A contribution to an understanding of landscape development through three-dimensional morphological analysis of a pedological cover (Paulinia, State of Sao Paulo, Brazil)

Contribution de l'analyse morphologique tridimensionnelle de la couverture pédologique à la reconstitution de l'évolution du modelé (Paulinia, Etat de Sao Paulo, Brésil)

René BOULET*, Pierre CURMI**, Joël PELLERIN***
AND José PEREIRA DE QUEIROZ-NETO****

Abstract

Three-dimensional organization of a pedological cover, comprising study of the geometrical relationship between horizons and, in particular, concordance/discordance relationship makes it possible to reproduce certain steps of a landscape development.

The studied slope, in the humid tropical zone (Atlantic Brazil), shows a very thick latosolic cover (> 10 m) with subhorizontal horizons upslope. The upper part of this cover is intersected by a thinner pedological differentiation which corresponds to the present day topography. The latter has developed, along the slope, throughout the successive horizons of the thick latosolic cover down to the depth of the substratum. When the substratum is reached, lithodependant soils develop successively on sandstones, siltstones and sandy clays of the Tubarao Formation (Permo-Carboniferous). This discordance between the superficial differentiation and the horizons of the latosolic cover suggests that the former is more recent than the latter. Further downslope a thick cover reappears which may be related to the one found upslope, by means of the study in the horizontal plane. Considering that the geometry of this latosolic cover (limits between horizons and between soil and saprolite) is approximatively parallel to the surface topography which occurred at the time of its formation, we may reconstitute the past topography. The reconstitution seems to show that present topography is partially embedded in the past topography.

Key-words : Ferrallitic soils, landscape development, geometrical relationship between horizons, Brazil.

Résumé

L'organisation tridimensionnelle d'une couverture pédologique, comprenant l'étude des relations géométriques entre horizons, et particulièrement des relations de concordance ou de discordance, permet de reconstituer certaines étapes de l'évolution du modelé.

Le versant étudié, situé en zone tropicale humide (Brésil atlantique), présente à l'amont une couverture ferrallitique très épaisse (> 10 m.) constituée d'horizons à limites subhorizontales. La partie supérieure de cette couverture est recoupée par une différenciation pédologique moins développée. Cette dernière est concordante à la topographie actuelle et s'est développée le long du versant à partir des horizons successifs de la couverture ferrallitique jusqu'au substratum. Lorsque ce substratum est atteint, des sols lithodépendants se forment à partir des

* Mission ORSTOM, Instituto de Geociencia DGG USP, CP 20899 CEP 01498-970 Sao Paulo SP Brésil

** INRA/ENSA, Laboratoire de Science du Sol, 65 Rue de Saint-Brieuc, 35042 Rennes Cedex, France

*** CNRS, Centre de Géomorphologie, Rue des Tilleuls, 14000 Caen, France

**** USP, Departamento de Geografia, CP 8105, CEP 05508 Cidade Universitaria, Sao Paulo SP, Brazil

grès, siltites et argilites de la «formation Tubarao» (permo-carbonifère). Cette discordance entre la différenciation superficielle et les horizons de la couverture ferrallitique implique que la première est plus récente que la seconde. Plus à l'aval, une couverture épaisse réapparaît qui a pu être raccordée à celle de l'amont par l'étude selon le plan horizontal. En considérant que la géométrie de la couverture ferrallitique (limites entre horizons et front de structuration pédologique) est conforme à la surface topographique contemporaine de sa formation, il est possible de reconstituer cette dernière. La topographie actuelle apparaît alors comme partiellement incisée dans cette topographie ancienne.

Mots-clés : Sols ferrallitiques, évolution du modelé, relations géométriques entre horizons, Brésil.

INTRODUCTION

Pedological organization of a portion of landscape has been studied in detail using a methodology which emphazises the geometrical relationships between the different soil horizons and permits discussion about their genesis. This approach enables a new insight in morphogenesis and pedogenesis interconnections. Though this notion is not new (Michel et Tricart, 1965 ; Bourgeat *et al.*, 1973), the proposed method permits a better balance, at a spatial scale, of the interactions between factors which contribute to shape a portion of the landscape.

