. It is therefore necessary in a next step to procede with more detailed characterization of organization levels related to the micro-scale (mineral, plasma and matrix). Indeed, the mechanisms and the soil formation processes are only perceptible on that scale. Consequently, it is important to make the distinction between the identification of soil systems already studied in detail where a superficial investigation concerning organization levels at macro-scale (matrix, system) can be sufficient, and the characterization of new soil systems where detailed studies at micro-scale are also necessary.

From this paper, it emerges that there is a very limited number of structure types at macro-scale (boundary structures of a matrix or a soil system). However, identical structures may contain different matrices and, on the contrary, different structures may include the same type of matrix. This explains the extreme diversity and, occasionally, the complexity of regoliths. In the same way, a limited number of soil systems appears to exist. However, the studies undertaken to date would suggest that they would not establish an exhaustive inventory of them and that more structural studies should be conducted.

This method also enables the establishment of affiliated linkage from one matrix to another, and the consideration of a relative chronology in the formation of all the listed matrices. Thus, the method is a mean of retracing the history of the regolith and also of predicting its future mode of evolution.

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