The selected area is located in the Brazilian humid tropical zone, 23° latitude South, at the Eastern border of the Parana Basin and the Ancient Massif. The landscape, typical of the peripheral depression of the Sao Paulo State, is made of hills and low plateaux over long convexo-concave gentle slopes - maximum altitude range between higher points of the landscape and main

*Fig. 1 – **Représentation en coupe de la couverture pédologique** (les tracés des coupes I et II apparaissent sur la fig. 2)*
Roches mères:
Grès
1 – Horizon sombre compacté de surface
2 – Horizon brun rouge foncé
3 – Horizon sombre de profondeur
4 – Horizon de transition
5 – Horizon 5 YR de la couverture ferrallitique amont
6 – Horizon 2.5 YR de couleur plus vive vers la base
7 – Horizon 2.5 YR vif de couleur constante (>9.5m)
8 – Altérite de grès jaune
8a – Sol de couleur rouge vif
8b – Ligne de nodules ferrugineux de grès
Siltites
9 – Siltite
9a – Sol peu épais sur siltite
Argilite
10 – Altérite argilo-sableuse 2.5 YR à reliques de grès et de siltite
10a – Horizon argilo-sableux, 5 YR, issu de l'altérite 2.5 YR (10)
10b – Niveau mince de nodules brun jaunâtre et brun rougeâtre faiblement indurés
10c – Nodules en plaquettes et globulaires issus de joints sédimentaires oxydés
11 – Horizon polyédrique brun pâle
12 – Horizon lessivé sableux
13 – Horizon jaune-argilo sableux
14 – Horizon hydromorphe sableux, jaune pâle puis gris clair

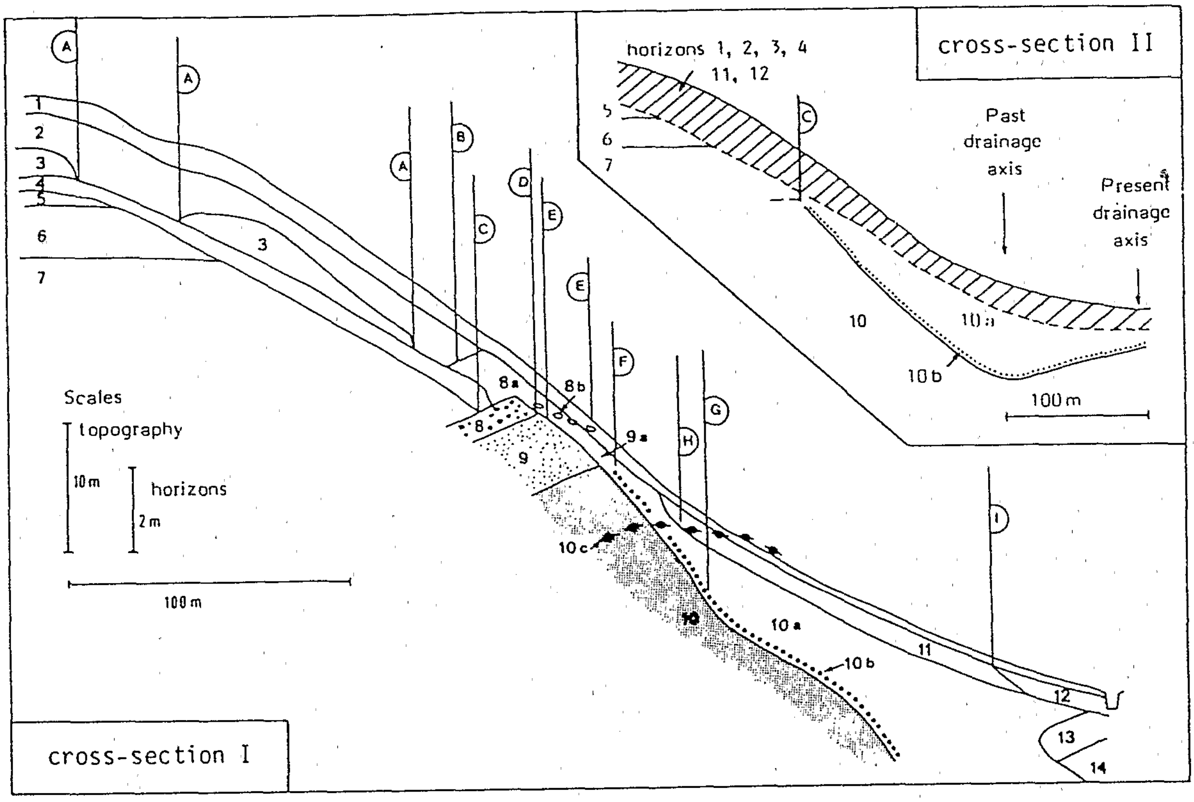

Fig. 1 – **Vertical representation of the soil cover** (cross-sections I and II are located on fig. 2)

Sedimentary parent rocks

Sandstone

1 – Superficial dark compact horizon
2 – Dark reddish brown horizon
3 – Subsuperficial dark horizon
4 – Transitional horizon between the upper dark horizons set and the horizons of the initial cover of soil
5 – Horizon 5 YR of the upslope cover
6 – Transitional 2.5 YR horizon with brighter chroma with depth
7 – Permanent bright chroma 2.5 YR horizon (>9.5 m)
8 – Weathered yellowish sandstone
  8a – Bright reddish brown coloured soil
  8b – Line of ferruginous nodules of sandstone

Siltstone

9 – Siltstone
  9a-Thin soil on siltstone

Sandy clay

10 – Red (2.5 YR) sandy clay saprolite with sandstone and siltstone pedorelicts
  10a – 5 YR soil issued from 2.5 YR saprolite (10)
  10b – Thin line of yellowish brown to reddish brown light indurated nodules
  10c- Platty or globular nodules issued from oxidized sedimentary joints
11 – Polyhedric light brown horizon
12 – Leached sandy horizon
13 – Yellow horizon above ground-water table
14 – Hydromorphic pale yellow and light gray sandy horizon

drainage axis never exceeds 100 meters, 60 m. in this particular site. These plateaux show some closed depressions a few 100 m. wide. This typical geochemical shape landscape is located near cuts, most likely quaternary, related to the Rio Parana sub-tributary (Journaux *et al.*, 1977). Therefore this site was found adequate for testing the three dimensional mapping method. However, in this paper, because of the scale of the study (1/1 000), the discussion will be limited to the data obtained from a small watershed. Some problems - which would need a study on larger watersheds- will remain unsolved for the moment.

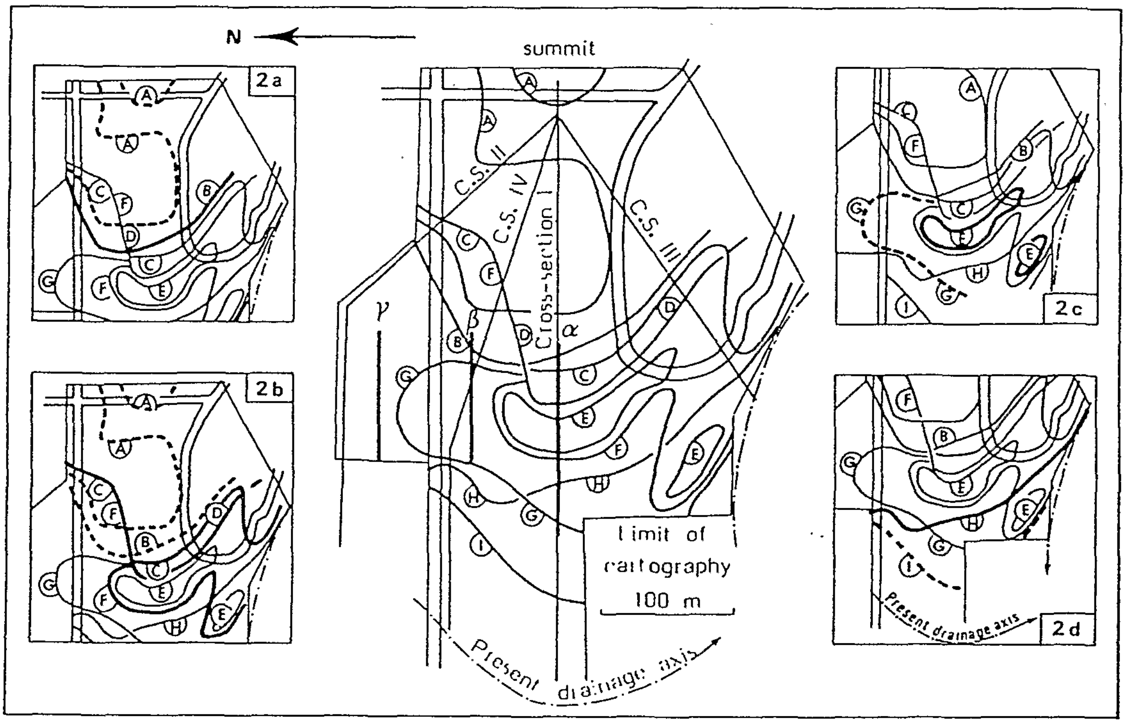

Fig. 2 – **Analytical map of the lateral soil differentiation**

A : Presence of the subsuperficial dark horizon ; B : Upper dark horizon set of less than 1 meter depth ; C : Disappearance of the red 2.5 YR horizon of initial cover ; D : Presence of sandstone at the base of the soil ; E : Presence of siltstone at less than 1 meter depth ; F : Presence of ferruginous nodules at the base of the soil ; G : Presence of nodules at more than 2 meters depth ; H : Polyhedric light brown horizon of more than 30 centimeters thick ; I : Presence of leached horizon associated with a B horizon.

2a : upslope humic latosol differentiation ; 2b : discordance between humic latosol and initial red latosol differentiation ; 2c : «weald» structure in the latosolic cover ; 2d : concordance between downslope differentiation and present topography.

*Fig. 2 – **Projection sur le plan horizontal des courbes d'isodifférenciation***

A : Présence de l'horizon sombre de profondeur ; B : Ensemble des horizons supérieurs foncés de moins de 1 m d'épaisseur ; C : Disparition de l'horizon rouge 2.5 YR de la couverture ferrallitique initiale ; D : Présence de grès à la base du sol ; E : Présence de siltite à moins de 1 m. de profondeur ; F : Présence de nodules ferrugineux à la base du sol ; G : Présence de nodules à plus de 2 m. de profondeur ; H : Horizon polyédrique brun pâle de plus de 30 cm d'épaisseur ; I : Présence d'un horizon lessivé associé à un horizon B.

2a : différenciation du latosol humique amont ; 2b : discordance entre la différenciation humique amont et la différenciation latosolique initiale ; 2c : structure en «boutonnière» dans la couverture latosolique ; 2d : concordance entre la différenciation aval et la topographie actuelle.

MATERIAL AND METHODS

The studied area corresponds to a portion of interfluve of about 10 ha, from the summit to the drainage axis. In the central part, sugar cane had been cultivated for the last six years after 30 years of eucalyptus production. On both sides, there remained a secondary forest that had never been cleared or cultivated. The geological substratum was formed by siltstones, claystones and sandstones from the permo-carboniferous period (Tubarao Group/ Itarare subgroup). This area had a wet tropical climate with 1 400 mm mean annual rainfall, and a rainy summer where mean temperature of the warmest month (January) exceeded 22°C.

Our methodology (Boulet *et al.*, 1982 ; Ruellan *et al.*, 1989)) firstly consisted of a vertical reconstitution of the soil organization along cross-sections parallel to the main slope. This reconstitution enables the definition of the outer boundary of the different horizons, in surface as well as in depth. In a second time, a map was plotted by the projection of these horizons on the horizontal plane (fig. 1 and 2). The lines which delimit these projections are called «isodifferentiation curves». These curves do not separate the space in homogeneous surfaces, as in classical maps, but only delineate either the boundary or thickness variation (arbitrarily chosen) of a horizon or the occurrence of one particular pedological feature. The graphic map thus obtained is a three dimensional representation of the unconsolidated superficial formation and displays distinctly the geometrical relationship existing between the different parts of this formation. It thus allows discussion about their dynamic relationships.

VERTICAL CROSS-SECTION ORGANIZATION

Description

The main cross-section organization (fig. 1) can be divided in three zones :

– upslope, thick, red to reddish brown, microaggregated soils (latosol) ;

– midslope, shallow soils strongly related to lithology ;

– downslope, soils which present polyhedric structures more developed near the surface and textural differentiation («podzolizados»).

a – Upslope, the thick cover (>9,50 m) is constituted by a dark brown superficial set (humic latosol), 2 meters thick and a thick reddish set.

The dark brown superficial set is made of the following horizons :

– 0 to 50 cm – a compact dark brown horizon (1), the high compacity is limited to the cultivated area ;

– 50 to 110/120 cm – a dark reddish brown horizon (2) ;

– 120 to 200 cm – a discontinuous, dark reddish brown horizon (3), darker than the previous. In this subsuperficial dark horizon, charcoal is abundant. This charcoal is also present – but in a weaker concentration – in the upper horizons ;

– 200 to 250 cm – a transitional horizon (4) which presents a lateral colour gradient.

The thick reddish set shows horizons with brighter colours, first 5 YR (5), then 2.5 YR brighter and still brighter (6), to reach, at 6 meters, a 2.5 YR 4/7 horizon (7) which colour remains constant in depth. The contour lines of the soil chroma emphasize the horizontal character of the pedological boundaries within the thick reddish set which are truncated by the dark brown superficial set.

Analysis of the transition between these two sets shows that the dark brown superficial set is developing from more and more deep horizons of the thick reddish cover, as indicated by the hue variation of the transitional horizon (4) directly related to the colour of the parent material. This truncation leads to the disappearance in bevel of the upslope thick reddish cover and raising of the underlying sedimentary formation near the surface.

b. Midslope, in a downward description the following is observed :

– Yellowish sandstones (8) weathering in a reddish clayey sand material. These fine sandstones are the only identified parent material of the upslope thick reddish cover, but upper layers of the sedimentary formation may also be weathered and transformed into this reddish cover.

– Yellowish siltstones (9) also weathering in a reddish clay material ;

– Reddish clayey sand material (10) including sandy pockets of centimetric to decimetric size. This saprolite presents nodular alignments (10c). The very hard ferruginous nodules have platty or globular shape and a friable, non ferruginous, sandy core characteristic of this formation. Alignments have a slant inverse of the slope and probably coincide with sedimentary joints. They run through the soil and constitute successive pavements of nodules at the soil surface.

On these weathered sedimentary layers, soils are shallow (< 1 m) and strongly related to lithology, concerning texture in particular (8a to 10a).

c. Downslope, (lower third), on the reddish clayey sand saprolite (10), the soil is firstly shallow and then becomes quickly deeper (> 4 m) (10 a). This thick pedological cover differs from the upslope one by the colour which is slightly less reddish (5 YR) and by the presence of a fine (5 cm thick) nodular horizon (10b) between soil and saprolite. This nodular horizon differs from the saprolite's nodular alignments (10c). It corresponds to weakly cemented, reddish brown to dark brown ferruginous nodules (< 1 cm diameter) which are located above the saprolite at the limit with the upper soil. Some of these nodules are also sparse in the whole upper soil.

On the upper part of this downslope pedological cover, several differentiations occur successively in the talweg direction :

* first, development of a subsuperficial polyhedric light brown horizon (11)

* then, development of a couple of sandy and clayey sand horizons (12). The upper sandy horizon presents stratifications related to cultural features and a digitated limit with the lower clayey sand horizon. The latter shows clay cutans on structural faces and tubular porosity which suggest that clay translocation is at least partially responsible for the sandy horizon development.

* and finally, close to the valley bottom, a thick sandy, hydromorphic set (13, 14), related to the drainage axis and corresponding to an underflow of water which infiltrates the talweg. The shape of this hydromorphic set can be explained by the downslope feed of the phreatic ground water which thus slightly extends back upslope.

Main cross-section interpretation

Study of this cross-section shows an upper sector with thick, clayey sand, red latosolic cover in which the horizonation is subhorizontal, truncated by a more recent humic latosol (latossolos humicos). The red latosol is the old (or initial) soil cover. The humic latosol is developing from the successive horizons of the red latosol and the humic differentiation is strictly limited to the upslope position.

Midslope, sedimentary rocks or saprolites lead up to the surface due to truncation of the old pedological cover. The in situ sandstone layer extends through the soil for about 10 m. by an alignment of yellowish sandstone relicts more and more oxidized and quartzitic pebbles originating from the sandstone itself. This alignment bends in direction of downslope and remains near the surface until the third part of the slope. Its continuity attests the pedological material autochtony. Its bending is due to the material loss which always follows the rock to soil transformation in well drained conditions. The shallow soils which develop in this portion of the slope are strongly rock dependent.

The downslope podzolic differentiation – light brown polyhedric horizon (11) and sandy horizon (12) – seems to be related to the present topography which will be confirmed by the mapping study.

Lateral variations on this main cross-section are thus controlled by the interference between two pedological developments. An old one which affected an earlier topography and a younger one which is concordant with the present topography and shows toposequential differentiations.

The truncation of the initial red latosol, probably related to erosion, was perhaps initiated by the depression of the dell located south of the section. The latter shows an amphitheatre head whose shape is similar to the closed depressions found in the neighbouring plateaux.

MAPPING STUDY : « ISODIFFERENTIATION CURVE »

«Isodifferentiation curves» have been delineated using three more cross-sections and intermediate observations (fig. 2).

Humic latosol differentiation thicker than 1 m. is limited by curve B (fig. 2a). It is confined upslope. Dark brown subsuperficial horizon (curve A) is discontinuous within the humic latosol (curve B). These curves A and B are crossed by curves C, D and F (fig. 2b) : this means that the humic latosol with its internal differentiation (curves A and B) is independent of the deeper soil differentiation (curves C, D and F) which follows.

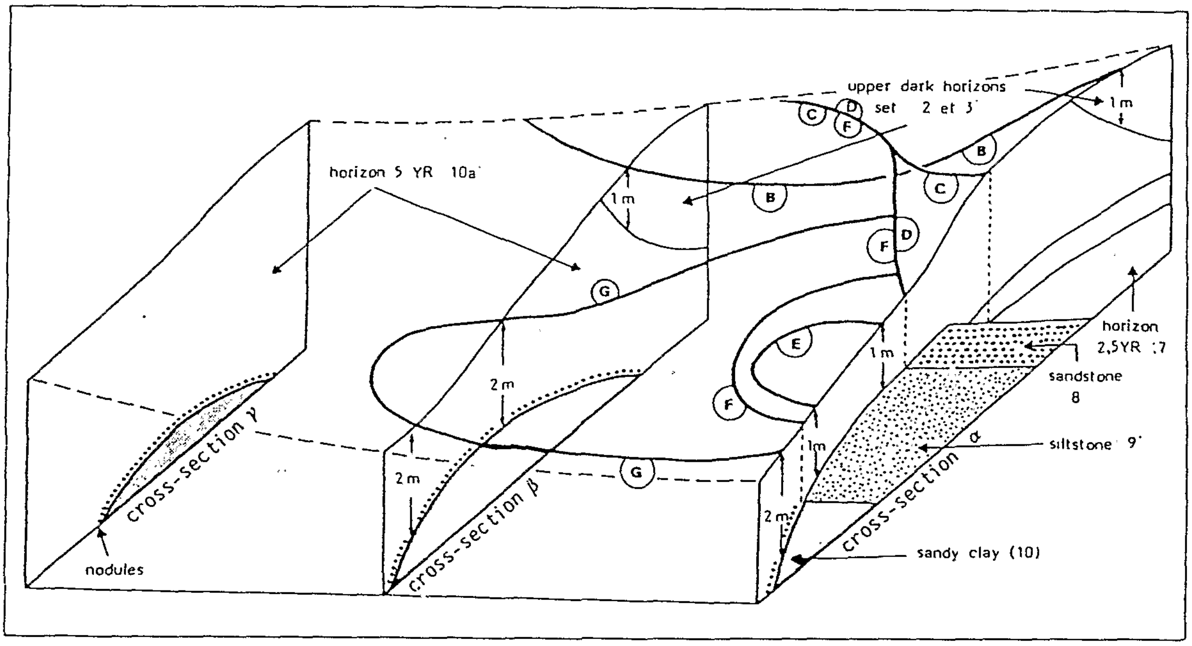

Fig. 3 – **Three-dimensional diagram of the «weald» in the ancient soil cover** (cross-section α, β, γ are located on fig. 2).

Fig. 3 – Bloc diagramme de la «boutonnière» dans la couverture pédologique ferrallitique ancienne (les coupes α, β et γ sont repérées sur la fig. 2).

Curve C delimits horizons with 2.5 YR colour. On cross-section I (fig. 1), it corresponds to the truncation of the thick, red latosolic cover by the topographical surface and to development of shallow soils on the sedimentary sequence (sandstone, siltstone and sandy clay). On cross-section II, the latosolic cover remains thicker than 2 meters but there is also a sharp limit of colour, 2.5 YR to 5 YR upslope to downslope, which could be related to a change in parent material : sandstone to sandy clay. Therefore, this curve which delimits an objective feature -colour- has a complex interpretation.

Curve D delimits sandstone at soil base. It corresponds to a geological limit. Curve E delimits siltstone presence at less than 1 m depth.

Presence of nodules between soil and sandy clay saprolite is delimited by curve F. Curve G marks the presence of these nodules at a depth of 2 m which delineate upper soil of less than 2 m depth (fig. 2c). Together with curve E which locate thinning of soil upon siltstone, they show that the raising to surface of saprolite corresponds to a «weald» in the thick latosolic cover. A second and smaller «weald» type structure appears in the south of the studied area. Three dimensional diagram of the first «weald» structure (fig. 3) shows that siltstones disappear from the sedimentary sequence to the north. In that way, on cross-section β, straight contact between sandstone which is the parent material of the upslope cover and sandy clay is observed from upslope to downslope.

All these curves show clearly in correlation with cross-section I, that the initial latosolic cover subsists with a thickness of at least 2 m on each side of the «weald» drawn by line E and G. The only detectable change into these deep horizons of the pedological cover is colour, underlined by curve C and related to a change in lithology (cross-sections II and III). One may assume there is a continuity between the upslope 2.5 YR latosolic cover developed from sandstone or from upper sediments and the 5 YR latosolic cover developed from the downslope sandy clay. This latter cover therefore belongs to the initial cover.

Lastly, shape of curve H and especially curve I (fig. 2d) which delineate downslope differentiations (polyhedric light brown horizon and sandy leached horizon) show that these differentiations are related to present topography. In fact, where it was mapped, curve I was parallel to the drainage axis.

It is thus possible to define two groups of isodifferentiations curves :

– curves related to truncation of the initial pedological differentiation (C, D, E, F and G) ;

– and curves related to present toposequential differentiation (A,B,H and I).

RECONSTITUTION OF THE SLOPE EVOLUTION

Analysis of the different cross-sections enables the spatial reconstruction of the topography of the old pedological cover. This topography is supposed to be parallel to the pedological structural fronts of the old cover. These fronts correspond upslope to subhorizontal horizonation of the red latosolic cover and downslope to saprolite/soil limit underlined by a fine nodular horizon. The reconstitution corresponds to the present stage of the pedological cover evolution because these fronts are not set and continue to deepen during the present pedogenesis.

The sketch of evolution that can be deduced from comparison between ancient and present topography (fig. 4) shows a smoothing of an initial convexo-concave slope by reduction of the slope rupture. This slope has been locally truncated by erosion, however local landscape has not been completely upheaved. During this geometrical evolution of landscape, equilibrium inside the old cover has been modified and a notable shift of present topography can be noticed. This shift can be appreciated when the location of the old pedological

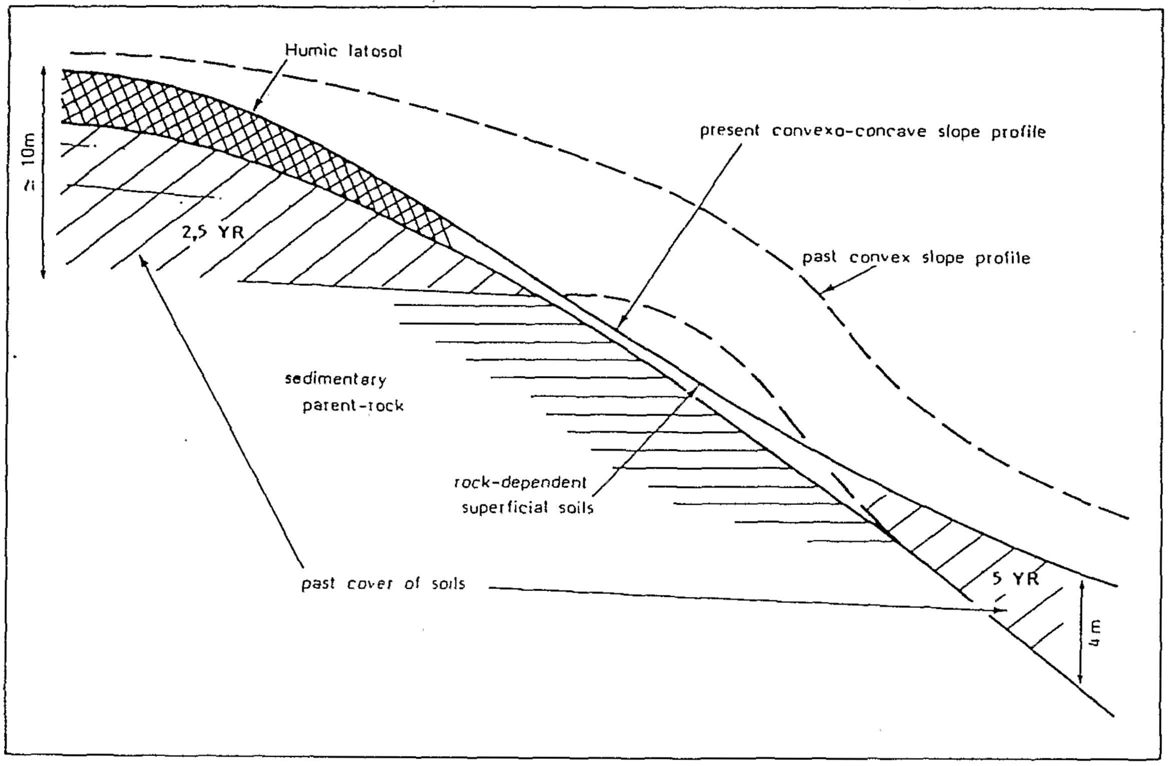

Fig. 4 – **Reconstitution of the slope evolution from results of the three-dimensional analysis** ; smoothing of the primitive break of slope.

*Fig. 4 – **Reconstitution de l'évolution du versant résultant de l'analyse tridimensionnelle** ; effacement de la rupture de pente initiale.*

cover foot-point which is supposed to be straight below its drainage axis is compared with the present drainage axis (fig. 1, cross-section II). In that way, a new topography is superimposed on the former without the complete guidance of the flow pattern of the latter.

CONCLUSION

Spatial relationship between an old pedological differentiation and a discordant more recent one, developing both from the old horizons of the first differentiation and from the parent rocks, is one of the main elements allowing understanding of this type of soil organization.

Nevertheless, if erosion appears as the main mechanism of this evolution, colluvial material has not be noticed downslope. On the contrary, sandstone relicts and ferruginous nodules distribution demonstrate material autochtony down to the last quarter of the slope. Further downslope, observed modifications can be attributed to pedological processes : leaching and clay illuviation, hydromorphy.

The study has shown that lateral variations of soils are related to successive and probably constant readjustments of pedogenic and morphogenetic processes. With regards to soils, lateral differentiations are correlated either with variation in parent material (from pedological or lithological origin), or with toposequential differentiation. With regards to landscape, when the mechanisms which are responsible for the slope unbalance are to be found at a larger scale in the landscape, it has been pointed that the local hydrographic network was not shaped during the recent period. Most of it was already existent. It is a matter of landscape evolution and not the development of a new morphology.

Finally, the detailed mapping makes it possible to quantify the importance of volumes which are concerned by landscape evolution of a small watershed. Estimation of the thickness of erosion truncation, at midslope, ranges between 10 meters (upslope latosol thickness) and 4 meters (downslope latosol thickness). The area affected by this erosion can be estimated using isodifferentiation curves E and G (fig. 2c) which delineate thickness of the present soil cover (fig. 2c). Three-dimensional mapping methodology is therefore not only a theoretical and qualitative approach of pedomorphic evolution but also a source of quantitative information.

Acknowledgments

This research was supported by France/Brazil bilateral conventions (CAPES-COFECUB and CNRS-CNPq) and by FASESP (Fundacao do Amparo a Pesquisa da Universidade de Sao Paulo)

References

Boulet R., Chauvel A., Lucas Y. et Humbel F.X. (1982) – Analyse structurale et cartographie en pédologie. I. Prise en compte de l'organisation bidimensionnelle de la couverture pédologique : les études de toposéquences et leurs principaux apports à la connaissance des sols. *Cah. ORSTOM* sér. Pédologie (XIX), 4, 309-322 – II. Une méthode d'analyse prenant en compte l'organisation tridimensionnelle des couvertures pédologiques, ibid., 323-339 – III. Passage de la phase analytique à une cartographie générale synthétique, ibid., 341-351.

Bourgeat F., Sourdat M. et Tricart J., (1979) – Pédogénèse et morphogénèse d'après des exemples à Madagascar. *Revue de Géographie de Madagascar*, 35, 9-54.

Journaux A., Pellerin J., Coutard J.P., Pereira de Queiroz Neto J., et Ozouf J.C. (1977) – Morphogénèse quaternaire et pédogénèse dans l'état de Sao Paulo, in Recherches Géomorphologiques sur le Quaternaire brésilien, Recherches Françaises sur le Quaternaire, INQUA 1977, supplément *Bull. Ass. Fr. Etude Quaternaire*, 50, 295-301.

Ruellan A, Dosso M et Fritsch E. (1989) – L'analyse structurale de la couverture pédologique. *Science du Sol*, 27, 4., 319-334.

Tricart J., Michel P. (1965) – Morphogénèse et pédogénèse, I – Approche méthodologique : géomorphologie et pédologie. *Science du Sol*, 2, 149-171.

7/24

Géomorphologie

Reliefs . Processus . Environnement

GFG

SEDES

Revue du Groupe Français de Géomorphologie